Geospatial Analysis of Potential Petrol Station Locations in the Cape Town District, South Africa.

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Abstract

Rapid urbanisation has increased the demand for essential infrastructure, including petrol stations. However, poor site selection for petrol stations can lead to significant environmental and safety risks. This study aims to identify spatially suitable locations for petrol station development in the Cape Town district using a Geographic Information System (GIS)-based site suitability model. The analysis incorporated multiple spatial datasets, such as roads, slopes, fault lines, waterbodies, public facilities, and protected areas, which were buffered and classified based on proximity and associated risk factors. The Analytic Hierarchy Process (AHP) was employed to assign relative weights to each criterion, with roads and slope exerting the greatest influence. A weighted overlay analysis was then conducted to produce a suitability map.

The results revealed that 39.7% of the study area is suitable for petrol station development, while 60.3% is unsuitable. Suitable areas were further categorised into high, moderate, and low suitability classes. Validation was conducted using geocoded data from 359 existing petrol stations obtained via web scraping. Findings indicated that 64% of existing stations fall within suitable areas, supporting the reliability of the model. High-suitability areas were found to be oversaturated with petrol stations, whereas moderate and low-suitability areas remain underdeveloped. The study recommends restricting further development in high-suitability areas and encourages more detailed investigations, including environmental impact assessments in moderate and low-suitability areas. These findings highlight the value of spatial analysis in supporting sustainable infrastructure planning.

1. Introduction

The rapid expansion of urban areas has led to an increasing demand for essential services, such as electricity, healthcare facilities, schools, petrol stations and other critical infrastructure. However, determining optimal locations for petrol station development within urban environments is complex (Khahro & Memon, 2017). This complexity is largely due to the significant environmental and safety risks posed by unforeseen disasters, given that petrol is a highly flammable and hazardous substance (Qonono, 2019; Aulia, 2011; Akbari & Saati, 2022). Several tragic incidents have highlighted the serious risks associated with poorly located petrol stations. For example, an explosion at the Mvoti Ultra City petrol station in Stranger, KwaZulu-Natal, South Africa, caused extensive damage to nearby residential buildings (Venktess, 2016). Similarly, Peprah *et al.,* (2018) reported a petrol station explosion in Ghana that resulted in at least 150 fatalities. Another case involved an explosion at a petrol station in Buena Vista, Virginia, which resulted in two fatalities and four injuries (Huang *et al.,* 2006). These incidents highlight the grave consequences of unsatisfactory site selection and reinforce the importance of thorough spatial planning and comprehensive risk assessment in the development and placement of petrol stations (Manugula & Amanu, 2023).

The legal framework regulating petrol stations in South Africa includes several key environmental statutes. Foremost among these is the National Environmental Management Act (NEMA), Act 107 of 1998, which lays the foundation for environmental management principles in Section 2. It also mandates environmental authorisations for certain activities under Section 24 and provides a process for rectifying the unlawful commencement of such activities through Section 24G. Complementing this is the Environment Conservation Act (ECA), Act 73 of 1989, which strengthens the regulatory framework through Section 21, by identifying activities likely to have a significant negative impact on the environment, and through Section 22, which prohibits the undertaking of these activities without proper authorisation. Additionally, the National Environmental Management: Waste Act (NEM: WA), Act 59 of 2008, reinforces these regulations under Section 7 by establishing norms and standards that include guidelines on safe distances from sensitive areas and the proper storage of hazardous substances.

These statutes provide norms and regulations that must be adhered to when determining appropriate petrol station locations. Khahro and Memon (2017), along with Akbari and Saati (2022), emphasise that conducting a site suitability analysis is essential to ensure compliance with the legal framework when establishing petrol stations. This forms the basis of the study's objective, which is to identify spatially suitable locations for petrol station development in the Cape Town district.

2. Study area

The Cape Town district study area has a total area of 2,445km2 and is situated in the Western Cape Province of South Africa (Figure 1). The region experiences a Mediterranean climate, with hot and arid summers, as well as chilly and wet winters. The main factor that influences this climatic condition is the cold Benguela ocean current. The Cape Town district is home to a population of 4,758,433 people, making it the second most densely populated district municipality in the country (Western Cape Government, 2021). The increase in population can be attributed to the phenomenon of inward migration, leading to the establishment of more residential structures within the region. This leads to pressure on the city's transportation system and road network.

