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ORIGINAL RESEARCH ARTICLE

Assessing the Impact of Urbanization, Mining, and Agriculture on Subsurface Structures Using GPR, ERT, and Seismic Reflection

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ABSTRACT

This study uses geophysical methods to explore the effects of urbanization, mining, and agriculture on subsurface features, including ground-penetrating radar (GPR), electrical resistivity tomography (ERT), and seismic reflection. A three-part systematic approach of scenario modeling, geophysical data collection, and interpretation was utilized to analyze how human activity modifies subsurface features by examining three scenarios of urbanization, mining activity, and agricultural practice. These modifications substantially impact groundwater structures, geological systems, and the stability of entire ecosystems, specifically resulting in changes in subsurface properties through anthropogenic activities. In the scenario of urbanization, ERT data highlighted resistivity of up to 3,000 Ωm in dry clay layers as a result of impenetrable surfaces, and the wave velocities determined via seismic reflection indicated velocities of over 2,500 m/s due to compaction of soil. The results from the mining activity also exhibited changes in excavated subsurface features and evidence of voids and fractures with seismic wave velocities substantially dropping from 2,500 m/s to1,600m/s, indicating structural failure while the agricultural practice scenario investigated through agricultural impacts via moisture retention with ERT data representing resistivity from high moisture of 200 Ωm to low moisture of 1,500 Ωm, exhibiting how intensive farming exploits subsurface moisture. These results highlighted the high importance of comprehensive geophysical assessments related to urban planning, mining regulations and agricultural practices. These identified quantifiable impacts rely on the methods mentioned to assess how human activities have impacts on subsurface structures. All of these assessments can be utilized as responsible subsurface resource management and environmental preservation tools, alerting stakeholders to the effects of increasing human encroachment on subsurface structures and properties affecting subsurface ecosystems.

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INTRODUCTION

The subterranean environment determines the general condition of the Earth's ecosystems (Zhai *et al*., 2021). Besides providing crucial resources such as minerals, fossil fuels, and groundwater (Parnell & Walawege, 2011), it is also a site for complex geochemical reactions promoting life above ground (Zhang *et al*., 2020). However, the most important changes in subsurface systems have resulted from human activities such as resource exploitation, industrialization, and urbanization (Molua *et al*., 2024). These transformations can hamper groundwater supply and quality, affect natural processes, and degrade geotechnical integrity (Xian *et al*., 2007; Mohamed *et al*., 2023). Coupling between human growth and geological settings has imparted significant benefits such as economic boom and improved living (Kwan & Reford, 2025). However, this progress often comes with a handful of negative interference with the subsurface structures, which can have long-lasting implications on the geological balance, water structures, and overall well-being of the ecosystem (Molua *et al*., 2024). Understanding human activities' impacts is critical for dealing with the stability between development and environmental stewardship (Zhang *et al*., 2020). In order to bring about sustainable, useful resource control and protect environmental health,

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it is important to understand how anthropogenic processes affect the subsurface structural build-up (Abdelfattah *et al*., 2023; Ikuemonisan & Ozebo, 2020). Land use and surface hydrology are affected by urbanization (Yang et al., 2011), usually resulting in more impervious surfaces that alter the hydrological mechanism and reduce natural groundwater recharge (Keisham *et al*., 2022; Balocchi, 2024). The stability of the subsurface environment may be altered due to industrial activities such as drilling and mining, which can result in ground subsidence (Chen *et al*., 2014; Ikuemonisan & Ozebo, 2020). Despite its usefulness for food production, agricultural activities can negatively affect the subsurface condition by tampering with moisture dynamics and soil compression (Mrudula *et al*., 2025). These alterations describe the way the subsurface health and surface mechanisms are intertwined (Pueyo-Anchuela *et al*., 2011). Effective monitoring and assessment are required to reduce the likely negative effects that may hamper subsurface environments (Reyes, 2023). Geophysical techniques have become a requirement for determining the conditions and alterations made to the subsurface structure, particularly those generated by human activities (Carlson et al., 2011). These techniques are intrusive approaches that enable scientists and practitioners to identify abnormalities, track temporal changes, and make effective land and resource management decisions because they enable each direct and indirect measurement of subsurface properties (Gabera et al., 2023). Seismic reflection, electrical resistivity tomography (ERT), and ground-penetrating radar (GPR) are the geophysical technologies most often applied for this purpose (Maju-Oyovwikowhe *et al*., 2024). Each technique has certain strengths and can offer supplementary information regarding subsurface properties, making entire know-how of all anthropogenic impacts and natural systems feasible. By exciting growing acoustic waves reflecting off base geological surfaces, seismic reflection uncovers the subsurface systems and stratigraphy (Abdelfattah *et al*., 2023; Hasan *et al*., 2021). This technique is effective, especially in identifying possible dangers like voids developed through mining processes and detecting structural changes developed through exploitation and urbanization (Fitzpatrick et al., 2005). ERT provides a measure of the electrical resistivity of sub-surface materials, which helps to identify changes caused by processes like contamination or compaction of soil (Umar et al., 2024; Abdelmoneim et al., 2025). ERT is also well-suited to identify the impact of agricultural activities and industrial pollutants on groundwater quality because it can recognize moisture content and impurities (Zahoor & Mushtaq, 2023). GPR provides high-decision data about shallow strata and subsurface anomalies by imaging the subsurface using radar pulses (Bowell, 2023). GPR is most useful in the detection of features like trenches, voids, and buried services in urban areas and near commercial zones with regard to effective evaluation (Abdelsamei et al., 2024). Researchers can thoroughly examine subsurface conditions by combining geophysical techniques with simulation and predictive modeling processes (Hossam *et al*., 2024; Li *et al*., 2020). Although geophysical techniques look promising, there are nonetheless a number of barriers to successfully assessing human impact on subsurface systems. Interdisciplinary collaboration between geophysicists, geologists, hydrologists, town planners, and policymakers is vital to effectively address the challenges posed by human activities on subsurface structures. Simulating extraordinary anthropogenic scenarios provides the anticipation of changes in subsurface structures, inclusive of potential risks and their implications for groundwater and the management of inherent resources (Xu & Zhang, 2024). Geophysical facts can inform policy choices, allowing stakeholders to put in force-centered interventions that improve sustainability and minimize poor environmental effects (Ojo *et al*., 2024; Morsy, 2025). The need for effective monitoring and control of subsurface resources is becoming increasingly indisputable as the world's population continues to progress geometrically and urbanization is briskly achieved. The purpose of this study is to use geophysical techniques to provide a complete evaluation of ways human activity affects underlying structures. Despite increasing awareness of geophysical methods, such as ground-penetrating radar (GPR), electrical resistivity tomography (ERT), and seismic reflection, the use of these methods to systematically detect the impacts on subsurface structures resulting from urbanization, mining, and agriculture remains inadequately studied. This study addresses that gap in the literature by using the three methods simultaneously so that a complete evaluation of subsurface changes can be done. By combining these geophysical approaches, we can gain insight into how complementary methods can enhance the understanding of anthropogenic impacts because certain features are more easily recognized by a particular geophysical survey method. Additionally, generating unique predictive models from simulated data can provide an idea of the future geologic state, thus assisting with the responsible management of subsurface resources and aiding in protective measures against anthropogenic impacts. A critical analysis of the impact of human activities in this research seeks to guide the development of functional approaches that will maintain the integrity of the subsurface environments and ecosystems for generations to come.

MATERIALS AND METHODS

The methodology exhibits a systematic approach taken in evaluating the causative effect of human activities on buried structures through the application of geophysics (Teweldebrihan, 2024). The method entails three (3) primary phases: simulation of data and development of scenario, acquisition of geophysical data using diverse strategies, and data interpretation and analysis (Oluwatobi *et al*., 2020). Each component is targeted towards addressing impacts stemming from agricultural practices, urbanization, and mining, giving room for a clear and deep knowledge of how these activities change subsurface features (Li *et al*., 2024).

Data Simulation and Scenarios

Datasets developed through simulation were to represent coverage of human interferences and their respective influences on subsurface systems (Duinker & Greig, 2007). To acquire this, three clear scenarios were modeled, giving rise to an evaluation of changing subsurface conditions and reactions to various human interventions.

Scenario 1: Urban Development

This scenario simulates the effects of new a vicinity brought about by urbanization, which is characterized by large impervious surfaces resulting from the construction activities on the land (Mahapatra, 2023). These surfaces affect natural groundwater recharge, tampering with the hydrological mechanisms of both the subsurface and surface environments (Netti et al., 2024).

