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Developing optimal road alignment using geospatial technologies: A case study from ginchi to chullute, oromia region

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ABSTRACT

Background: Route selection is a critical step in road design and construction, particularly in landslide-prone areas were environmental and economic challenges demand innovative solutions. Geospatial technology provides a robust framework for optimal route planning by integrating various decision-support tools. Although global research has extensively addressed route optimization, limited studies have focused on landslide-prone areas in Ethiopia, highlighting a gap in the application of advanced geospatial techniques in such regions.

Objective: This study aimed to develop an optimal road alignment connecting Ginchi to Chullute in the Oromia Region by employing geospatial tools to address engineering, environmental, and landslide-related challenges.

Methods: The study incorporated Sentinel 2A satellite imagery, ALOS DEM, geological maps, population data, SPOT 5 imagery, and field visits to identify key alignment factors. The Analytical Hierarchy Process (AHP) was used to assign weights to factors, generating engineering, environmental, and landslide cost surfaces. A hybrid cost surface, integrating these factors with equal weighting, was developed for least-cost path modelling using GIS tools. Landslide susceptibility was assessed using the Frequency Ratio Method, and the model's accuracy was validated with an AUC score of 0.756.

Results: The hybrid least-cost path was identified as the optimal route, reducing the existing road length from 122 km to 103.46 km. Compared to other modelled paths (104.3, 105, and 98.3 km), the proposed route was less susceptible to landslides and more feasible from an engineering perspective.

Conclusion: This study highlights the effectiveness of integrating geospatial tools for environmentally sustainable and cost-efficient road planning. These methods can also be extended to the design of other linear infrastructures, including drainage, pipelines, and railways.

KEYWORDS

Analytical hierarchy process (AHP); Geospatial technology; Landslide; Least-cost path analysis (LCPA); Optimal road alignment

ARTICLE HISTORY

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Introduction

Road infrastructure is vital for societal development, enabling connectivity, trade, and economic growth. Roads facilitate the movement of goods and people, fostering regional integration and access to essential services [1]. Central to road infrastructure development is road alignment, which involves planning the centerline of a road. This process balances economic benefits with environmental sustainability while ensuring long-term functionality [2]. While roads bring enhanced mobility and economic opportunities, they also present challenges, including environmental degradation, resource depletion, and habitat disruption.

Effective route selection significantly influences construction costs, environmental impact, and operational safety. However, traditional methods relying on manual surveys and visual assessments are time-consuming, resource-intensive, and often inefficient [3]. These limitations are especially evident in regions with complex topographies or geohazards, such as landslide-prone areas, where traditional approaches struggle to address multifaceted challenges.

Geospatial technologies, particularly Geographic Information Systems (GIS) and remote sensing, have emerged as transformative tools for overcoming these limitations [4]. By integrating factors such as topography, geology, land use, and environmental constraints, these tools facilitate comprehensive route planning. Least-Cost Path Analysis (LCPA), a GIS-based method, is particularly effective for road alignment, as it combines spatial data to minimize construction costs and environmental impacts. Unlike traditional methods, LCPA enables systematic evaluation of terrain and constraints, offering a robust framework for route optimization [5]. In landslide-prone regions, geospatial tools play a critical role in mitigating risks to infrastructure. Landslides increase maintenance costs, disrupt transportation, and pose significant safety concerns. Despite the potential of geospatial technologies, their application in regions like Ethiopia remains limited, particularly in addressing geohazards [6].

Ethiopia's road infrastructure plays a pivotal role in economic growth and connectivity. However, road alignment

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practices often prioritize topography while neglecting geological stability, environmental impacts, and socioeconomic factors. As a result, many roads face frequent maintenance issues, safety risks, and limited resilience. The Ginchi to Chullute corridor in the Oromia Region exemplifies these challenges [7]. The existing 122-kilometer road traverses complex terrain and is highly susceptible to landslides, leading to frequent disruptions and increased repair costs. Current alignment practices inadequately address the corridor's geotechnical and environmental complexities, leaving significant room for improvement. Traditional road alignment methods in Ethiopia face notable limitations. These approaches rely on manual surveys and subjective assessments, often overlooking critical factors such as slope stability, drainage, and land use conflicts [8]. The lack of integration of advanced tools for assessing geohazards like landslides further exacerbates these challenges. Additionally, socioeconomic and environmental constraints, such as land ownership and habitat preservation, are often insufficiently addressed, resulting in long-term operational difficulties.