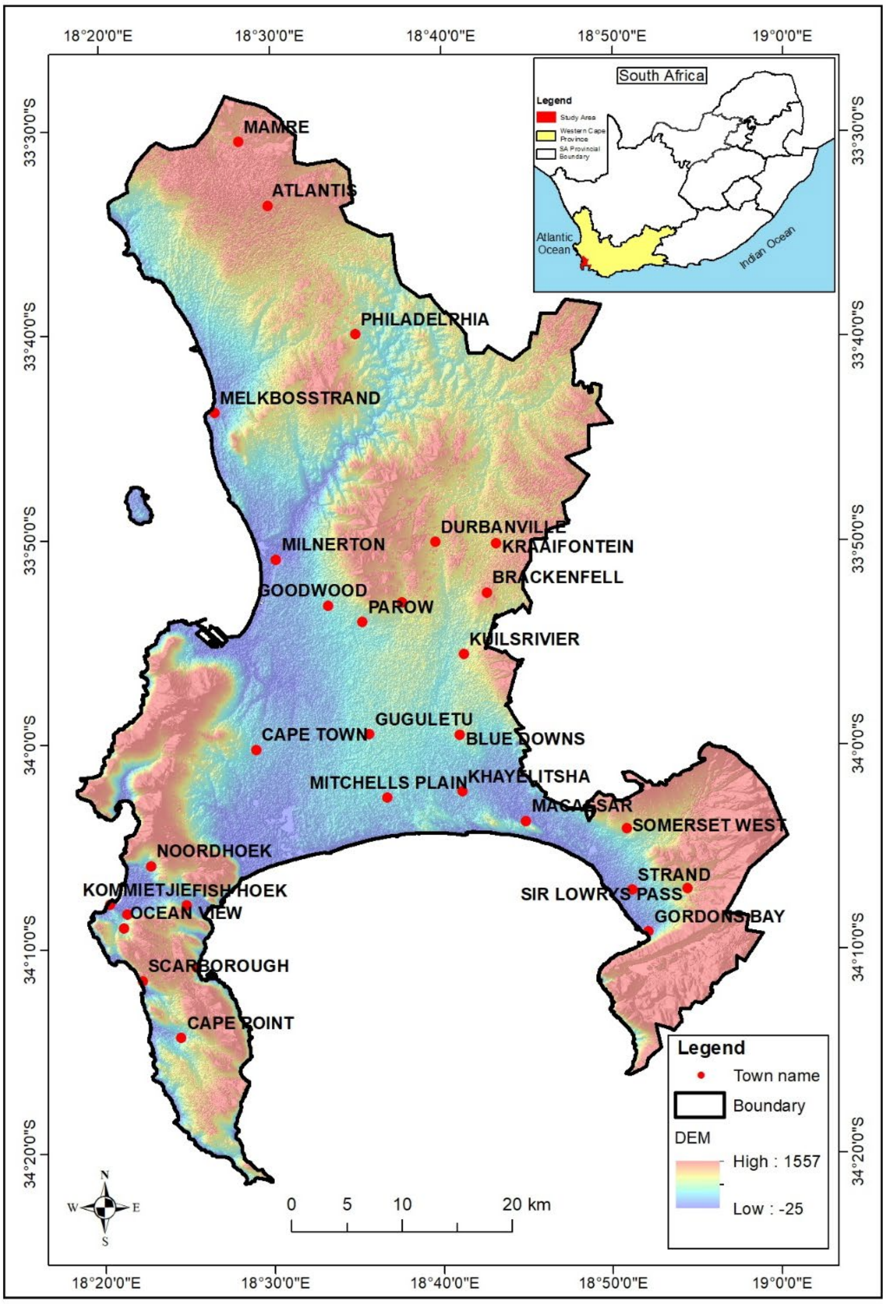

Figure 1: Study area map of the Cape Town district.

The Cape Town district is also a major tourist destination, known for its iconic landmarks such as Table Mountain and Cape Point, as well as its rich biodiversity and cultural heritage. The municipality actively promotes sustainable development, balancing urban growth with the protection of its unique natural landscapes (Municipal Spatial Development Framework, 2023).

2.1. Vegetation

Ecologically, the district is situated within the Cape Floristic Region, the smallest but most botanically diverse of the world’s six recognised floristic kingdoms (Goldblatt, 1997). This region supports over 9,000 vascular plant species, about 69% of which are endemic and found nowhere else on Earth (Cowling *et al.,* 1996). Much of this biodiversity is concentrated in the fynbos biome, a fire-prone Mediterranean-type shrubland that provides both ecological and economic value. The fynbos biome contributes several million rands annually through eco-tourism and wildflower harvesting (Cowling *et al.,* 1996).