- **Model Setup**: The simulation entailed creating an artificially made geological model representing different soil layers (e.g., sand, gravel, clay.) common in urban areas (Netti et al., 2024).
- **Parameterization**: Salient parameters comprised changes in resistivity and hydraulic conductivity due to soil lumping and artificial land seals (Jian et al., 2021). Groundwater levels were also modeled to simulate variability in recharge patterns common in urban catchments (Steinman et al., 2004).
- **Outcome Projections**: Anticipated outcomes include the reduction of groundwater upwards migration levels and variability in permeability (Zhai *et al.*, 2021), indicating evidence of the role of achieved urbanization on hydrology and subsurface stability beneath.

Scenario 2: Mining Activities

This scenario evaluates the impact of subsurface mining processes, such as open pits and underground reduction on geological stability and groundwater flow dynamics (Takele *et al* ., 2025).

- **Model Setup**: A three-dimensional model joining geophysical features representing a mining location was developed (Khan *et al.*, 2022). This included layers of mineral deposits and different nearby rock formations (Duinker& Greig, 2007).
- **Parameterization:** Changes in mechanical properties, such as Poisson's ratio and elastic moduli, were characterized to reenact the impacts of excavation (Altun et al., 2010). The remaining voids caused by mining exercises were too checked to analyze the possibility of ground subsidence.
- **Outcome** Forecasts: The recreation pointed to anticipate changes in groundwater flow ways (Zhang *et al.*, 2020), with an expected diminish in aquifer pressure and proof of potential surface distortion as a result of mining operations.

Scenario 3: Agricultural Practices

This scenario simulates the effects of serious agrarian hones on soil properties and groundwater quality (Mihelič et al., 2021).

- **Model Setup**: The simulation entailed different types of soil commonly found in agrarian districts and joined practices such as culturing and irrigation systems (An & Zhang, 2022).
- **Parameterization**: Changes to soil features, such as water holding capacity, compaction levels, and the profile of inherent contaminants (e.g., fertilizers, pesticides) were figured into the developed model (Rajan *et al.*, 2023).
- **Outcome Forecasts**: Anticipated outcomes included expanded soil compaction influencing water invasion rates and changes in electrical resistivity due to the presentation of agrarian chemicals into groundwater frameworks (Akankpo & Igboekwe, 2011).

Improvements in the Simulation Process

Our human activity scenario simulation process was intended to give a feeling of real-world conditions by using various parameters that exhibit normal geological settings. Many of the same it is obligatory to be aware of both the basic principles and the limitations that we may meet in the course of our modeling.

Assumptions:

• The assumption underpinning the creation of soil profiles was that they were the typical urban and agricultural ones which are also present in areas with soil profiles identical to the ones observed in this study. For instance, median values of hydraulic conductivity were supposed: silt was depicted with a hydraulic conductivity level of 5×10^{-4} m/s, while fine sand was given a lower value of 1×10^{-6} m/s (Jian *et al.* 2021).

• The dielectric constants that would be used for the different materials employed in the GPR simulations were calculated from the literature that was available. For example, soil layers had limit values of 4 (for sandy soil) and 30 (for moist clay) to convey the feeling of normal conditions (Poluha *et al.*, 2017).

Limitations:

• A good part of the variables that are found in the real world are not the subject of representation by the models, e.g., seasonal changing groundwater levels and diurnal temperature, which causes the change in soil moisture.

• Our simulations have no provisions for transient events such as severe weather conditions that would, in turn, initiate strange subsurface responses.

Geophysical Data Collection

For each scenario, geophysical estimations were simulated utilizing program bundles optimized for particular techniques (Salmi & Sellers, 2022). The subsequent methods were employed to survey the underground structures:

Seismic Reflection

1. **Generation of Data**: Synthetic seismic simulating reflection data were created by program tools such as wave propagation simulation tools that were used to detail topographical models (García-Muñoz *et al.*, 2023). This involved specifying sample seismic velocities for topographical layers and supplying parameters for the properties of a wave source (e.g., frequency, source type).

2. **Analysis Parameters**: The parameters employed were reflection and incidence angles, enabling the simulation of seismic wave interactions with modified geological structures (Tiwari et al., 2023).

3. **Output**: The reconstructed data produce analyzable reflection profiles to detect alterations in subsurface layering and identify inconsistencies caused by human interventions (Forte *et al.*, 2014).

Electrical Resistivity Tomography (ERT)

1. **Simulation of Data**: ERT data were simulated with the assistance of expressing resistivity measurements of various geological media in terms of scenario-dependent conditions (e.g., lumped, unsaturated soils vs. unfastened, saturated soils) (Umar et al., 2024).
2. **Measurement Configuration**: The existing ERT configuration (e.g., Wenner, dipole-dipole) has been applied, and resultant resistivity has indicated changes due to the stimulated human activity (Parnell & Walawege, 2011).
3. **Outcome**: The simulation facts of ERT offer details regarding resistivity profiles that reflect lumping or contamination zones, showing the impact of agriculture, mining, and urban development on subsurface conditions (Michot et al., 2003).

Ground-Penetrating Radar (GPR)

1. **Data Simulation**: GPR data were developed to show radar wave engagement with varying below-surface substances and embedded structures underlying each of the situations (Xian et al., 2007).

2. **Scenario-Specific Modifications**: Parameters that are related to the dielectric constants of each identified material layer were adjusted based on the expected modifications due to human activities (Poluha et al., 2017).

3. **Output**: The statistics of the resultant GPR clearly show the reflectivity profiles, pinpointing anomalies in the subsurface inclusive of voids or potential contamination areas that are the resulting effects of different human interference situations (Xie et al., 2025).

For effective simulation and data analysis, several software packages were employed throughout the process:

- **Seismic Reflection:** Data was simulated using specialized software such as SeisImager and GeoDepth. These tools generate synthetic seismic reflection data based on input layer parameters.

- **Electrical Resistivity Tomography (ERT):** Resistivity modeling was conducted using RES2DINV. This software allows for the inversion of resistivity data collected through various array configurations like Wenner and dipole-dipole.

- **Ground-Penetrating Radar (GPR):** GPR data was simulated and analyzed with GPR-SLICE or GPRMAX. These tools facilitate modeling electromagnetic wave propagation in the subsurface and provide outputs related to signal amplitude and reflection profiles.

Parameter Values

A comprehensive, detailed parameter value used in the modeling scenarios is shown in Table 1 below.

Table1: Parameter Values Used in Modeling Scenarios

Parameter	Urban Scenario	Mining Scenario	Agricultural Scenario
HC (m/s)	5 x 10^{-4} (sand)	2 x 10^{-5} (comprised layers)	1 x 10^{-6} (clay)
Poisson's Ratio	0.3 (soil)	0.25 (compacted areas)	0.3 (tilled soil)
Dielectric Constant	4-30	Variable based on voids	6-25 depending on moisture content

HC = Hydraulic Conductivity

Empirical data from literature and previous field studies informed the choice of the numerical ranges to enhance the model's realism.

Data Interpretation and Analysis

The simulated geophysical data were analyzed using installed interpretation strategies tailored to every approach, extracting significant insights regarding subsurface modifications induced via human activities (Oluwatobi *et al.*, 2020).

Seismic Reflection Data Interpretation

1. **Inversion Techniques**: Seismic inversion algorithms have been implemented to transform mirrored image information into underground models (Hasan *et al.*, 2019). These algorithms

reorder the geological features and identify regions altered by human actions.

2. **Migration Methods**: Traditional seismic migration methods were used to correct for wave propagation outcomes (Gabera et al., 2023), enabling improved visualization of subsurface structures and understanding of their spatial relationships (Dzulkefli *et al*., 2023).

Electrical Resistivity Tomography (ERT) Data Interpretation

1. **Inversion Algorithms**: ERT information has been interpreted utilizing inversion algorithms that restructure resistivity models based totally on the amassed information (Reid & Castka, 2023). The algorithms visually represent resistivity changes, highlighting areas affected by human activities (Gonçalves *et al*., 2021).

2. **Spatial Analysis**: The obtained data underwent spatial analysis methods to correlate the variation resistivity with specific human activities, assessing features that symbolize contamination or compaction (Carrera *et al*., 2024).

Ground-Penetrating Radar (GPR) Data Interpretation

1. **Hyperbola Analysis**: Interpretation of GPR data involves analyzing hyperbolic reflections to select subsurface structures which are typical of human interferences (Fitzpatrick et al., 2005). Every hyperbola matches voids, discontinuities, or interfaces beneath the ground.

2. **Feature Extraction**: Automation strategies have been used to extract features, inclusive of voids or layers representing changes from diverse human activities (An & Zhang, 2022), thus aiding quantitative evaluation of the influences figured out by means of the simulations.

Geophysical Methods Description

Geophysical methods provide a set of non-invasive techniques that enable researchers to acquire essential information about subsurface underlying structures and their properties (Yin *et al*., 2025). Utilizing these methods facilitates the assessment of human effect in a manner that minimizes disruption to the environment (Li et al., 2024, Romero-Ruiz et al., 2018). Here the focal point will be on three primary geophysical methods: seismic reflection, electrical resistivity tomography (ERT), and ground-penetrating radar (GPR).