While the potential of geospatial technologies in road planning is well-documented, their application in landslide-prone areas remains underexplored in Ethiopia [9]. Current studies focus predominantly on economic and environmental factors, with limited attention to geohazards. Moreover, advanced decision-making tools such as the Analytical Hierarchy Process (AHP) and LCPA are underutilized in Ethiopian road alignment projects [10]. Addressing this gap requires research that integrates engineering, environmental, and social factors into a cohesive framework for route optimization.

This study addresses these gaps by developing an optimal road alignment for the Ginchi to Chullute corridor using geospatial tools. The research employs GIS-based techniques, including LCPA and AHP, to evaluate and prioritize factors such as slope, lithology, drainage, and land use [11]. Data from satellite imagery, digital elevation models, geological surveys, and field visits are integrated into a comprehensive framework for route selection. By proposing a route that reduces the existing road length, mitigates landslide risks, and minimizes environmental impacts, this study demonstrates the utility of geospatial technologies in road planning [12]. The findings aim to inform policymakers, engineers, and urban planners about the benefits of adopting advanced tools for transportation infrastructure design. Beyond its immediate application to the Ginchi to Chullute corridor, the study highlights broader implications for using geospatial tools in sustainable and resilient road development across regions prone to geohazards.

Study Area

Location

The Ginchi-Shukute-Chullute road is situated in central Ethiopia, within the West Shoa Zone of Oromia Regional State. Spanning 122 kilometers, it crosses multiple administrative divisions, including Dendi, Jeldu, Abune Gindeberet, and Gindeberet. Recent administrative changes have subdivided Jeldu Woreda into Jeldu and Chobi, and Dendi Woreda into Dendi, Elfita, and Ejersa Lafo [13,14]. The starting point, Ginchi town, is located 73 kilometers from Addis Ababa at 09°02'N and 38°06'E, while the endpoint, Chullute, lies northwest at 9°39'21.22"N and 37°45'49.77"E (Figure 1).

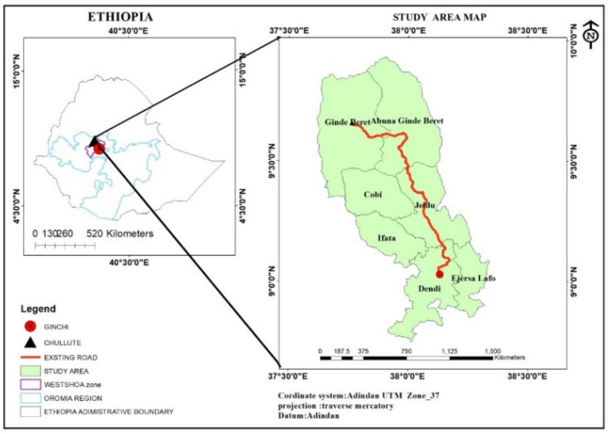

Figure 1. Location map of study area (source: BOFED, 2020).

Topography

The study area features diverse terrain, with elevations ranging from 920 meters to 3,307 meters above sea level. Dendi Woreda includes plateaus and mountains, with altitudes between 1,500 and 3,270 meters, while Jeldu Woreda is characterized by undulating terrain at 2,900 to 3,200 meters. Gindeberet and Abune Gindeberet Woredas primarily consist of rugged lowlands and flat mid-highland plateaus [15]. This varied topography presents challenges for road alignment, requiring careful evaluation to mitigate steep slopes and uneven landscapes (Figure 2).

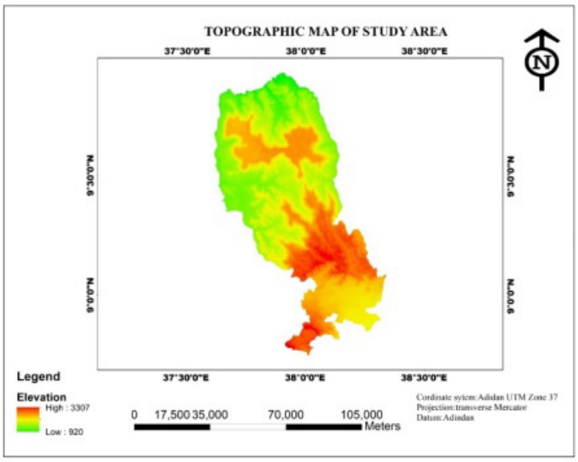

Figure 2. A Topography of study area [Source: ALOS DEM (2021)].

Land use

Agricultural land dominates the study area, covering 54% (284.99 km²), followed by dense forests at 21% (110.5 km²). Built-up areas, bare land, and water bodies occupy 13% (70 km²), 7% (35.1 km²), and 4% (21.6 km²), respectively [16]. Chillimo Forest, a dense forest of ecological and economic importance, spans 19.93 km². Population growth and increased demand for farmland have led to significant deforestation, posing challenges for environmental conservation and sustainable road alignment (Figure 3).