2.2. Geology

The region's unique biodiversity is closely tied to its complex geological foundation, which consists of three major formations. The Malmesbury Group, the oldest, is composed of sedimentary and metamorphic rocks such as greywacke and shale and is exposed along the coast at Sea Point and Bloubergstrand (Tham & Johnson, 2006). The Cape Granite Suite includes massive granite intrusions that penetrate the Malmesbury rocks, forming notable features such as the Peninsula and Helderberg ranges. Overlying these formations is the Table Mountain Group, made up primarily of quartzitic sandstone, which contributes to the rugged terrain of the Cape Fold Belt (Tham & Johnson, 2006).

3. Methodology

This study used a Geographic Information System (GIS)-based site suitability model to determine suitable locations for petrol station development. The model was developed through several key stages, including the identification of relevant datasets, data processing, suitability map generation, and validation (Figure 2). To validate the model's output, web scraping and geocoding techniques were used to collect current information on existing petrol stations within the study area. It was assumed that the locations of these existing stations represent highly suitable areas. The collected data were then compared with the model's predicted suitable sites to assess its accuracy and reliability.

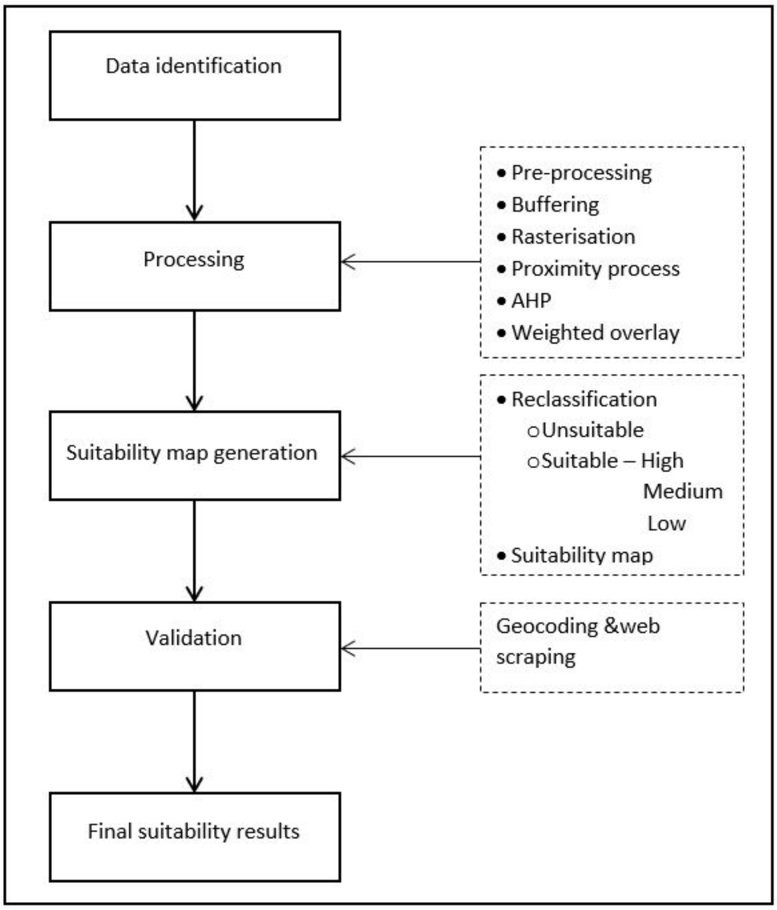

Figure 2: Methodological flow diagram for petrol station site suitability analysis.

3.1. Dataset identification

The spatial datasets used in this study were primarily sourced from the integrated topographic data provided by the Chief Directorate: National Geospatial Information (CD: NGI). These included vector datasets for roads (comprising national and main roads), waterbodies (including rivers, dams, and wetlands), public facilities (such as schools, city colleges, libraries, and healthcare centres), and protected areas. Additional fault line data were acquired from the Council for Geoscience, formerly known as the South African Geological Survey. Slope data were derived from the 30-metre resolution Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) dataset, made publicly available by the United States Geological Survey (USGS).

The selection of these spatial datasets was guided by their relevance to environmental conservation, public safety, and data availability. Their significance is illustrated through several examples. For instance, in the event of a hazardous spill or explosion at a petrol station, it is critical to identify and protect environmentally sensitive areas, especially waterbodies and conservation areas, to prevent ecological degradation and contamination (Peprah *et al.,* 2018). Similarly, ensuring a safe buffer distance between petrol stations and public buildings such as schools and healthcare centres is essential for safeguarding human life in the event of an emergency (Xu *et al.,* 2002; Aluko *et al.,* 2012; Ogunkoya & Alabi, 2017).

