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# Integrating GIS, RTK GNSS, and subsurface geophysical surveying for smart, climate-resilient infrastructure planning in underserved U.S. Regions

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## Abstract

The work is based on the concept of employing Geographic Information Systems (GIS), Unmanned Aerial Vehicles (UAV), Real-Time Kinematic (RTK) GNSS and subsurface geophysical surveying to improve infrastructure resilience in underserved areas. These technologies allow detailed real-time data, which allows making more informed decisions related to planning instruments and managing infrastructure. GIS enables the spatial analysis and mapping of environmental hazards; UAVs provide aerial image coverage at high resolution in the infrastructure monitoring process and RTK GNSS can provide accurate geospatial positioning. Elasticity of the soil and groundwater conditions are subsurface geophysical data that supplements surface results. The paper identifies the role played by these combined technologies in helping to conduct vulnerability assessments, predictive modeling, and climate change adaptation strategies. Although the results are promising, it is observed that there are challenges like the data integration, the overfitting of the model and that there is a requirement of the accurate real time data. The study suggests the use of such technologies to develop more evolving, responsive infrastructure planning schemes that can withstand effects of climate change and in the long-term the infrastructure will sustain and be resilient.

**Keywords:** Geographic Information System (GIS); Unmanned Aerial Vehicles (UAV); RTK GNSS; Subsurface Geophysical Surveying -Resilient Infrastructure; Predictive analysis

## 1. Introduction

Experts have largely increased the demands of climate resilient infrastructure due to climate change, particularly in underserved areas within the United States. With the frequency and severity of climate-related events, floods, heatwaves, and severe storms take on a more prominent role in the daily life of these communities in terms of maintaining and upgrading their infrastructure systems (Alabi, 2024). Easy targets the vulnerable infrastructure, which may be roads, bridges, water systems, energy grids, etc., is often unable to cope with the demands that the changing environmental conditions place on them. These systems, even in areas with the least served ones, already grow old or poorly maintained, therefore becoming even more vulnerable to climate change.

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The issue of resilient infrastructure has led to the demand of some innovative solutions to surpass conventional arrangements of planning. Modern technologies and products such as Geographic Information System (GIS), Real-Time Kinematic (RTK) Global Navigation Satellite System (GNSS), Unmanned Aerial Vehicles (UAVs), and subsurface geophysical surveying have great potential to improve infrastructure planning (Abdulhassan, 2025). The technologies allow mapping more accurately, monitoring in real-time, and making better decisions, which allows intervening in the place of the greatest danger. The integration of these tools enables the planners to develop dynamic infrastructure systems that are resistant to the impacts of climate change, which tend to make these systems sustainable and resilient in the future to be of good services to the underserved populations.

*Objectives*

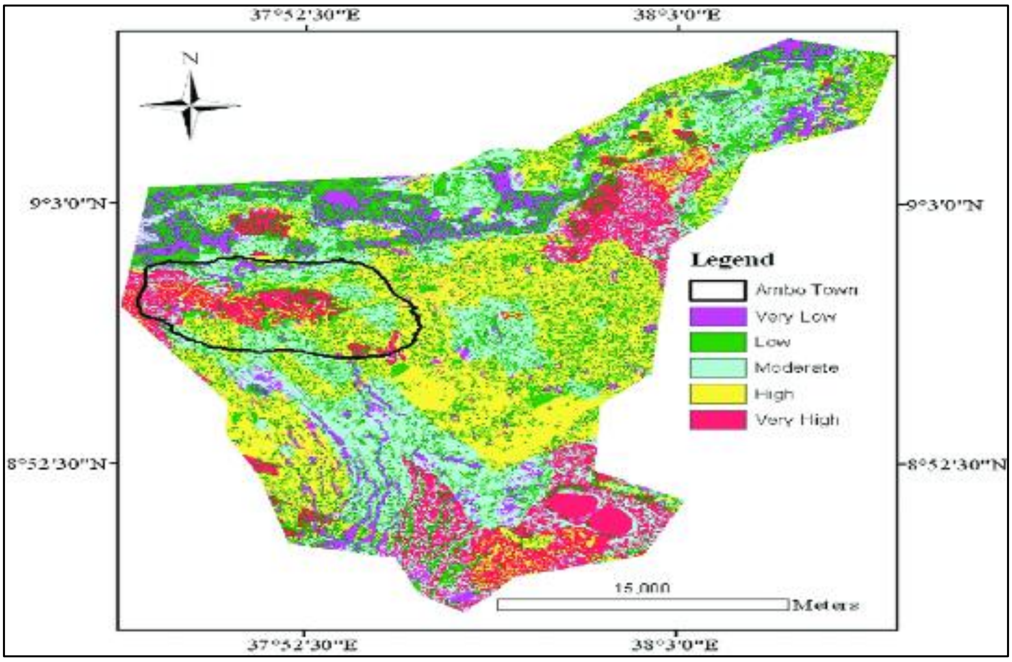
- To Analyze Climate-Resilient Infrastructure Needs Using GIS and UAV/GNSS Data
- To Incorporate Subsurface Geophysical Data for Infrastructure Planning
- To Optimize Smart Infrastructure Planning with Real-Time Data Integration