Seismic Reflection

Seismic reflection is a crucial geophysical approach that entails the generation of seismic waves, which travel through the Earth and show the mirror image of subsurface geophysical interfaces (An & Zhang, 2022). By studying the waves of the mirrored image, researchers can determine the stratigraphic sequence and the underlying structure of subsurface environments (Omunguye & Akpila, 2013). This is especially a deep approach to delineating geological layers' modifications resulting from activities like urban development and resource exploitation, which are human-precipitated (An & Zhang, 2022). Alterations in the velocities of seismic waves help in the detection of variations in subsurface materials and their densities. This data is essential for identifying areas affected by the activities of human, like pollution or imbalance (Hasan et al., 2019). For instance, sites frequently used for heavy construction work often lead to the alteration of ground response to seismic waves. This is indicative of soil lumping due to compaction and the use of heavy engineered materials (Bertoni et al., 2020). The capacity of seismic mirrored image to provide vertical resolution makes it a useful tool for characterizing several layers' underlying structures in urbanized areas (Forte *et al*., 2014).

Electrical Resistivity Tomography (ERT)

Electrical resistivity tomography (ERT) is a geophysical method that assists in measuring the electric resistivity of subsurface environments (Liu *et al*., 2024). This approach introduces electric currents into the subsurface and analyzes the resulting voltage variations (Bricker *et al*., 2024). The geological environment's resistivity can provide information about its composition, moisture content, and potential level of pollution (Ünal *et al*., 2020). Human activities can significantly affect the profile of subsurface resistivity (Ávila-Carrasco et al., 2023). For instance, long-lasting soil compaction from urbanization typically spikes the resistivity values due to a reduction in pore space and controlled moisture-holding potential made possible by providing developmental amenities like bridges (Jat *et al*., 2009). Conversely, areas impacted by pollution, such as industrial runoff, may also display decreased resistivity values due to accelerated conductivity from contaminants (Omunguye & Akpila, 2013). ERT's functionality to map resistivity changes in more than one dimension permits for comprehensive analysis of changes in subsurface conditions, making it particularly credible for monitoring hydrogeological effects (Wu *et al*., 2022).

Ground-Penetrating Radar (GPR)

Ground-penetrating radar (GPR) is a geophysical technique of high resolution that uses radar pulses to mirror the underground environment (Poluha *et al*., 2017). It is particularly active in mapping near-surface stratigraphic characteristics and pinpointing discontinuities, like structural voids, subsurface fractures, or anthropogenic build-ups (Akinsunmade, 2021). GPR works by emitting electromagnetic (EM) radiations that penetrate the subsurface and mirror off materials based on the peculiarity of their dielectric features (Abdelsamei et al., 2024). This method is particularly applicable in urban settlements where underground features, like historical remnants or buried utilities, may exist with human-induced variations (Famiglietti *et al*., 2024). GPR can show underlying anomalies brought about by excavation, agricultural practices, or construction, making available important information for mitigating impending risks associated with underground instability (Di Prinzio *et al.*, 2010). The fast and high-resolution output acquired by using GPR makes it an effective practical technique for detecting impacts in various geographical settings (Di Prinzio *et al.*, 2010).

Human Activities Impacting Subsurface Structures

Human activities exert huge pressure on subsurface systems, resulting in a series of environmental impacts. Key areas of challenge include agricultural practices, urbanization, and resource extraction, all contributing to significant alterations of underground features (Mahapatra, 2023).

Agricultural Practices

The other significant human activity that contributes to subsurface features is agriculture (Mojžiš *et al.*, 2024). Intensive farming practices like irrigation, ploughing and fertilization can lead to an enormous alteration in soil, which can directly disrupt moisture retention and groundwater permeability (Mpanga, 2022). When the soil's structure becomes damaged, it can prevent water from soaking into the ground properly. This can cause severe soil erosion and make water flow quickly over the land's surface. According to a study by Agrawal et al. (2021), this is a significant concern. Modern agricultural practices, like the use of pesticides and fertilizers, can cause the chemicals to percolate into the soil. Leakage of the used chemicals contaminates water sources and lower underground water quality Rajan *et al.*, (2023). Issues like this can hamper the well-being of soil and inherent water well-being, making careful approaches to reduce effects very important when embarking on any agricultural activities (Shukla et al., 2023). Urbanization, mining, city and agriculture pressurize the subsurface systems (Bikis et al., 2025). Scientists use geophysical techniques to gather essential and valuable information about changes in the subsurface and these pieces of information are germane in making policies targeted at resource protection and long-lasting environmental practice support, as stated by Yang *et al.*, (2021).

Urbanizations

As urbanization expands, construction activities restructure land cover and near-surface hydrology (Bikis *et al.*, 2025). The spread of impervious surfaces, such as concrete and asphalt, disrupts natural groundwater recharge mechanisms, usually resulting in alteration in groundwater flow patterns and reduction in aquifer renewal (Jat *et al.*, 2009). Urbanization can exacerbate challenges such as flooding due to enormous surface runoff and reduced water permeation rate (Agrawal *et al.*, 2021). Additionally, the compaction and excavation of soil at some construction stages can snowball into alterations in subsurface stress distribution, leading to potential risks like land subsidence and structural collapse (Xie *et al.*, 2025).

Resource Extraction`

Resource exploitation activities, including oil drilling, gas extraction, and mining, indirectly and directly impact underground environments (Keisham *et al.*, 2022). The aforementioned practices often involve the displacement and removal of geological constituents, resulting in the development of voids or underground instability (Wegenast *et al.*, 2024). Mining activities can lead to strong ground vibrations and large ground subsidence, which can destroy the environment and cause structural failure on the ground above. Additionally, extraction of other natural resources can disrupt groundwater refill mechanisms as the change in the pathways of water and its flow pressure can result in groundwater depletion or pollution.

The approach outlined in this study demonstrates an effective method to evaluate the impacts of anthropogenic activities as they pertain to subsurface features through geophysical methods. The scope of this research aims to measure and define the dynamic characteristics of the earth's subsurface using different approaches for specific conditions, thereby contributing to effective environmental management and monitoring (Chukwuma et al., 2023). Using data simulation, collection, and sturdy analysis, the results are anticipated to decide future environmental strategies and interventions to mitigate anthropogenic activities' outcomes (Steinman *et al.*, 2004).

Scenario Justifications

The justification for geological models is elucidated below:

Urban Development

The selection of sand, gravel, and clay layers reflects common construction materials and soil types found in urban settings (Netti *et al.*, 2024). These soil types were chosen due to their prevalent use in pavement and construction, thus modifying subsurface hydrological dynamics.

Mining Activities

Geological models incorporated voids and fractured formations representative of typical mining operations such as open-pit and underground mining effects (Takele *et al.*, 2025). Such features have been verified with field data indicating disruptions commonly associated with mineral extraction activities.

Agricultural Practices

For agricultural simulations, soil types ranging from compacted soils to moist irrigated layers were selected based on common agricultural practices in the region (Mihelic *et al.*, 2021). The inclusion of fertilizers and moisture content provides an overview of the implications of agricultural management on subsurface structural integrity.

Field Validation

To ensure the modeling approach's validity, the simulated data findings were compared with field measurements obtained using GPR, ERT, and seismic reflection techniques in respective anthropogenic settings. Validation studies have been conducted in collaborative projects with local universities and government agencies, corroborating the simulated scenarios with real-world geological surveys (Chukwuma *et al.*, 2023).

RESULTS AND DISCUSSION

Results

In this section, results from the utilization of geophysical techniques, particularly seismic reflection, electrical resistivity tomography (ERT), and floor-penetrating radar (GPR), are discussed in relation to the three human activities assessed: urban development, mining activities, and agricultural practices. Every chapter of the study describes critical findings that correspond with predictions made during the simulations.

Urban Development

We observed the impact of urban expansion on the subsurface layers, which is a remarkable finding. These changes were primarily found using seismic reflection, which is a wave-based imaging technique (Parsons, 2021). The data from the seismic measurements indicated a notable increase in wave velocity in the superficial ground layers. This could be attributed to superior soil compaction and the extensive use of construction materials (Bricker *et al.*, 2024). Table 2 shows the seismic reflection data for urban development and Figure 1 is the depth against velocity of the same data.