Topography, particularly slope, is another critical factor in site suitability analysis. Areas with steep slopes are more prone to landslides during flooding which poses risks to infrastructure and safety. Moreover, highly sloped areas may reduce site accessibility, limit storage capacity, and complicate fuel delivery logistics, thereby compromising the operational viability of petrol stations (Manugula & Amanu, 2023).

The incorporation of the above-mentioned factors enables the analysis to identify petrol station sites that are environmentally responsible, safe, and practically viable for sustainable development and long-term operation.

3.2. Data processing

All spatial datasets used in this study, including roads, waterbodies, public facilities, protected areas, and fault lines, were available at the national scale and provided in vector format. The only exception was the DEM, used to derive slope data, which was available in raster format. The WGS-1984 ellipsoid, Transverse Mercator projection, and Hartebeesthoek-1994 datum were adopted as the coordinate system to ensure alignment with South Africa's national geospatial standards and to support accurate local spatial analysis. To constrain the analysis within the designated study area, each dataset was clipped to the boundaries of the Cape Town district. Subsequently, buffer zones were applied to delineate areas of influence around identified spatial features, thereby enhancing the precision of the site suitability assessment.

The determination of buffer distances in this study was guided by environmental risk mitigation principles, accessibility considerations, and insights from existing literature (He *et al.,* 2022; Akbari & Saati, 2022; Macfarlane *et al.,* 2014; Xu *et al.,* 2002). Buffers are spatial zones applied around geographic features to delineate areas of influence, manage potential risk, and support informed decision-making.

The road network was categorised into two types: main roads, which were assigned a five-metre buffer to ensure proximity for convenient access, and national roads, which were allocated a 100-metre buffer to account for higher traffic volumes and safety considerations (Akbari & Saati, 2022).

For waterbodies, the dataset was divided into two classes: rivers, which were buffered by 80 metres, and hydro-regions (e.g., wetlands and dams), which were assigned a 500-metre buffer. Aligning with environmental conservation standards (Macfarlane *et al,* 2014), these distances were chosen to protect ecologically sensitive areas from potential contamination due to fuel leaks or hazardous materials.

Public facilities, including schools, healthcare centres, and libraries, were assigned a 100-metre buffer to ensure human safety and reduce the risk of exposure in the event of explosions or toxic emissions from petrol stations (Xu *et al.,* 2002). Fault lines were buffered by 30 metres to minimise the structural risk associated with geological instability, particularly given the flammable nature of fuel and the infrastructure involved in petrol station operations (He *et al.,* 2022). However, the protected area dataset was not buffered, because it already defines ecologically significant boundaries and serves as a natural exclusion zone. Consequently, further buffering was deemed unnecessary.

Following the buffering of the datasets, namely roads, waterbodies, fault lines, and public facilities, each dataset was converted into a raster format to enable proximity analysis. This technique assesses spatial relationships by measuring the distance between geographic features (Chakraborty & Maantay, 2011; Tah, 2017; Steinmaus & Smith 2017; Malavolti *et al.,* 2023). This study employed proximity analysis to classify areas into three levels of suitability: low, moderate, and high.

Proximity to roads was considered beneficial in this study. Areas located within 100 metres of roads were assigned a class value of 3 (high suitability), reflecting convenient access. Locations between 100-500 metres received a class value of 2 (moderate suitability), while those beyond 500 metres were assigned a class value of 1 (low suitability), indicating reduced accessibility.

Conversely, for other spatial features, such as waterbodies, public facilities, protected areas, and fault lines, the classification values were inverted. Greater distances from these features were associated with higher suitability, as this reduces environmental and safety risks. Consequently, areas located close to these sensitive features were classified as low suitability, while those further away were considered as highly suitable. The specific distance thresholds applied in the classification are summarised in Table 1.

Table 1: Proximity analysis

Buffered Spatial datasets	Proximity criteria		
	Low suitability	Moderate Suitability	High suitability
Roads	distance greater than 500m	distance greater than 100m but less than or equal to 500m	distance greater than 0m but less than or equal to 100m
Fault Lines	distance greater than 0m but less than or equal to 100m	distance greater than 100m but less than or equal to 500m	distance greater than 500m
Waterbodies	distance greater than 0m but less than or equal to 100m	distance greater than 100m but less than or equal to 500m	distance greater than 500m
Public Facilities	distance greater than 0m but less than or equal to 100m	distance greater than 100m but less than or equal to 500m	distance greater than or equal to 500m