## 2. Literature Review

### 2.1. Climate Resilience in Infrastructure

Climate resilience of infrastructure We define climate resilience of infrastructure as the ability of built-up systems to endure, revive and adapt to climatic stresses and extreme events. Communities in most of the under-serviced areas in the United States are especially susceptible to the effects of climate due to the aging infrastructure and insufficient investment. Road systems, bridges, water systems, and power systems in such places do not usually feature the design capabilities they require to accommodate rising levels of floods, heat waves, and extreme storms (Alabi, 2024). Since these infrastructures play a vital role in the day-to-day operations of those living in the area, any form of disruption has ripple social and economic impacts on populations that have already experienced systemic problems.

Climate change is transforming the planning of infrastructure by making vulnerability assessments a part of the project design, and not an addition. Planners and engineers have now been required to predict future climatic conditions and have structures that can sustain the changes that are estimated to take place (Srinivasa et al., 2025). This shift in the paradigm is particularly immediate in disadvantaged areas where the consequences of climate may serve to strengthen existing disparities. To illustrate, when floods occur in low-income areas, transportation and utilities are often interrupted leading to an extended recovery and a higher cost. Similarly, heat waves in regions that lack friendly power grids overcome energy delivery systems, as well as present health risks to the population.



Source: (Flood Risk GIS Map Underserved Communities)

**Figure 1** Flood Risk GIS Map Underserved Communities

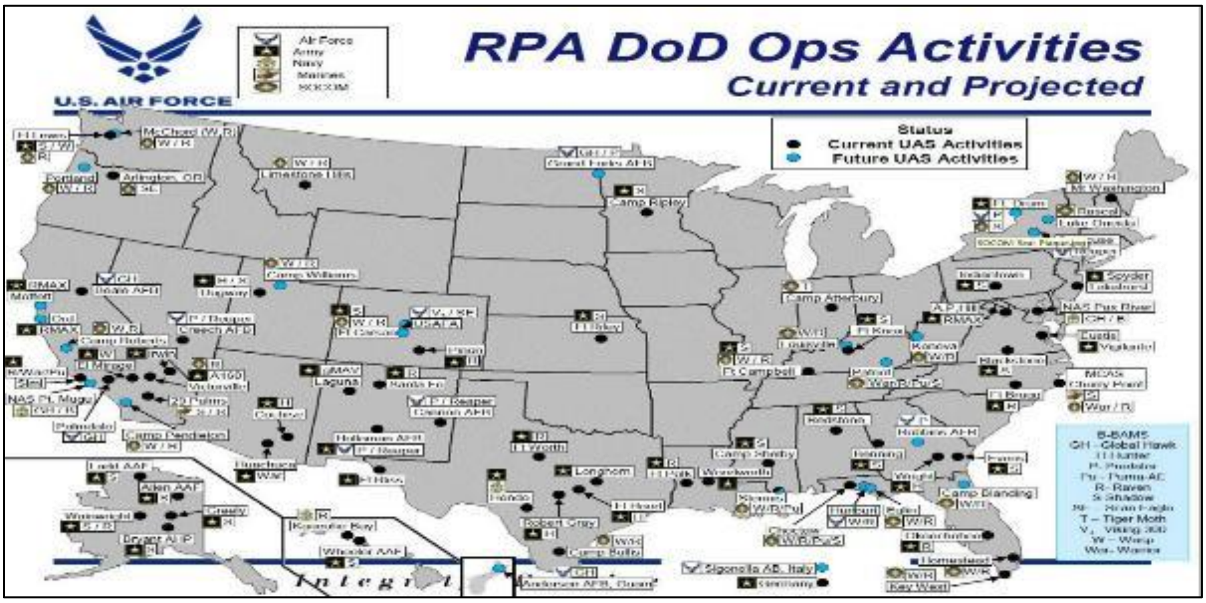
The figure above represents a flood risk map that identifies the areas of vulnerable infrastructure in underserved communities. Through spatial analysis of GIS, the map has been able to identify areas that are vulnerable to high flood risks through environmental and topographical conditions.