Table 2: Seismic Reflection Data for Urban Development

Depth (m)	Velocity (m/s)	Layer Type
0	2000	Compacted Soil
10	2500	Sand
20	1500	Clay
30	1800	Gravel

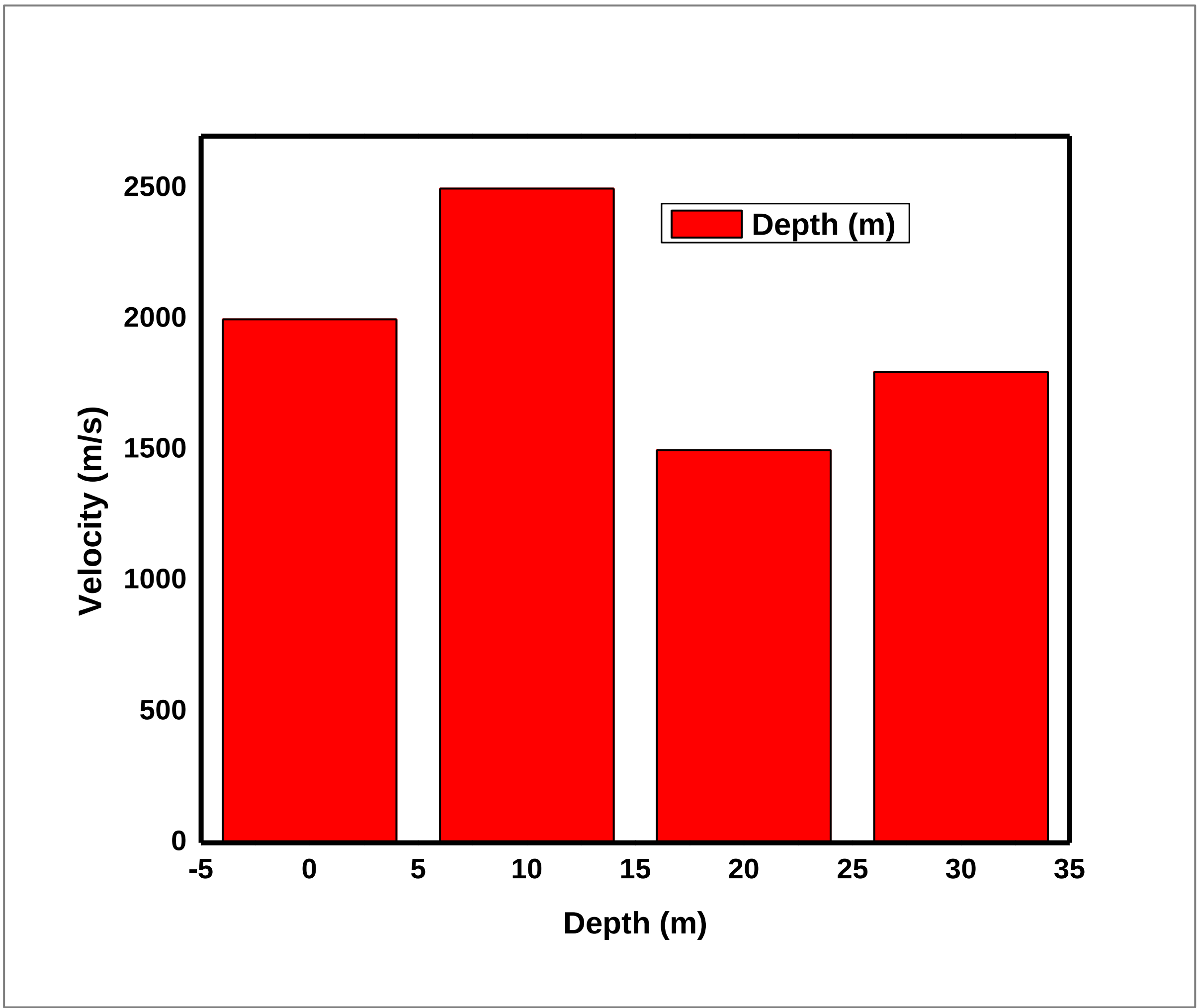

Figure 1: Graph of Depth (m) Against Velocity (m/s)

This change reveals to a total shift in subsurface features attributable to urbanization. The ERT results also indicated a rise in resistivity values closer to the surface due to the presence of impermeable pavements e.g., asphalt and concrete (Chen *et al.*, 2014). The ERT-type data as it relates to urban development can be found in Table 3 and Figure 2 is the depth against resistivity of the same data.

The increased resistivity values had been coupled with adjustments in the groundwater model, illustrating the disruption of natural recharge procedures (Uhlemann, 2017, An & Zhang, 2022). It can visualize the typical moisture channeling within an urban area, indicating how urbanization can redirect and confine pathways of groundwater movement (Omunguye & Akpila, 2013). All in all, the results from this case study illustrate that urbanization now affects surface hydrology but, more importantly, alters subsurface moisture and geological activity (Yang et al., 2021).

Table 3: ERT Data for Urban Development

Depth (m)	Res. (Ωm)	Soil Condition
0	1000	Dry Compacted Soil
10	500	Saturated Sand
20	3000	Clay (Dry)
30	1500	Gravel

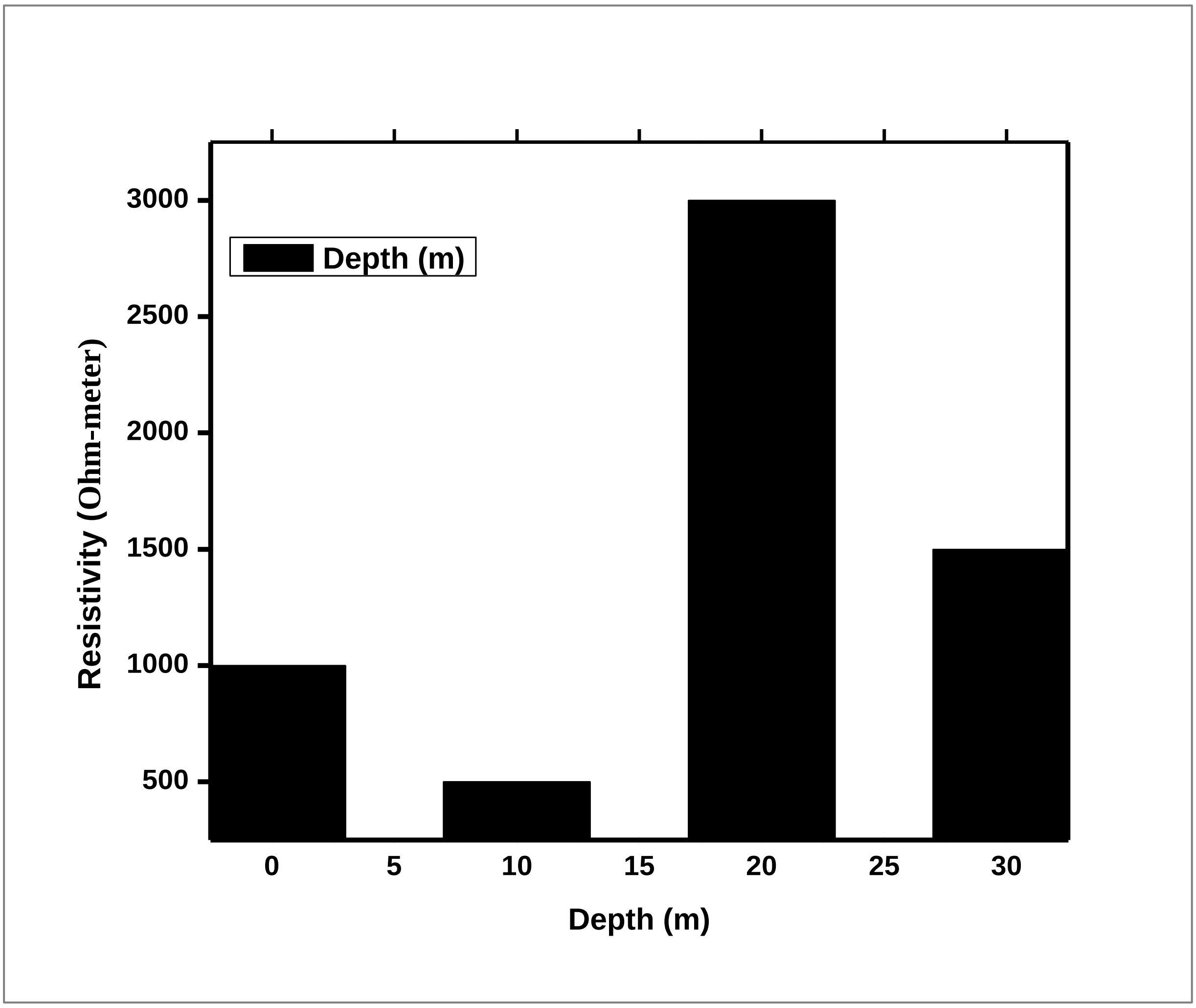

Figure 2: Graph of Depth (m) Against Resistivity (Ωm).