Slope data provide a foundation for terrain analysis and play an essential role in site suitability assessment. For this study, slopes were classified into three classes: Class 1 (0°–7°), Class 2 (>7°–20°), and Class 3 (>20°). Class 1, which represents flat to gently sloping terrain, is considered highly suitable for petrol station development due to its easier construction, reduced cost, and safe vehicle access (Jankowski, 1995; Rahman *et al.,* 2013). Class 2 includes moderately sloped areas that, while less ideal, can still be developed with additional engineering measures, such as slope stabilisation and drainage management, although these increase construction complexity and cost (Chen *et al.,* 2010). Class 3 consists of steep slopes that are generally unsuitable due to heightened erosion risks, limited accessibility, and the need for extensive earthworks (Store & Kangas, 2001). Integrating slope data into the suitability analysis helps identify unsuitable areas early, thereby enhancing the safety, cost-effectiveness, and overall efficiency of the site selection.

The Analytic Hierarchy Process (AHP) was applied to assess the relative importance of each spatial dataset in determining suitable locations for petrol stations. Developed by Saaty (1980), AHP is a structured, multi-criteria decision-making technique designed to handle complex problems by breaking them down into a hierarchy of criteria, conducting pairwise comparisons, and deriving quantitative weights that reflect the relative priority of each factor (Saaty, 1980; Ishizaka & Labibi, 2011).

This study applied AHP to prioritise the spatial factors influencing the suitability of petrol station sites. Through systematic pairwise comparisons, each criterion was assessed relative to others and based on its perceived importance. The outcomes were then normalised to derive a set of weights representing the proportional influence of each dataset on the overall suitability analysis. This structured approach provided a transparent and replicable framework for assigning relative importance to each spatial dataset (Malczewski, 1999).

The final weights derived from the AHP were: roads (38%), slopes (25%), fault lines (16%), waterbodies (10%), public facilities (7%), and protected areas (4%). These results highlight that accessibility via road networks and topographic slopes were considered the most influential variables, whereas protected areas had the least impact on site selection decisions. This prioritisation formed the basis for integrating the spatial layers in the weighted overlay process.

Subsequently, a weighted overlay analysis was then performed, in which each raster dataset was multiplied by its respective AHP-derived weight. This produced a composite suitability score ranging from 0 to 3. These resulting scores were reclassified to generate the final site suitability map: a score of 0 was classified as "not suitable," while scores of 1, 2, and 3 were categorised as "low suitability," "moderate suitability," and "high suitability," respectively.

3.3. Validation

The model was validated using a geocoded petrol station dataset obtained through web scraping and based on the assumption that current stations reflect strategically chosen and suitable locations. Web scraping is a method used to automatically extract structured data from websites and convert it into usable formats such as spreadsheets or databases (Zhao, 2017; ten Bosch *et al.,* 2018; Souza *et al.,* 2021). The underlying premise of this technique is that websites often host current and reliable data, making them valuable sources for information.

This study sourced data from the South African Fuel Directory (www.fueldirectory.co.za), an independent online platform that regularly updates information on petrol station locations, physical addresses, fuel prices, and contact details. A customised web-scraping script was developed to systematically extract relevant records from the site. The resulting data, primarily consisting of petrol station addresses, was cleaned and compiled into an Excel spreadsheet for further processing.

The next step involved geocoding, a process that converts textual location data into geographic coordinates (latitude and longitude), which were then projected to the reference system adopted for this study. This geocoding procedure enabled the transformation of address-based records into spatial point features suitable for mapping and spatial analysis within a Geographic Information System (GIS).

The final output of this process was a geospatial dataset containing 359 accurately geocoded petrol station locations across the study area. This dataset was instrumental for validating the site suitability model by allowing a comparison between predicted suitable areas and the actual spatial distribution of existing petrol stations.

4. Results and discussion

This section presents the outcomes of the GIS-based petrol station site suitability analysis. The analysis incorporated a range of spatial datasets, including roads, waterbodies, fault lines, public facilities, protected areas, and slope data (Figure 3). The processing of these datasets followed established geospatial methodologies, including buffering, rasterisation, proximity analysis, application of the Analytic Hierarchy Process (AHP), and weighted overlay analysis. The final stage reclassified the output to generate a comprehensive suitability map.