## 2.2. Geospatial Technology and Its Role in Infrastructure Planning

Geospatial technologies are changing the mode of collection, analysis, and application of infrastructure information in decision making. Geographic Information Systems (GIS) can add a spatial context but allow the engineers and the planners to combine layers including land use, topography, climate risks, and infrastructural networks (Enwin et al., 2024). Visualizing several datasets simultaneously, GIS helps to understand more about where the systems are at risk and which mitigation measures will be the most efficient.

Unmanned Aerial Vehicles (UAVs), also known as drones, enhance the possibilities of the classic mapping with high resolutions in the form of an overhead image and a terrain model. The drones have the ability to provide an overview of extensive areas that cannot be easily reached and provide centimeter-level details of the infrastructure status (Quamar et al., 2023). As an illustration, UAVs have the potential to obtain images of bridges prior to the storms and post-storms to determine damage, or track the roads in order to evaluate surface deformation due to a change in the soil moisture.

High accuracy GNSS (Global Navigation Satellite System), particularly, Real Time Kinematic (RTK) GNSS, is another important technology that allows making an accurate place. The combination of GNSS information with UAVs aerial images will create the most precise spatial data allowing to assist with activities such as elevation modeling, transportation routes alignment, and benchmarking of essential assets (Djaja, 2017). With this integration in place, the planners will be dealing with information that is reflective of the actual geographic setting of infrastructure systems.



Source: (UAV Infrastructure Mapping USA)

**Figure 2** Mapping of geographic distribution of UAV infrastructure

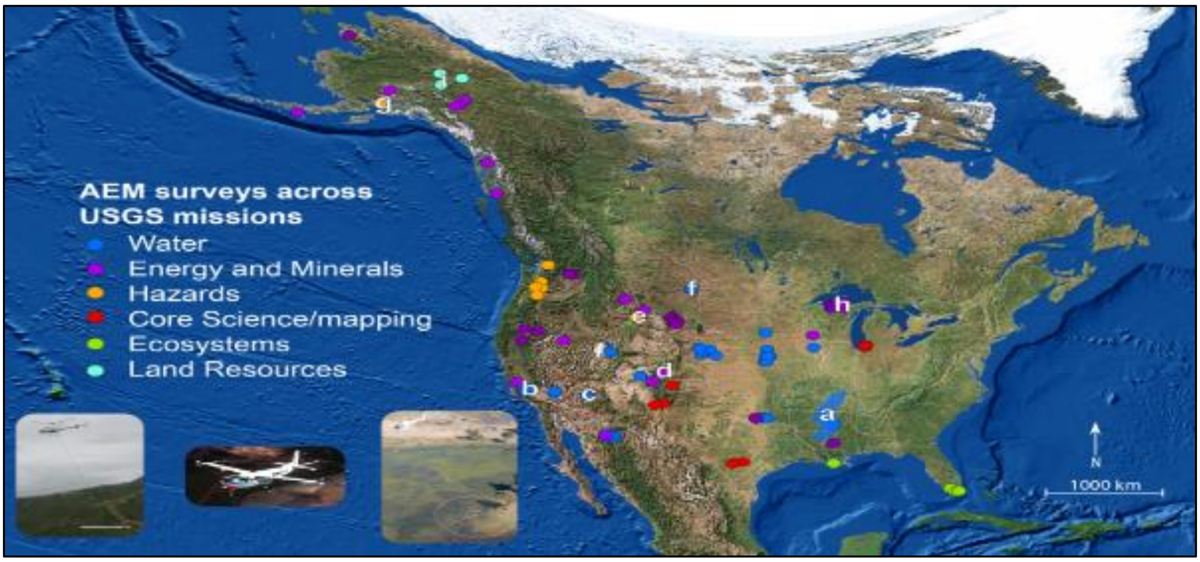
The figure above represents the spatial distribution of Remotely Piloted Aircraft (RPA) operations in the United States, indicating both existing and potential locations of activity. The map shows the geographic distribution of UAV infrastructure, which helps analyse the scope of operation, strategic placement, and the role of air technologies in the comprehensive monitoring and management of infrastructure on a large scale.

## 2.3. Subsurface Geophysical Data in Infrastructure

The superficial information may not suffice in thorough planning of infrastructure, particularly in situations when the ground conditions are quite unpredictable. Geophysical data of the subsurface allows the planner to know what is under the surface, such as soil layers, depth of groundwater, depth of bedrock, and other features of what lies under the surface (Hill et al., 2023). The information is essential in the regions prone to flooding, loose soil texture, or even earthquakes since the ground conditions determine the effectiveness of infrastructure and its durability.