Mining Operations

The assessment of mining operations with geophysical techniques also indicated considerable subsurface changes (Jat et al., 2009). Simulated GPR data played an invaluable role by providing unambiguous images of voids and fractures presumably indicating mines (Bowell *et al*., 2023). Table 4 shows the GPRdata for mining activities and Figure 3 is the depth against feature type of the same data.

Table 4: GPR Data for Mining Activities

Depth (m)	FD	Description
0	Void	Excavation Site
10	Fractures	Structural Weakening
20	Band	Remnant Ore Layer

FD: Feature Detected

The hyperbolic anomalies found in the GPR investigated were indicative of excavated areas, revealing the potential for ground subsidence (Bricker et al., 2024). The seismic reflection records elucidated the extent of structural integrity loss of surrounding geological formations. The imaging indicated the deformation and faulting of subsurface strata adjacent to the mines, which showed the implications that mining had on the geology and local rock units (Ewusi *et al*., 2024). The seismic mirrored image records for the mines are listed in Table 5 and Figure 4 is the depth against velocity of the same data..

Table 5: Seismic Reflection Data for Mining Activities

Depth (m)	Vel. (m/s)	Anomaly Type
0	1800	Deformed Layer
10	1600	Excavated Void
20	2000	Normal Formation

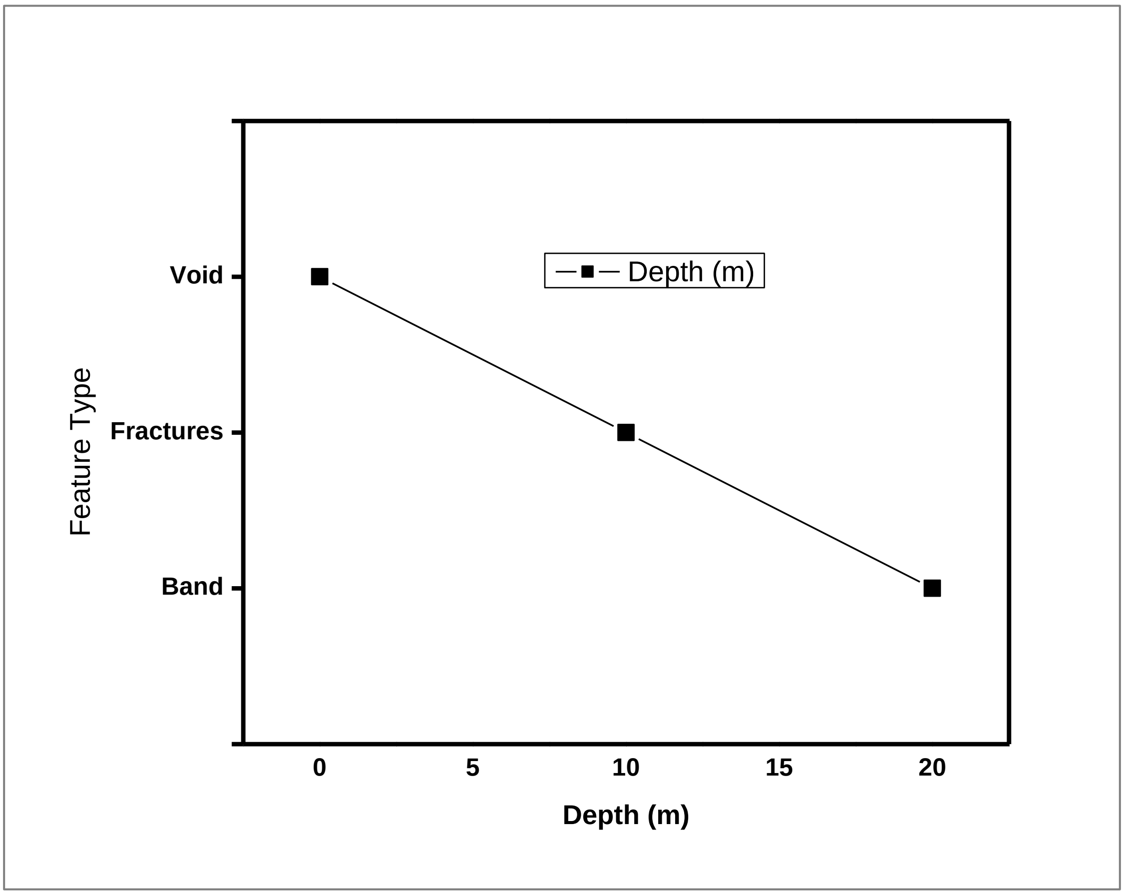

Figure 3: Depth (m) against Feature Type Graph

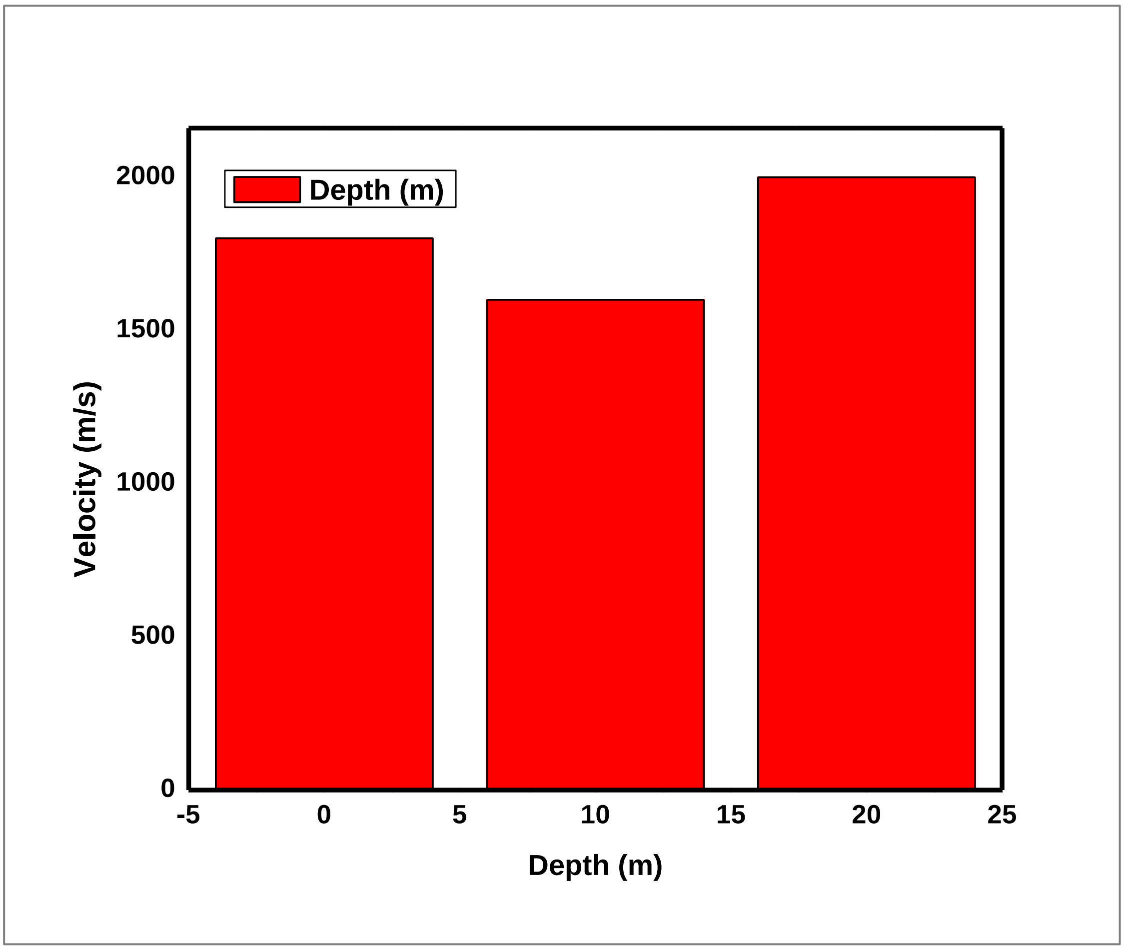

Figure 4: Graph of Depth (m) Against Velocity (m/s)

Multiple ERT results showed increased conductivity levels associated with mining areas, which suggested contamination in the subsurface water likely from leachate loading with mining materials as the variables (Akankpo & Igboekwe, 2011). This demonstrates significant risks to the quality of subsurface water and environmental quality.

Agricultural Practices

The agricultural practices and how they impact the mechanisms below the surface were evaluated using GPR, ERT, and seismic methods to identify countless important trends. Findings GPR results identified changes in soil stratigraphy with significant soil compaction identified (Mahapatra, 2023). Table 6 identifies the GPR data for agricultural practices and Figure 5 is the plot of depth against soil type of the same data.