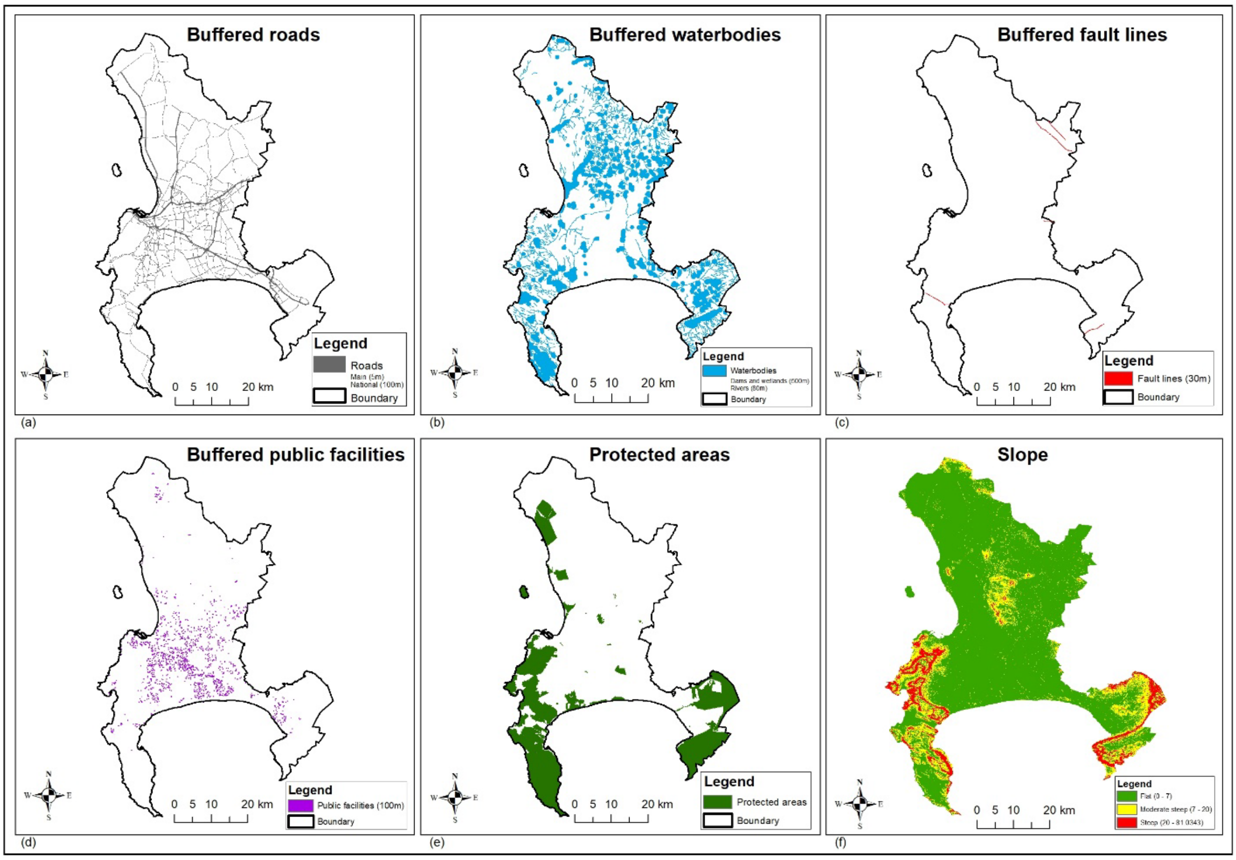

Figure 3: Spatial dataset used in the petrol station suitability model (a) roads, (b) waterbodies, (c) fault lines, (d) public facilities, (e) protected areas, and (f) slope.

The resulting site suitability map classified the study area into suitable and unsuitable (or not suitable) areas for petrol station development (Figure 4). The areas classified as “not suitable” are represented in dark green colour in Figure 4. The “suitable areas” are further categorised into low suitability (light yellow), moderate suitability (blue), and high suitability (red). According to the results, 39.7% of the total study area is suitable for petrol station development, while 60.3% is unsuitable. Among the suitable areas, 28.7% are classified as low suitability, 7.4% as moderate suitability, and 3.6% as high suitability (Figure 5).