In the underground survey techniques such as ground penetrating radar, electrical resistivity tomography and seismic refraction surveys are used to identify the differences in the materials of the underground. These data are applied by engineers to determine the stability of soil, identify voids or weak areas, and approximate the level of water table (Lee et al., 2021). Together with GIS surfaces, subsurface layers augment spatial models that are utilized in predicting the response of the ground to climate pressures.

High groundwater table and permeable soils may also increase impacts of floods in flood prone areas such as in areas where infrastructure is present, since water can find its way through the foundation of infrastructure easily. By mapping these conditions by using the subsurface surveys, the planners can plan a drainage system, reinforce the foundations, or move the resources to more stable zones (Becker et al., 2022). Likewise, subsurface geology in seismic regions enhances foundation design as well as informs construction or restructuring location decisions on possible activities to resist ground shaking.



Source: (Subsurface Geophysical Survey Map USA)

**Figure 3** Subsurface geophysical survey map

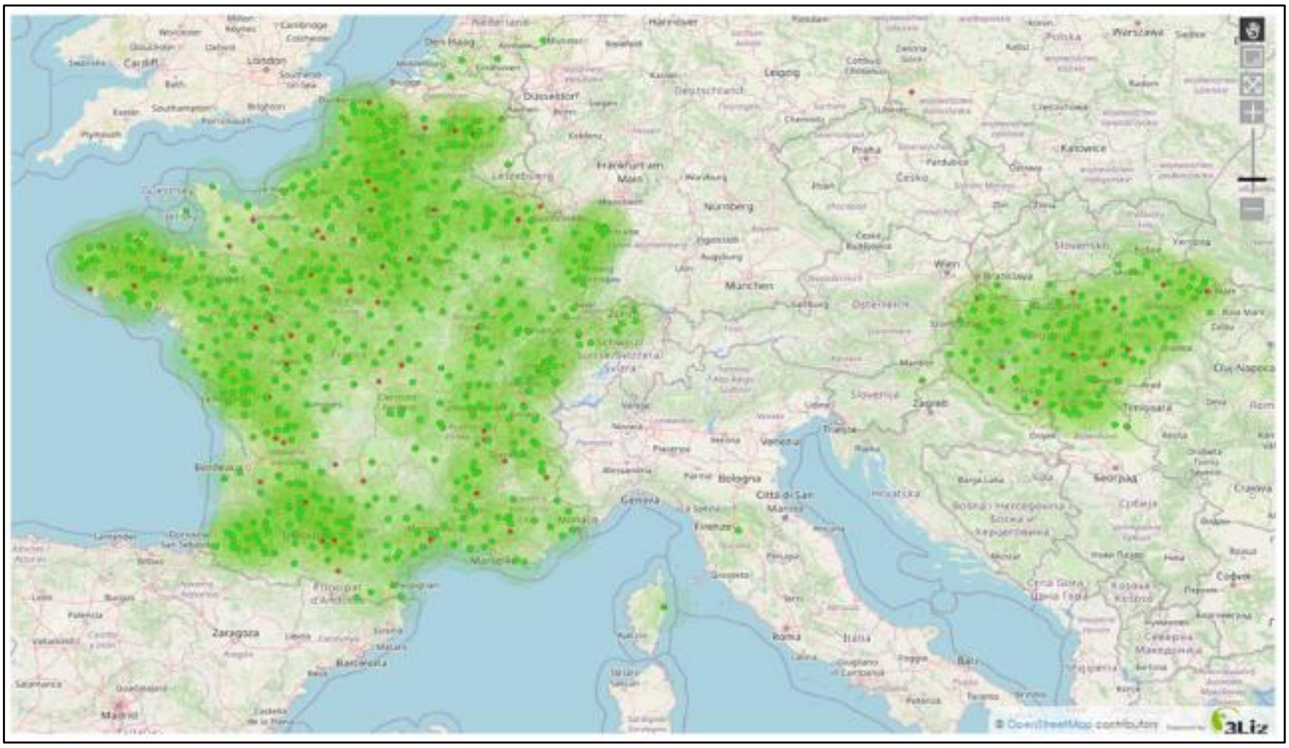
This figure above represents a subsurface geophysical survey map that illustrates the distribution of airborne electromagnetic (AEM) survey missions in the United States. Various colored markers indicate different areas of study such as water resources, energy and minerals and hazards. The map shows the significance of the subsurface data to assist in the infrastructure planning and environmental assessment.