Table 6: GPR Data for Agricultural Practices

Depth (m)	Soil Type	Condition
0	Compacted Soil	Poor Infiltration
10	Irrigated Layer	Moisture Retention
20	Untilled Soil	High Permeability

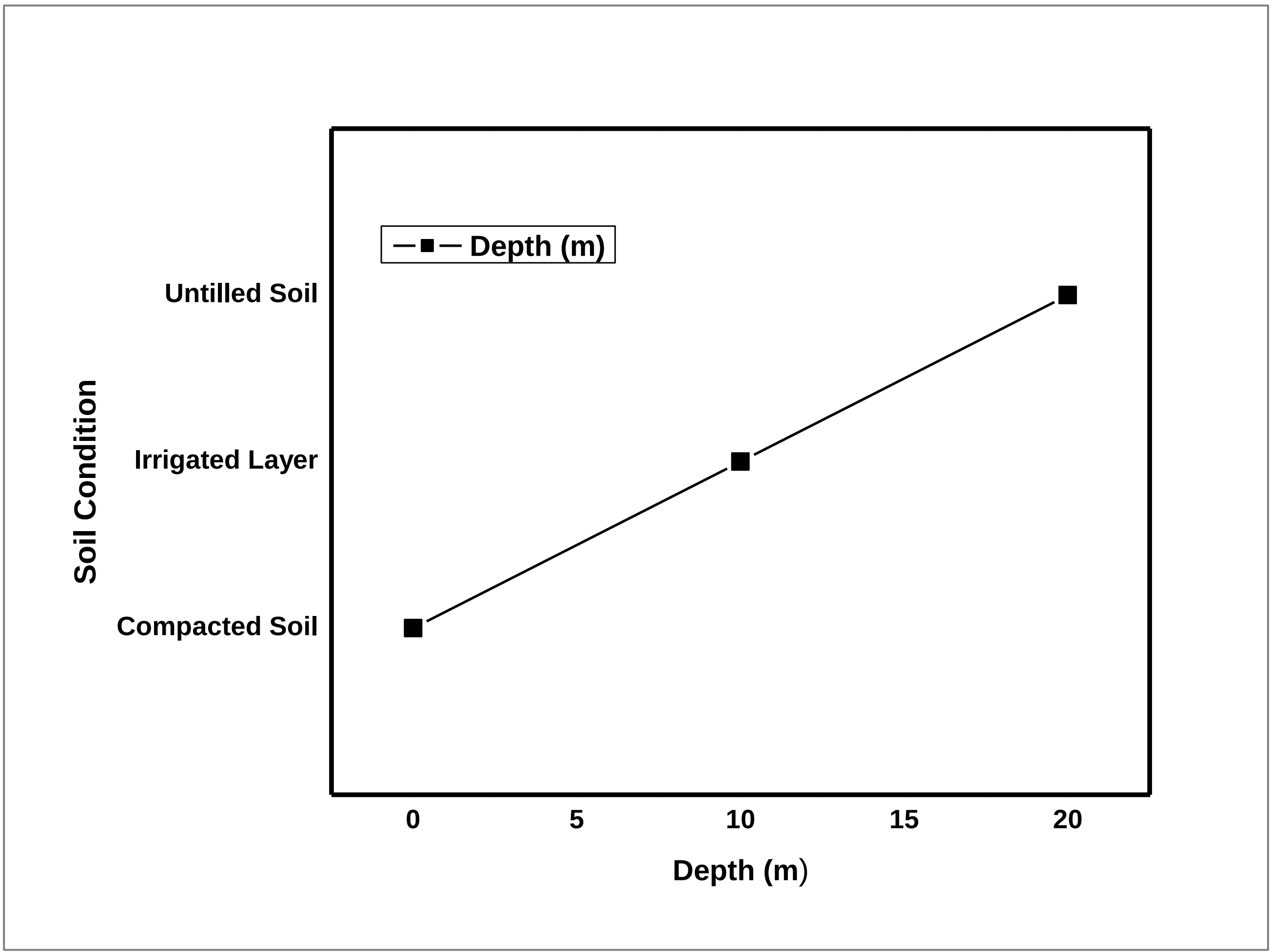

Figure 5: Graph of Depth (m) Against Soil Condition.

These modifications had been correlated with agricultural activities like tillage and heavy equipment use, which often resulted in reduced infiltration and adjusted drainage characteristics (Mojžiš et al., 2024). ERT data complemented these discoveries by illustrating reduced resistivity values in agricultural fields associated with large soil moisture contents resulting from irrigation (Michot et al., 2003). Table 7 shows the ERTdata for agricultural practices and Figure 6 is the plot of depth against resistivity of the same data.

This highlights a dual effect: agricultural activities can help moisture contents which are beneficial for crop growth while concurrently affecting the soil's electric properties (Unal *et al*., 2020). Seismic data indicated variations in subsurface densities, suggesting shifts in soil features and highlighting issues relating to long-period soil fertility and sustainability (Mechri *et al*., 2024). The outcomes show that even as agricultural practices are crucial for food production, they can bring about negative implications for subsurface systems if not controlled sustainably, mainly concerning soil health and water retention capacities (Shukla et al., 2022).

Table 7: ERT Data for Agricultural Practices

Depth (m)	Res. (Ωm)	Impact
0	200	High Moisture Content
10	800	Moderate
20	1500	Low Moisture Retention

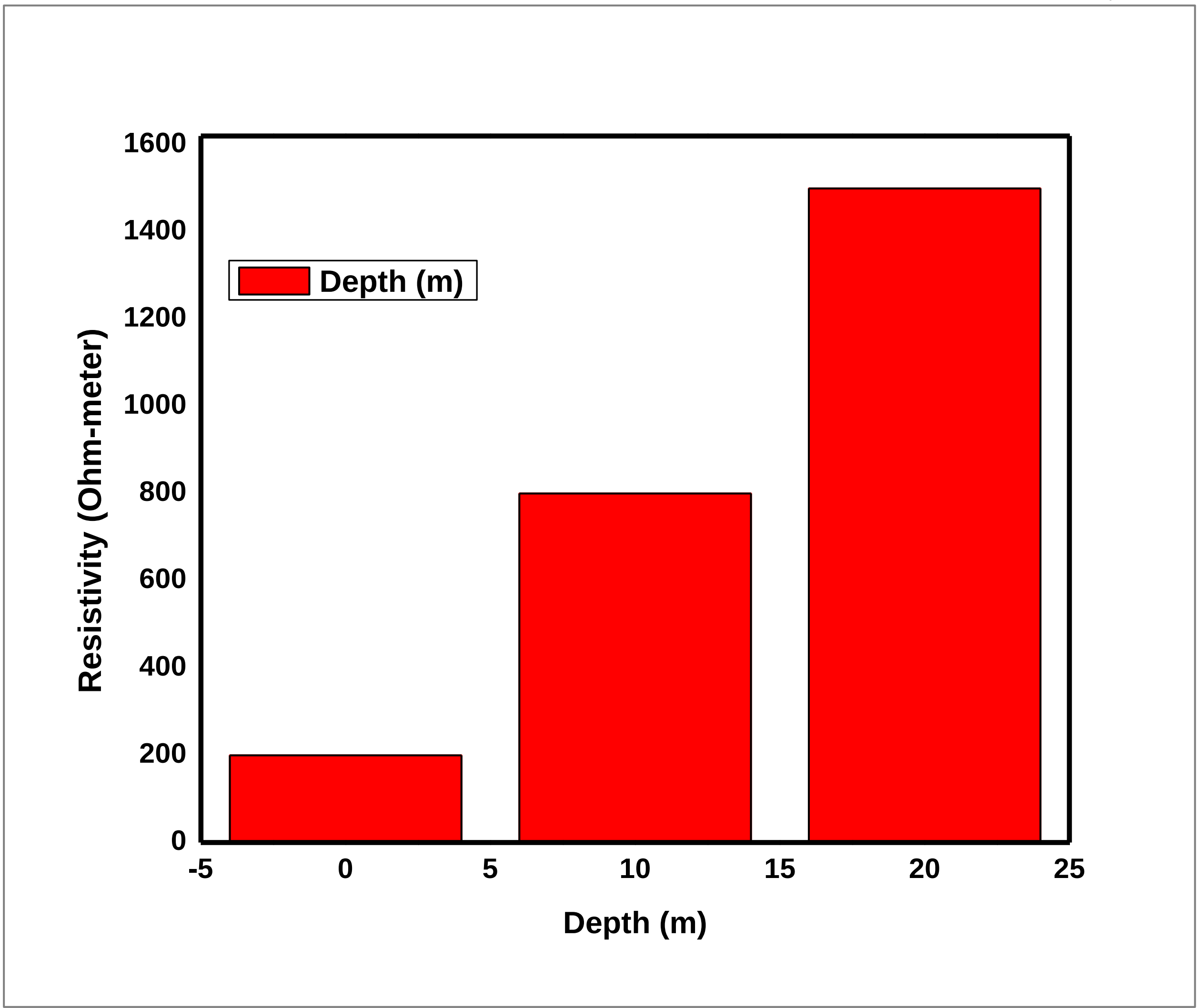

Figure 6: Graph of Depth (m) Against Resistivity (Ωm).