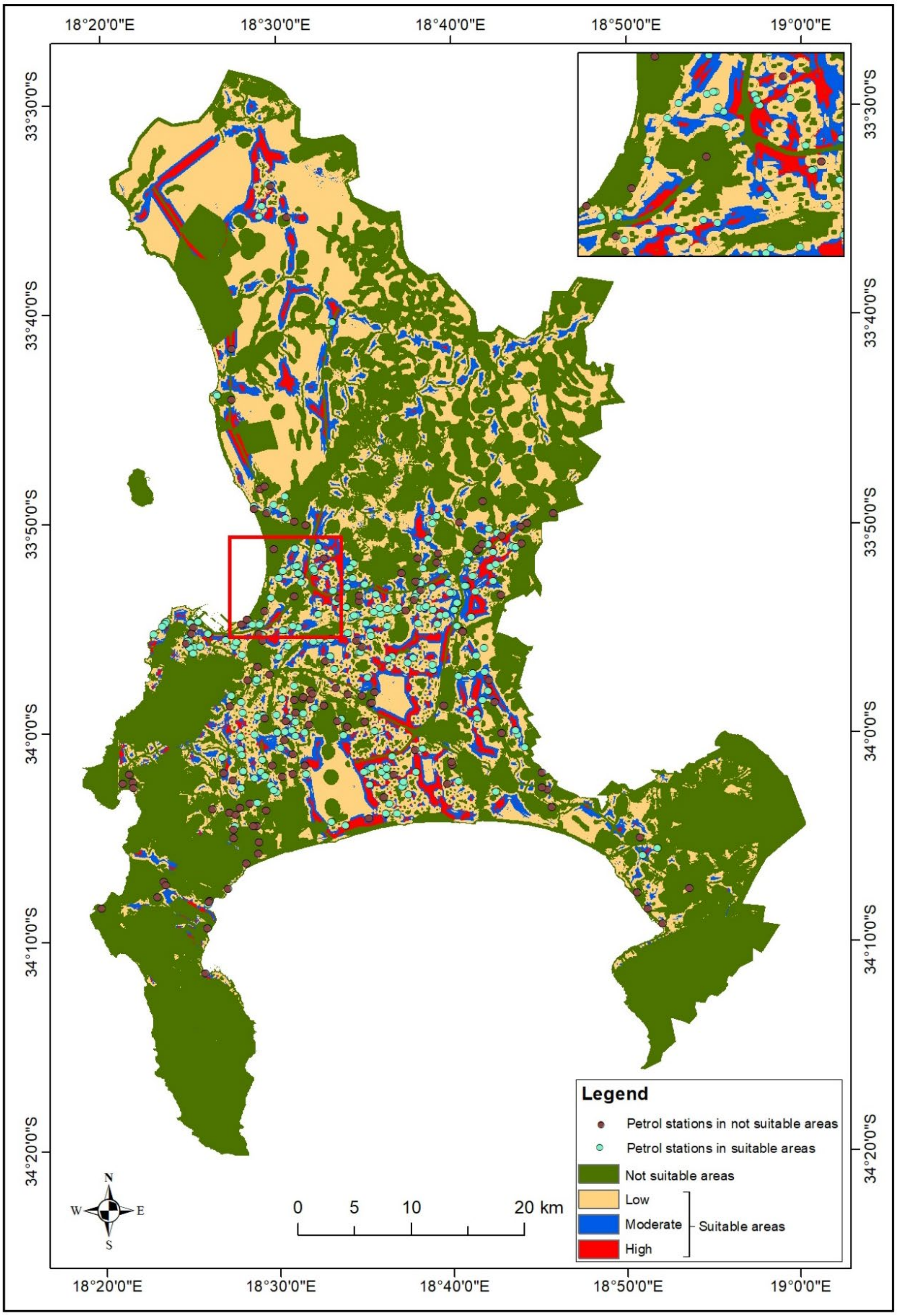

Figure 4: Spatial distribution of petrol stations relative to the suitability map derived from the GIS-based model.

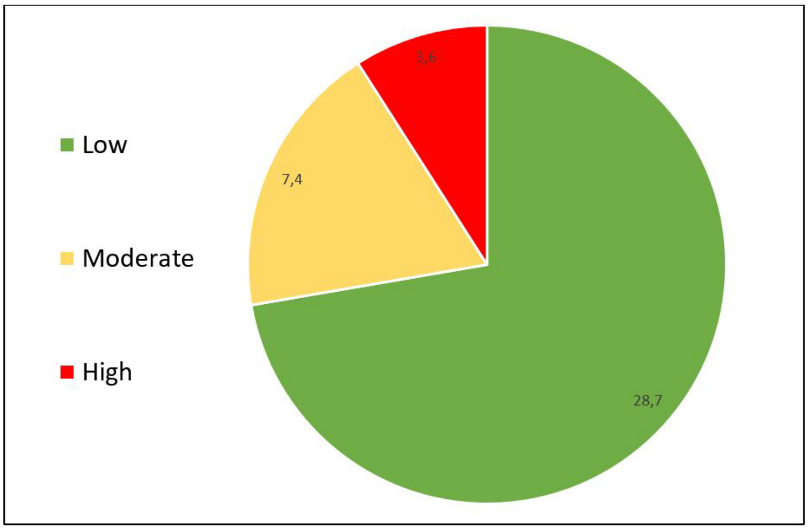

Figure 5: Overview of the distribution of suitability ratings categorised as low, moderate, and high.