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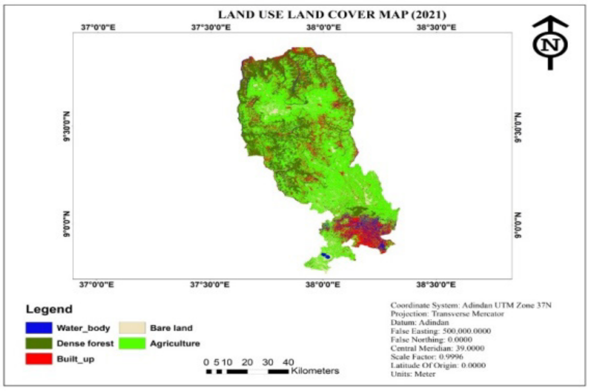

Figure 3. Land use land cover map of study Area (source: google earth and USGS, 2021).

Drainage structure

The study area has a dense dendritic drainage network, part of the North Abay Basin. Major rivers, including Tutu, Kersa, Fele, and Litu, and tributaries such as Qarasa Saden and Dongage Jawaro, ultimately join the Abay River. The largest stream, Urgaha, spans 17.5 kilometers. The drainage network, totaling 1,763.24 kilometers, necessitates engineering solutions for bridges and culverts to address flood-prone areas and river crossings (Figure 4).

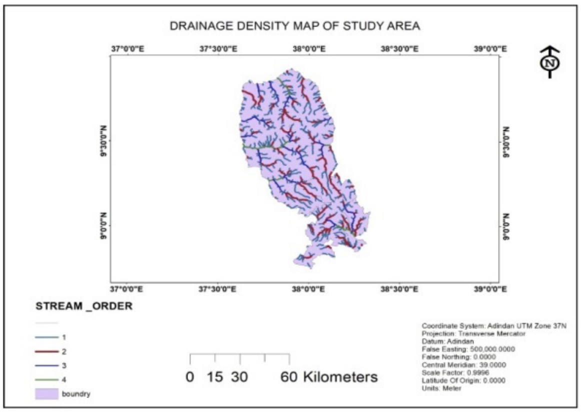

Figure 4. Drainage Map of Study area [source: ALOS DEM, (2021)].

Climate and rainfall

The study area falls under two agroecological zones: Woina-Dega (71%) and Dega (29%). Dendi Woreda receives 750–1,170 mm of annual rainfall, with temperatures ranging from 9.3°C to 23.8°C. Abune Gindeberet and Gindeberet Woredas experience rainfall between 700 and 1,600 mm, with average temperatures between 10°C and 18.5°C. These climatic conditions demand attention to seasonal flooding and erosion when planning road alignments [17].

Geology

The geology includes sedimentary and volcanic rocks from the Mesozoic and Cenozoic eras. Sedimentary formations reflect coastal, fluvial, and lacustrine depositional environments, while volcanic features are basaltic and formed from fissure-flow magma [18].Geological characteristics significantly influence construction, requiring adaptations for unstable formations and hard rock areas (Figure 5).

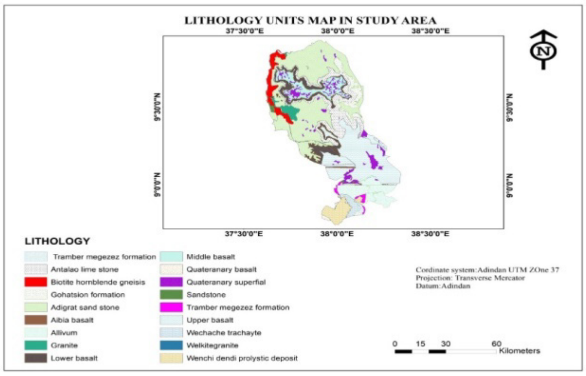

Figure 5. Lithology map of the study area [source: Ethiopia geological survey, (2019)].

Soil types

Soil types in the area include chromic cambisols, dystric nitisols, eutric regosols, and pellic vertisols, with textures such as loam, sandy loam, and clay. These soils vary in construction suitability, influencing road stability and requiring careful selection of alignment paths (Figure 6).