Discussion

Mechanisms behind the Observed Geophysical Changes

All geophysical changes observed in this study have been causally linked directly to many human influences: mining, agriculture, and urbanization. All such processes introduce corresponding introductions into the subsurface environments with well-definitive sets of specific mechanisms:

• Urbanization: Urban development creates impervious surfaces such as asphalt and concrete that effectively disrupt natural hydrological processes. This altered groundwater recharge rates and increased surface runoff (Yang *et al.*, 2011). Soil within urban areas has higher seismic wave velocities due to more concentrated soil particles (Tiwari *et al.*, 2023). The ERT with higher resistivity values in the urban zone emphasizes the water confinement and decreased pore space, resulting in decreased groundwater recharge potential (Unal *et al.*, 2020).

• Mining Activities: Physical mining operations disturb geologic structures, creating voids and fracture that impact subsurface hydrology significantly. Effective overburden removal creates pressure changes in aquifers, often leading to subsidence (Keisham *et al.*, 2022). As seen in our study, subsidence is proven with slow seismic wave velocities, from 2500 m/s in undisturbed areas to 1600 m/s in mined areas. Moreover, the presence of contaminants from mine tailings that can infiltrate surrounding groundwater is a sign of how mining affects subsurface water quality in the long term (Ojo *et al.*, 2024).

• Farming Practices: Intensive farming practices result in extreme alterations of soil structure. Heavy machinery compaction reduces hydraulic conductivity and soil porosity, resulting in low moisture retention and increased surface runoff (Hanna & Comin, 2021). Moreover, fertilizer application alters soils' chemical composition, influencing resistivity values as shown by our ERT data (Koteswara *et al.*, 2024). This emphasizes the need for sustainable agricultural practices that are empirically observed to be sensitive to subsurface alterations.

Discussion of the Figures

The figures presented in this study serve as compelling visual and quantitative manifestations of the profound impacts that human activities particularly urbanization, mining, and agriculture exert on subsurface structures. These visualizations not only confirm the theoretical and empirical relationships established in prior literature but also deepen our understanding of the complex interactions between anthropogenic processes and the geological subsurface. By integrating seismic velocities, resistivity profiles, and GPR anomalies, the figures collectively illustrate how human interventions alter the physical, chemical, and hydrological properties beneath the surface, often with long-lasting implications for environmental stability and resource sustainability.

Beginning with Figure 1, the depth–seismic velocity profile in urban areas reveals significant variations that are emblematic of the effects of urban development on the subsurface. At the shallowest depth of 0 meters, the seismic velocity is recorded at 2000 m/s, which increases to 2500 m/s at 10 meters, then decreases sharply to 1500 m/s at 20 meters, and slightly increases again to 1750 m/s at 30 meters. This pattern reflects a stratification influenced by soil compaction, construction materials, and land sealing typical of urban environments. The elevated velocities near the surface are indicative of increased soil density resulting from compaction and cementation processes driven by heavy machinery and infrastructure development. These findings corroborate Forte et al. (2014), who established that seismic wave velocities are sensitive indicators of soil stiffness and anthropogenic disturbance. Similarly, Tiwari et al. (2023) emphasized that urbanization often increases seismic velocities due to soil densification and compaction, which can influence the stability of underground infrastructure and the risk of subsidence.

Complementing this, Figure 2 presents resistivity data across the same depth range, revealing resistivity values of 1000 Ωm at the surface, decreasing to 500 Ωm at 10 meters, then rising sharply to 3000 Ωm at 20 meters, and slightly decreasing to 1500 Ωm at 30 meters. This variation reflects the complex moisture and contamination dynamics within the subsurface. The low resistivity at 10 meters suggests higher moisture content, likely due to residual pore fluids or infiltrated pollutants, whereas the high resistivity at 20 meters indicates drier, less conductive materials or zones of cementation and compaction. These resistivity patterns align with the work of Li et al. (2022), who demonstrated that urban impervious surfaces hinder natural recharge, leading to moisture depletion in certain zones and accumulation in others due to surface runoff and drainage modifications. The high resistivity zones may also indicate the presence of artificial materials such as concrete or asphalt, which are electrical insulators and further disrupt the natural hydrological regime. This stratification of resistivity is critical because it influences groundwater recharge rates, contaminant migration pathways, and the overall stability of subsurface structures, as emphasized by Balocchi (2024). The combined seismic and resistivity data thus reinforce the notion that urbanization fundamentally alters both the mechanical and hydrological properties of the subsurface.

Moving to Figure 3, the GPR anomalies observed at depths of 0, 10, and 20 meters reveal the presence of voids, fractures, and remnant ore layers, respectively. The hyperbolic reflections characteristic of GPR are consistent with the signatures of subsurface cavities and discontinuities caused by mining activities. These anomalies are in line with findings by Bowell et al. (2023) and Khan et al. (2022), who demonstrated the efficacy of GPR in mapping underground voids and fractures that compromise the integrity of mine sites. The detection of such features is vital because voids and fractures can serve as conduits for groundwater contamination or zones of structural weakness that may lead to land subsidence or collapse. Notably, the seismic velocities at these depths—recorded at 1750, 1600, and 2000 m/s—further suggest that the zones containing voids and fractures are characterized by reduced bulk density and increased porosity, indicative of structural degradation. The lower seismic velocities, especially at 10 meters, reflect the presence of fractures and fractured zones that diminish the soil's stiffness and strength. These findings corroborate the research of Altun et al. (2010), which highlighted that excavated and fractured subsurfaces are prone to land subsidence and stability issues. Such alterations necessitate ongoing monitoring using seismic and GPR methods to identify early signs of instability, especially in regions with active or historic mining operations.

Figure 4 presents seismic reflection data revealing the velocity variations associated with mining-induced deformations. At increasing depths from 0 to 20 meters, velocities fluctuate from 1750 to 1600 m/s and then rise again to 2000 m/s. These oscillations indicate heterogeneous subsurface conditions, with zones of weakening and reinforcement. The lower velocities in the shallower zones are indicative of fracturing, voids, and possibly fluid infiltration, all of which compromise the integrity of the geological strata. The subsequent increase at greater depths suggests some degree of compaction or consolidation, possibly as a result of overburden pressure or natural stratification. These findings are consistent with the work of Zhang et al. (2024), who demonstrated that seismic velocity reductions are typical of zones affected by mineral extraction and structural failure, while the increase at deeper levels may reflect more stable, compacted strata. Such detailed seismic profiling allows for the early detection of subsurface instability, which is paramount for risk mitigation and environmental protection around mining regions.

Turning to Figure 5, the GPR data in agricultural settings depict stratigraphy with significant implications. At shallow depths of 0 meters, the soil appears compacted, with poor infiltration characteristic of intensive tillage and machinery passage, as discussed by Mojžiš et al. (2024). At 10 meters, the profile indicates an irrigated, moisture-retentive layer, while beyond 20 meters, the soil is tillage-free and exhibits high permeability. These anomalies are consistent with the hyperbolic reflections typical of soil compaction, moisture variation, and layering differences. The resistivity data at these depths 200 Ωm at the surface, rising to 1500 Ωm further depict the moisture gradient, with low resistivity corresponding to high water content and high resistivity indicating dry, well-drained soils. Such patterns mirror the findings of Koteswara et al. (2024) and Mechri et al. (2024), who emphasized that intensive irrigation and tillage significantly modify subsurface moisture and soil density. These modifications have profound implications for groundwater recharge, soil fertility, and crop productivity. Overly compacted or overly irrigated soils can lead to reduced permeability, increased runoff, and groundwater contamination through leaching of fertilizers and pesticides, as documented by Unal et al. (2020) and Shukla et al. (2023). The resistivity profile's gradual increase with depth signifies the stratification of moisture content, which underscores the importance of adopting sustainable agricultural practices that balance crop needs with subsurface health.