Model validation was conducted using a geocoded petrol station dataset obtained through web scraping and based on the assumption that existing stations represent strategically selected, operationally suitable locations. The validation results revealed that 64% of existing petrol stations were located within areas identified as suitable by the model. These findings are consistent with the studies by Peprah *et al.* (2018) and Manugula and Amanu (2023), who also reported a strong spatial correlation between operational petrol stations and suitable areas identified through a similar GIS-based model. Notably, 20% of these stations were situated in high suitability areas, 17% in moderate, and 63% in low suitability areas (Table 2). These findings indicate that while most stations are in suitable areas, a notable proportion still operate in less-than-ideal or low-suitability locations.

Table 2: Density of petrol stations within each suitability area

Petrol station-generated points			Density of petrol stations (per km$^{2)}$
Suitability area	Suitability points		
Category	Number	Percentage	
Low	145	63%	4.8
Moderate	39	17%	4.6
High	46	20%	1.9

A spatial density analysis further revealed that highly suitable areas had a higher concentration of petrol stations (approximately one per 1.9 km^2), compared to one station per 4.6 km^2 and 4.8 km^2 in moderate and low suitability areas, respectively (Table 2). These spatial patterns highlight the impact of location-specific factors such as accessibility, terrain, and regulatory compliance, elements similarly noted in the works of Mahmud *et al.* (2020) and

Tuan and Navaratnam (2005). For instance, Mahmud *et al.* (2020) found that petrol stations tend to cluster in areas with better road access and service demand, aligning with the higher density observed in highly suitable areas in this study. Likewise, Tuan and Navaratnam (2005) emphasised terrain and regulatory constraints, which may explain the reduced station density in moderately and poorly suitable areas, where slope restrictions are more prevalent.

The guideline established in the MEC for Agriculture judgment of 2006 which prohibits the development of new petrol stations within three kilometres of existing ones in residential or built-up areas highlights the importance of maintaining spatial separation to prevent overconcentration. This regulation, upheld by South Africa's High Court of Appeal, mirrors concerns expressed by Glasson *et al.* (2012) regarding the cumulative environmental impact of clustered petrol stations. According to their findings, closely situated stations can intensify environmental risk such as soil and groundwater contamination, increased air pollution from fuel emissions and traffic, and elevated noise and congestion levels, particularly in urban or residential areas (Glasson *et al.,* 2012). Additionally, overconcentration of petrol stations may amplify the severity of hazards during accidents. While this study similarly cautions against placing additional petrol stations in already saturated areas, it also finds that moderate and low suitability areas do not currently exhibit excessive clustering. Nonetheless, the results reinforce the importance of conducting further site-specific evaluations to ensure environmentally and socially responsible development.

For petrol station development in moderate or low suitability areas, GIS-based analysis should be supplemented with comprehensive investigations encompassing environmental, social, regulatory, and economic considerations. This includes conducting Environmental Impact Assessments (EIAs) to evaluate potential risks to soil, groundwater, biodiversity, and air quality, as well as hydrogeological and soil stability studies (DEA, 2017; Fatta *et al.,* 2007). Compliance with zoning regulations (DPLG, 2006) and economic feasibility assessments (Tuan & Navaratnam, 2005) is also essential for sustainable and context-sensitive planning. Collectively, these approaches align with integrated planning models advocated in spatial planning research and policy frameworks (Khahro & Memon, 2017; Akbari & Saati, 2022).

5. Conclusion

This study aimed to identify optimal locations for petrol station development in the Cape Town district using a GIS-based site suitability model. The analysis incorporated key spatial datasets such as roads, slopes, fault lines, waterbodies, public facilities, and protected areas, which were prioritised using the Analytic Hierarchy Process (AHP). Roads were identified as the most influential factor. The resulting suitability map indicated that 39.7% of the area was suitable for development, while 60.3% was classified as unsuitable.

Model validation, using 359 geocoded existing petrol stations, revealed that 64% were located within areas classified as suitable by the model. Distance-based distribution analysis indicated an oversaturation of petrol stations in high-suitability areas. Conversely, moderate and low-suitability areas exhibited wider spacing between stations, suggesting greater potential for future development.

Based on these findings, the study recommends limiting further development of petrol stations in already saturated high-suitability areas. However, it encourages exploring development opportunities in moderate and low-suitability areas, provided that comprehensive site-specific assessments are conducted. These assessments should encompass environmental, social, regulatory, and economic factors to ensure that future developments are sustainable, legally compliant, and contextually appropriate.

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