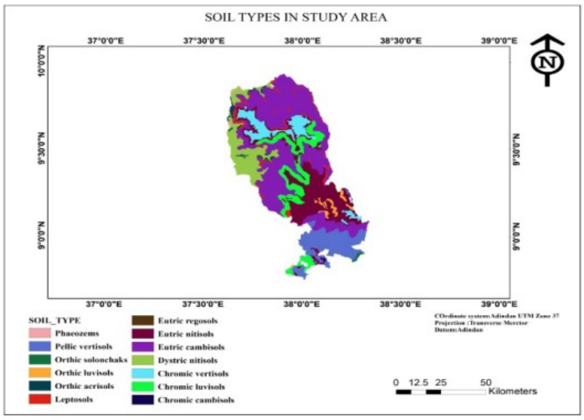

Figure 6. Soil types in the study area [source: MOWIE, (2020)].

Population

The projected 2020 population is 941,597, based on the 2007 census, with 466,879 males and 474,757 females. Population density is highest in Jeldu and lowest in Cobi Woredas. Higher population density influences the need for accessible and direct routes to support economic and social activities, emphasizing the importance of effective road planning (Figure 7).

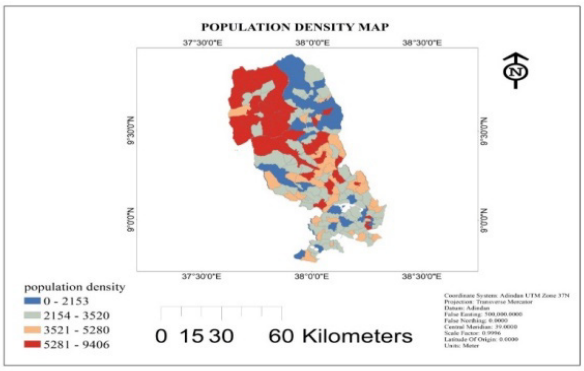

Figure 7. Population density map (source: CSA).

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Materials and Methods

Data collection

This study utilizes a combination of spatial and non-spatial datasets to analyze and identify factors influencing road alignment in the Ginchi to Chullute corridor. Spatial datasets include Sentinel-2A satellite imagery with 10-meter resolution, ALOS Digital Elevation Model (DEM) with 12.5-meter resolution for precise elevation data, geological maps for lithological information, land use/land cover data for vegetation and agricultural patterns, and population distribution data for demographic considerations [19]. These datasets provide critical inputs for generating thematic maps and assessing alignment factors such as slope, lithology, drainage, and land use.

Field visits complement the spatial datasets by validating the data and providing additional non-spatial information. These visits focus on ground-truthing slope characteristics, verifying soil conditions, identifying drainage features, and assessing areas prone to landslides [20]. By integrating field observations with remote sensing data, the accuracy of thematic maps is improved, ensuring a reliable basis for analysis.

Criteria selection

The criteria influencing road alignment are selected based on engineering, environmental, and social factors. These include:
Slope: Steep slopes are avoided to minimize construction costs and risks of instability.

Lithology: Geological stability is prioritized to ensure the durability and safety of the road infrastructure.

Soil: Soil texture and type are analyzed for their impact on road stability and construction feasibility.

Drainage: High drainage density and proximity to water bodies are considered to mitigate risks of flooding and erosion.

Land Use: Agricultural lands, forests, and built-up areas are evaluated to minimize land conflicts and acquisition challenges.

Population: Population density data is incorporated to align the road with connectivity needs in densely populated regions.

Each criterion is carefully reclassified into thematic layers, and weights are assigned based on their relative importance. The Analytical Hierarchy Process (AHP) is used to ensure systematic prioritization by deriving numerical weights through pairwise comparisons.

Analysis techniques

The Analytical Hierarchy Process (AHP) provides a structured framework for assigning weights to the selected criteria. By conducting pairwise comparisons, AHP evaluates the relative importance of each factor, ensuring that engineering, environmental, and social considerations are systematically integrated [21]. The consistency ratio is calculated to validate the reliability of the weight assignments.

GIS-based Least-Cost Path Analysis (LCPA) is used to generate alternative routes by calculating the least-cost path across a cumulative cost surface derived from the weighted criteria. This method overlays thematic layer such as slope, land use, and drainage within a GIS environment, enabling the identification of optimal alignments that minimize construction and environmental costs [22].

Landslide susceptibility mapping is performed using the Frequency Ratio Method. This statistical approach evaluates the relationship between landslide occurrences and contributing factors, such as slope, lithology, and drainage density [23]. The model's performance is validated using Receiver Operating Characteristics (ROC) and the Area Under the Curve (AUC), where a score of 0.756 indicates good predictive accuracy.

Workflow

The methodological workflow follows a structured sequence to ensure comprehensive analysis and reliable outcomes:

Data Preparation: Pre-processing spatial datasets involves georeferencing, clipping, and reclassification to create thematic layers. Field data is integrated into these layers for refinement and validation.