Finally, Figure 6 illustrates the resistivity variation with depth in agricultural zones, providing critical insights into the moisture dynamics and soil health. The resistivity values—200 Ωm at the surface, increasing to 800 and eventually 1500 Ωm at deeper levels—reflect the influence of irrigation practices and soil management on pore water content and soil structure. These observations confirm prior research (Netti et al., 2024; Mojžiš et al., 2024), which established that moisture content and soil compaction are tightly coupled with resistivity measurements. The increasing resistivity with depth indicates diminishing water content and soil permeability, which could negatively impact plant growth and groundwater recharge if not managed properly. These findings further emphasize the necessity of employing geophysical techniques in designing sustainable farming practices that optimize water use efficiency while preserving subsurface integrity. The correlation between resistivity and soil moisture content provides a quantifiable metric for monitoring and managing agricultural impacts, supporting the call for integrated land management strategies as advocated by Ojo et al. (2024). In synthesizing these observations, it becomes evident that the geophysical signatures captured in these figures are not isolated phenomena but are interconnected manifestations of human activities that alter the Earth's subsurface. The seismic velocities' increases and decreases reflect compaction, fracturing, and stratification changes induced by urban development and mining, consistent with the findings of Forte et al. (2014), Zhang et al. (2024), and Altun et al. (2010). The resistivity profiles reveal moisture redistribution and contamination pathways, aligning with studies by Li et al. (2022), Yang et al. (2021), and Balocchi (2024). The GPR anomalies serve as direct indicators of subsurface voids and fractures, confirming the assessments by Bowell et al. (2023) and Khan et al. (2022). Collectively, these data underscore the importance of multi-method geophysical approaches for comprehensive subsurface monitoring, which is vital for early warning systems, risk mitigation, and sustainable resource management. Furthermore, these findings are not only consistent with prior research but also extend current understanding by illustrating the spatial and depth-dependent variability of anthropogenic impacts. They reinforce the critical role of integrating seismic, resistivity, and GPR data to capture the multifaceted nature of subsurface alterations. Such integration allows for a more nuanced assessment of the extent, severity, and potential risks associated with human interference. This approach aligns with the frameworks proposed by Lombardi et al. (2022) and Martorana et al. (2023), who emphasized the importance of combining geophysical techniques to achieve reliable, high-resolution subsurface models. The implications of these findings extend beyond academic inquiry into practical policy and management spheres. Urban planners must incorporate routine geophysical surveys to identify zones of high compaction and altered hydrology, informing decisions on land use and infrastructure development (Yang et al., 2011; Yadav, 2024). Mining operations require continuous seismic and resistivity monitoring to mitigate land subsidence and groundwater contamination, as advocated by Bowell et al. (2023) and Wen et al. (2023). Agriculture must adopt sustainable practices guided by resistivity and GPR data to prevent soil degradation and water resource depletion, echoing the calls of Mojžiš et al. (2024) and Zhang et al. (2024). These strategies are crucial for safeguarding the integrity of subsurface ecosystems and ensuring long-term resource availability, aligning with the overarching goals of sustainable development and environmental resilience. In conclusion, the detailed analysis of the figures reveals that human activities leave measurable geophysical footprints that, when interpreted through seismic, resistivity, and GPR techniques, can inform effective management policies. These insights underscore the necessity of adopting integrated geophysical monitoring as a cornerstone of responsible land-use planning, resource extraction, and agricultural management. The scientific dimensions elucidated through these figures spanning mechanical, hydrological, and chemical subsurface parameters highlight the intricate ways in which anthropogenic pressures reshape the Earth's crust. By advancing our understanding of these processes, we can develop targeted interventions that mitigate adverse impacts, promote sustainable development, and preserve the subsurface integrity vital for ecological balance and human well-being.

Discussion on Impacts of Human Activities

The integration of geophysical methods in this work offers a broad perception of anthropogenic activities' influences on the subsurface environments (Hasan *et al.,* 2021). All the situations demonstrated different outcomes, highlighting the intricacy of human impacts on geological structures, subsurface water systems, and the overall balance of the ecosystem (Abdelmoneim et al., 2025).

Policy and Practice Implications

The findings from this research carry profound policy and practice implications, especially in dealing with subsurface resources. Urban development, agriculture, and mining regulations must include geophysical monitoring:

•Urban Planning: Geophysical surveys need to be integrated into the early development phases by city planners in order to establish subsurface trouble zones addressing groundwater recharge and pathways for

contaminants. Permeable surfaces and green infrastructure need to be key priorities in future urban planning to address the effects of increased impermeability (Hanna & Comin, 2021).
• Mining Regulations: Current geophysical monitoring schemes need to be mandated to assess the impact of mining activities on regional groundwater systems. This may be in the form of real-time ERT and seismic surveys, which would facilitate quick assessment of subsurface conditions and potential causes of contamination (Molua *et al.*, 2024). Regulations need to be enacted to minimize adverse impacts, with an emphasis on sustainable mining activities (Molua *et al.*, 2024).
• Farming Practices: Our policymakers must promote sustainable farming practices that align with the findings of our study. Investment in technology and education can enhance farm efficiency without causing detrimental effects on foundations beneath the soil. Implementation of best management practices will reduce the compaction of soils and enhance water infiltration (Unal *et al.*, 2020).

Urban Development Impacts

Results from the urbanization scenario show that human actions greatly interfere with natural hydrological cycles (Akinsunmade, 2021). As urbanization extends, alteration of the characteristics of soil and groundwater processes poses threats such as reduced aquifer recharge and high flooding risk potential (Liang *et al.*, 2023). The above-mentioned areas highlight of where, thus, environmental managers and urban planners need to critically assess the subsurface impacts of land development decisions (Yadav, 2024). Proper urban development planning should incorporate geophysical assessments to guide the choices regarding the site, drainage system, and storm-water management plans (Bricker *et al.*, 2024).

Mining Risks

Mining activities have great outcomes associated with it. Therefore, mining activities bear enormous risks concerning water quality and stability of the ground (Molua et al., 2024). This is because mining activities cause direct physical disruption of geological structures and open up the local water resources to contamination vulnerabilities (Molua *et al.*, 2024). The benefit of geophysical methods in monitoring mining areas is that continuous monitoring can be detected where there are changes in subsurface environments that may lead to contamination or destabilization events, and hence, constant change is required in policy making and management (Ewusi *et al.*, 2024). This has, therefore, called for geologically better policies and procedures that should be under strict investigation before and during mining operations to mitigate threats (Mahapatra, 2023).

Agricultural Sustainability

The scenarios of agricultural practices present important implications, example of the tenuous balance between environmental stewards and tangible, food-producing practices (Wegenast et al., 2024). Soil lumping and alterations to subsurface hydrology can lead to grievous effects over time, such as reduced fertility and increased risks associated with extreme weather (Xian *et al.*, 2007). Simple farming methods and farm practices, based on our knowledge of the Earth's topography, foster improved soil health and water efficiency (Pueyo-Anchuela et al., 2011). New studies on agricultural methods that are ecologically sustainable should incorporate research from the Earth's surface. This perspective can help quantify the impacts of diminishing the ecological effects of farming practices above and below ground (Mpanga et al., 2022). The outcomes from these studies make clear the need for responsible and sustainable subsurface resource management, and monitoring with geophysical methods and methods (Ojo *et al.*, 2024). Stakeholder groups, from researchers, developers, property managers, land environmentalists, public policymakers, and planners in particular, will be able to benefit from this research and ideas and develop better management plans to mitigate the adverse effects of construction and any human action (Reid & Castka, 2023).

Comparison with Other Environmental Monitoring Techniques

Although geophysical techniques like seismic reflection, GPR, and ERT have a lot of information to contribute to subsurface structures, other environmental observation methods like satellite imagery and remote sensing can further be used along with them.
• Remote Sensing: Remote sensing technologies promise to enable large-scale measurements of land cover and vegetation change, which can indirectly indicate changes in subsurface conditions. For instance, studies have shown that satellite imagery can identify areas of soil moisture stress that are consistent with our observations of reduced moisture content related to urbanization and agriculture (Reid & Castka, 2023).
•Satellite Imagery: Satellite sensors, such as optical and radar, provide high-resolution data that can be paired with geophysical data to create comprehensive subsurface models. This integrated approach enhances precision in predicting groundwater behavior under changing land use (Bertoni *et al.*, 2023). Furthermore, combining these methods can lead to cost-effective management practices for assessing subsurface resources and environmental monitoring (Reid & Castka, 2023).

CONCLUSION

These methods offer insights into the disruption of subsurface structures based on real-world experiments that focus on single aspects of human influence. We showcase how geophysical methods allow us to identify and evaluate the impact that human intervention (on the subsurface) through mining, agricultural practices, and urbanization has on existing subsurface structures. Urbanization was shown as a disturbance of regional groundwater systems and soil properties, with prolonged ecological outcomes. As the threat to our environment is growing, the use of an experimental approach and geophysical methods will provide a foundation for the development of future policies and sustainable management of ecological impacts. Mining creates similar building issues and contaminates the space; the need for regular and sustainable monitoring in these regions is clear. Although agriculture has significant potential for food production and can jeopardize groundwater and soil health, it raises long-term sustainability concerns. This methodology can provide new insights into the management of subsurface resources of the future. Future studies must rely on such methods for subsurface space impacted by human activity and the establishment of sustainable monitoring as a plan of action. Identifying and mitigating human impacts using geophysical techniques can create value-added contributions to holistic ecosystem resilience combined with sustainable management action. Efforts towards sustainable human development are also not mutually exclusive to the protection of the ecosystem.

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