### 2.4. Real-Time Data and Predictive Analytics in Infrastructure Optimization

Infrastructure planning and management is made dynamic through real time monitoring and predictive analytics. Unlike conventional assessment, which is based on snapshots in time, the model of real time systems continually feeds information into models that are able to identify changes on demand and model projections on conditions (Sudhaka, 2025). This strategy facilitates preventive decision making and not reactive repair of failures after they arise.

The use of a GNSS networks to maintain records on positions of infrastructure assets with constant monitoring helps in detecting fine movements that could represent settlement or shifting soils or building deformers. UAVs that fly on a schedule will be able to provide real-time imagery to perform time sensitivity (Starek et al., 2026). Feeding these live data streams into predictive models, the planners would be able to find out those hotspots which are vulnerable to the pressures of a changing climate and prioritize the interventions.

Predictive analytics uses the past data, observed environment, traffic volume, and sensor data in order to predict the future infrastructure behavior (Erinjogunola et al., 2025). By way of illustration, the effect of a structural deterioration on a bridge when subjected to repeated heat-stress can be predicted using models or the effect of increased precipitation on road surfaces. Such insights assist in a budgetary allocation of maintenance and minimize the chances of failure at any given moment.



Source: (Real-Time GNSS Monitoring Infrastructure Map)

**Figure 4** Real-Time GNSS Monitoring Infrastructure Map

The figure above represents GNSS real time monitoring infrastructure map showing the spatial distribution of reference stations in Western and Central Europe. Dense station density can be observed in France, and other clusters in the neighboring countries. Active stations are marked in green and they offer coverage to positioning, navigation and geospatial applications throughout the region in real time.

## 3. Methodology

In this research, the enhanced geospatial technologies are combined with a possibility to evaluate infrastructure vulnerability and resilience in underserved areas. To conduct the given analysis, the data was received in Kaggle, which was selected according to its extensive reference to infrastructure and environmental conditions (Cook, 2019). The essence of such a methodology is based on the combination of Geographic Information Systems (GIS), Unmanned Aerial Vehicles (UAV), and Real-Time Kinematic (RTK) GNSS technology to provide high precision and dynamism regarding infrastructure and its adaptability to climate stressors.

The initial measure is GIS and UAV/GNSS integration of the infrastructure vulnerability assessment. The GIS offers the spatial framework required in mapping the infrastructure and environmental hazards. UAVs are fitted with high-resolution cameras to take aerial photographs of infrastructure assets and this is processed and integrated into GIS platforms. The RTK GNSSs are employed to provide geospatial positioning of high accuracy that guarantees all the data that is being mapped, such as in the case of the UAV, is located within a range of centiliters (Quamar et al., 2023). GeoPandas and folium tools will be needed in the process, as GeoPandas makes it possible to manipulate geographic data and conduct a spatial operation, whereas Folium makes interactive displays of the map and visualizes the infrastructure vulnerability (Quamar et al., 2023). Matplotlib can also be useful in extending the analysis of these results, e.g., any hotspots of the infrastructure or may that be at risk due to environmental factors, e.g., flood risks or soil erosion. Python logic is executed in order to load, handle and visualize this data in Google Colab, allowing a seamless assignment of all geospatial data sets.

The important thing is to include the subsurface geophysical information to learn about the underlying conditions that involve infrastructure stability. Geophysical surveys offer necessary information on the characteristics of the ground, the levels of groundwater, and seismic danger, which are relevant in determining the robustness of infrastructure (Wahba et al., 2024). Python libraries NumPy and SciPy are used to perform the necessary calculations and Matplotlib is used to present the results of calculations in form of visual data. After mapping this underground data on the GIS layers, a more holistic view of the infrastructure vulnerability would be built, considering the surface and underground aspect.

Intelligence in the real-time integration of data and predictive modeling can improve the ability of the infrastructure systems to adapt to environmental changes (Zeeshan, 2024). The RTK GNSS and UAV sensors make it possible to monitor the infrastructure in real-time through constant results on its status. This information is, in turn, inputted into machine learning models and can potentially identify possible problems, including structural flaws or points of failure, grounded on real-time information about the surrounding environment. Predictive analytics allows to make infrastructure maintenance proactive instead of reactive with the aim of reducing the probability of failures and improving general resilience (Zeeshan, 2024). Scikit-learn used to create machine learning models and Google Colab integration tools are an efficient tool to optimize infrastructure management strategy.

## 4. Results and Discussion

### 4.1. Climate-Resilient Infrastructure Needs Using GIS and UAV/GNSS

This demonstrates a geospatial visualization of the high earners in various regions, and it was made through GeoPandas. This is presented in the plot as the levels of high earners differ in higher amounts as shown between 600 and above 500,000. The information has a clear distribution; however, lacking definite geographical coordinates, it is hard to find direct correlation with definite vulnerabilities of the infrastructure. This illustration gives a simplistic testament of economic inequalities that may be significant in prosecuting climate jeopardy, particularly neighborhoods that represent under-developed regions. The following would be the next steps, which would entail overlaying this data with geographical or environmental variables to analyze it further.

**Figure 5** Mapping vulnerability zones using Folium for the San Francisco Bay Area.

The figure above illustrates a geographic map of San Francisco Bay Area, which was compiled with the use of Folium in order to map the areas of vulnerability. The map singles out various areas of the Bay Area such as San Francisco, one of the major cities, and others such as Oakland and San Jose. Protected areas depicted as well by the map also include the North Farallon Islands State Marine Reserve and the Point Reyes National Seashore. The spatial plan provides information about the way infrastructure in these regions may be exposed to environmental hazards, including the rise in sea levels, since they are very close to the shoreline. These characteristics are useful to evaluate areas that might need improved actions in the area of climate resilience.

### 4.2. Incorporate Subsurface Geophysical Data for Infrastructure Planning

Figure 6 shows how soil conditions with the different values of one to four are distributed on a scale that depicts the various type or conditions of soil. The table of frequency of the values of soil condition indicates that Condition 1 (the mostly happening) has more than 20 instances, then there is Condition 2 with nearly 15 instances. Conditions 3 and 4 are not prevalent enough, and there are less than 10 cases of them. This histogram can be displayed to get some information about the distribution of various types of soils within the dataset, which can help determine the stability of soil and identify ways that soil properties may affect the infrastructure design and its resilience.

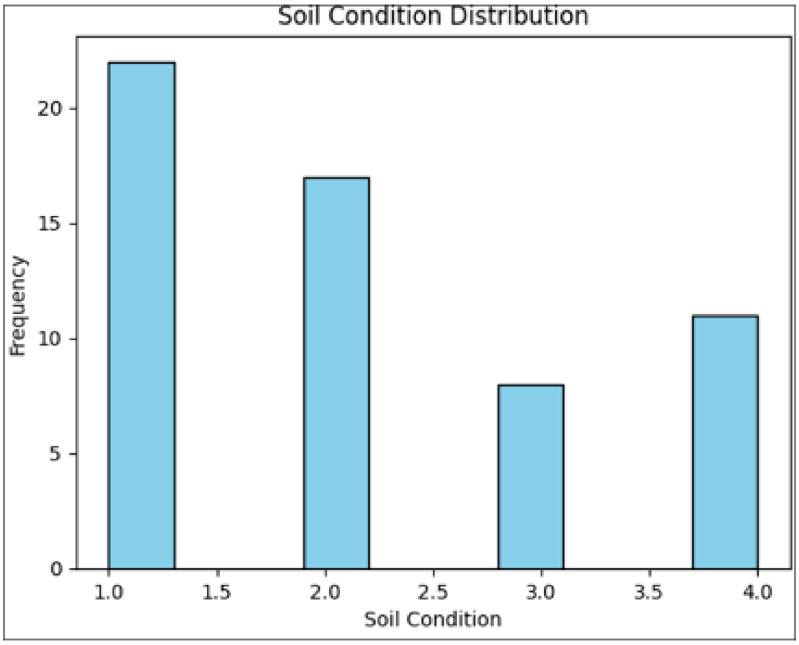


**Figure 6** Soil condition distribution showing the frequency of different soil conditions.

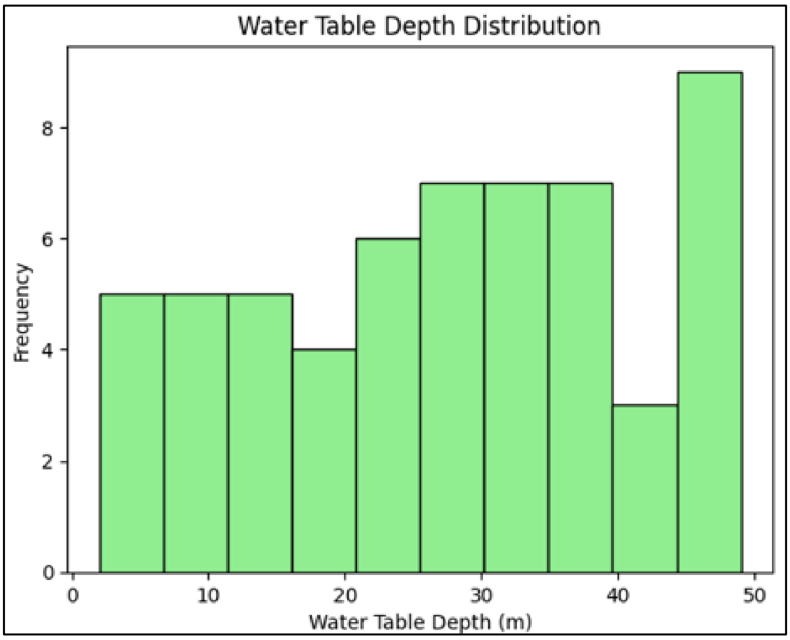


**Figure 7** Water table depth distribution across the dataset.

The graph above shows the water table depth distribution in the data set in meters. Its depths are 0-50 meters though the common ones are between 20 and 40 meters. The distribution indicates that there are some peaks at 30 meters and 40 meters, and the frequency of cases is significantly higher at the height of 50 meters. The occurrence frequency decreases with increase in depth whereby the shallow depths (less than 10 meters) are less frequent. Based on this histogram, deeper water tables are more prevalent in this area that is critical to comprehend issues associated with groundwater management.

### 4.3. Smart Infrastructure Planning with Real-Time Data Integration

**Table 1** Results of Linear Regression Model and Mean Squared Error for Predicting High Earners.

| **Predicted Values** | **145696** | **673** | **3088** | **517** | **5559** | **261** | **114989** | **376** | **900** |
|---|---|---|---|---|---|---|---|---|---|
| Mean Squared Error (MSE) | 0.0 | | | | | | | | |

The results obtained using a Linear Regression model to predict high earners are presented in table 1 in regards to the available data. Some of the model values including 145696, 673, 3088 and 517 among others are the outputs of the model which represents the predicted model values of various data in the data set. Interestingly, the model gives a Mean Squared Error (MSE) value of 0.0 that indicates that the model is fitted to the training data perfectly that is, there was no error in prediction. This would not normally happen in real-life problems and it could be a sign of over-fitting whereby the model fits the data exactly but it might not extrapolate to previously unobserved data. The lack of error would suggest that the model is very specific to the presented dataset, and it would require additional validation with newer data to evaluate how it will predict it in the real world (Quamar et al., 2023).

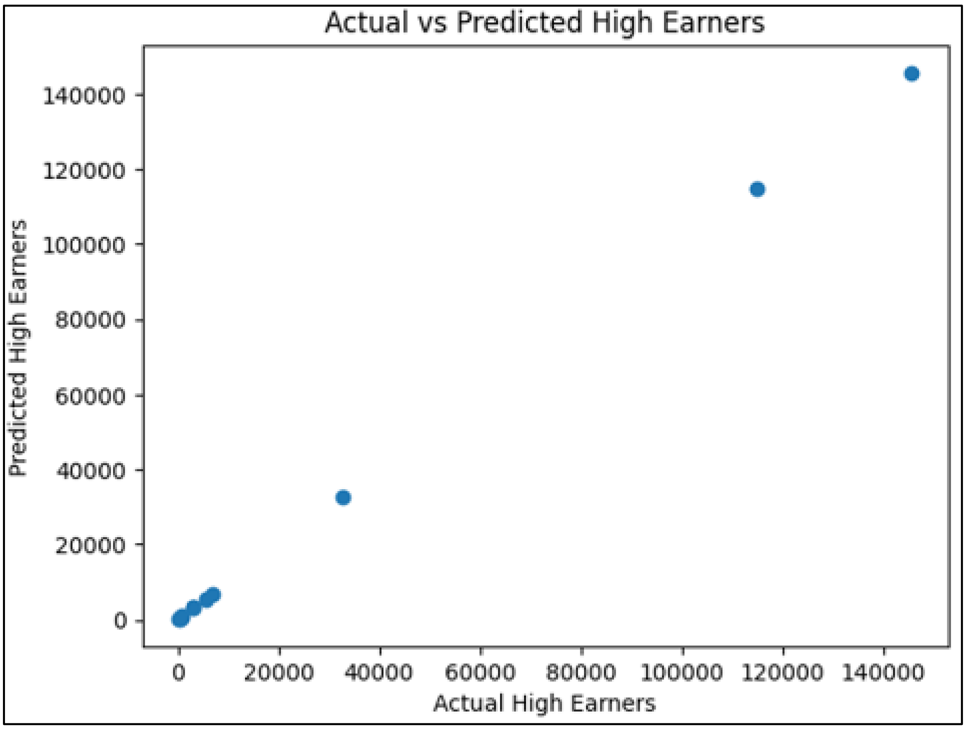


**Figure 8** Actual vs predicted high earners.

The figure above represents a scatter plot of real versus expected high earners according to the linear regression model. The actual value of the high earners is reported by the x-axis and predicted by the y-axis. The plot shows a prominent deviation, and the majority of the foreseen values are concentrated at the lower range (near 0) and limited values depict large differences in higher values like, 120,000 and 145,696. It implies that the model is not very effective with lower values but fails to accurately forecast higher high earners and this could be an indication of overfitting or underfitting data at its upper end.

### 4.4. Comparison of the Proposed Methods with Traditional Infrastructure Planning Methods

The classic infrastructural planning process usually makes use of historic and predictive data through the use of traditional trends and engineering assumptions. These approaches have worked in the previously past although are usually constrained by their incompetence to precisely determine the consequences of climate change, environmental threats and the evolving societal forces. The classical models of planning pay primary attention to the superficial structures of the infrastructure with less emphasis on real-time data and the underground conditions (Zeeshan, 2024).

Moreover, they fail to consider how the environmental stressors are dynamic, thus there may be sudden climatic events or an accelerated technological development.

The suggested techniques, on the other hand, which combine GIS, UAV, GNSS, and subsurface geophysical surveying, provide a more dynamic and real-time solution. These technologies offer informative, real-time information, which is detailed and up to date to guide planners on the vulnerability of the infrastructure. GIS enables spatial analysis and overlays of environmental information, whereas UAVs have a high-resolution image to monitor extensive amounts of space, particularly in remote access areas. GNSS guarantees a high level of accuracy in mapping infrastructure and the geophysical survey of the underground gives the important information about the stability of the soil and the state of groundwater. These technologies combined form a complex, dynamic system that allows a dynamic planning and real-time monitoring, an enormous improvement to the old, less responsive systems (Wahba et al., 2024).

### 4.5. Limitations of the Current Approach and Areas for Future Research

Although the combination of GIS, UAV, GNSS, and ground geophysical data has potential opportunities in improving infrastructure resilience, the current solution has a number of limitations. The dependency on the availability and quality of real-time data is one of the key constraints. As an example, the UAVs can only offer imagery in the regions where it has access and GNSS systems demand a clear view of the sky where there are satellites which might be blocked in heavily populated areas. Moreover, the processing of very large amounts of real-time data provided by various sources makes their integration rather difficult in the data processing process and compatibility of various technologies (Zeeshan, 2024).

Predictive models also have another constraint: overfitting. As observed in the analysis of high earners, linear regression model might give one high accuracy results compared to given dataset but lacks much external or unobservable data. The models might require additional development to deal with the problem of imbalance between data or to incorporate more problematic factors, such as socioeconomic aspects or different climate conditions (Srinivasa et al., 2025).

Future studies are needed in enhancing the accuracy and scalability of real-time data integration and optimizing machine learning models to process large and diverse data. There are other sensors that can also be studied further and real time monitoring of the environmental change like air quality or temperature variation added to enhance the information presented in the infrastructure planning and adaptation plan (Wahba et al., 2024).

## 5. Conclusion

This research has pointed to the immense advantages of using GIS in conjunction with UAV and GNSS and underground geophysical survey in infrastructure planning particularly in climate resilience preparation. The main discoveries show that these technologies offer greater accuracy in space, real-time data, and comprehensive knowledge of the surface and underground conditions, enabling to make more informed decisions. GIS allows mapping and vulnerability assessment in detail; a UAV is the source of data offering high-quality monitoring of infrastructure and GNSS allows determining the exact position or location of objects and geophysical data on the ground helps to obtain valuable information about the soil structure and groundwater level.

However, the suggested methods would warrant infrastructure planners to engage the multi-disciplinary approach involving the integration of GIS, UAV, GNSS, and underground surveys as early as in the preparation of projects to maximize the ability of these technologies. This will facilitate a more active, dynamic, and flexible planning that will be more responsive to the issues of climate change. In addition, integrating real-time data into the planning and maintenance cycle will enable to monitor the progress, as well as respond timelier to any arising problems, thereby making infrastructure more resilient.

Finally, smart climate-resilient infrastructure solutions should be integrated so that sustainable communities can be developed that can endure climate change effects that are continuously increasing. The implementation of these new technologies allows infrastructure planning to be more responsive, efficient and future-ready, with a high level of protection and its durability.

## Compliance with ethical standards

### *Disclosure of conflict of interest*

The author declares that there is no conflict of interest regarding the publication of this paper.

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