Criteria Weighting: AHP is used to assign weights to the selected criteria. Expert judgments guide the pairwise comparison process, and the consistency ratio is calculated to ensure the reliability of the weights.

Cost Surface Generation: Thematic layers are overlaid in a GIS environment to create cost surfaces for engineering, environmental, and landslide-specific scenarios. A hybrid cost surface is also generated by combining these factors with equal weighting, offering a balanced approach to alignment optimization.

Route Modeling: The Least-Cost Path function in ArcGIS Spatial Analyst is applied to the cost surfaces. The starting point (Ginchi) and endpoint (Chullute) are used as inputs to model alternative routes.

Validation and Optimization: Landslide susceptibility mapping undergoes validation through AUC-ROC analysis to confirm model accuracy. Alternative routes are compared based on length, cost, and environmental impact, and the hybrid least-cost path is identified as the optimal alignment (Figure 8).

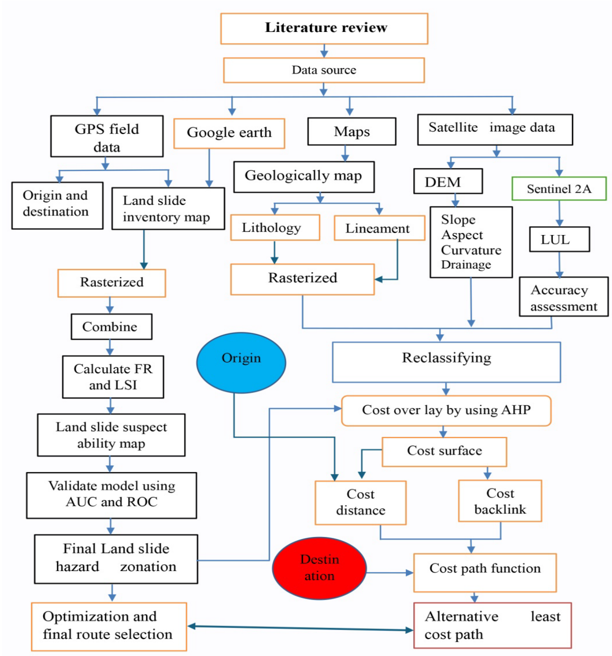

Figure 8. Flowchart showing the methodology.

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Results and Discussion

Criteria maps

Thematic maps for slope, drainage density, lithology, and land use provide comprehensive insights into the factors influencing road alignment in the Ginchi to Chullute corridor [24]. Slope analysis highlights significant variations, with steep slopes exceeding 30% concentrated in the highland regions of Jeldu and Gindeberet Woredas. These areas are deemed unsuitable for road construction due to high costs, increased risks of instability, and the need for extensive earthworks [25]. Conversely, gentle slopes predominantly found in the mid-highlands and lowlands present favourable conditions for alignment, reducing construction challenges and minimizing environmental disruption.

Drainage density mapping reveals a dense and intricate hydrological network, with high-density zones located near tributaries of the Mugher River. These regions require careful planning to mitigate flooding risks and ensure sustainable drainage management. Areas with low drainage density, on the other hand, offer fewer challenges for road construction, making them more suitable for alignment [26]. Lithology maps identify varied geological formations, including stable volcanic basalts in the mid-highlands and less stable sedimentary formations in the lowlands. Basalts provide a solid foundation, reducing construction risks, whereas sedimentary formations necessitate additional reinforcement to prevent erosion-related failures.

Land use reclassification demonstrates that agricultural land dominates the area, covering 54% of the total region, followed by forests at 21%. Dense forests, including Chillimo Forest, hold ecological significance and require special consideration to prevent deforestation and biodiversity loss. Built-up areas and water bodies, though smaller in coverage, are critical for ensuring minimal disruption to human settlements and natural ecosystems [27]. Together, these thematic maps enable an integrated evaluation of terrain suitability, guiding decisions to balance engineering feasibility with environmental sustainability.

Cost surfaces

The cost surfaces generated for engineering, environmental, and landslide-specific scenarios provide detailed comparative analyses. The engineering cost surface, incorporating slope, lithology, soil, and drainage features, identifies optimal routes in areas with moderate gradients and stable geological formations. These routes minimize earthworks and ensure structural stability [28]. The environmental cost surface prioritizes routes that avoid dense forests, water bodies, and ecologically sensitive zones. This surface highlights the need to reduce ecological disturbances while maintaining connectivity.

The landslide-specific cost surface, derived from susceptibility mapping, identifies high-risk zones, particularly in steep and unstable areas near dense drainage networks. These regions require alignment decisions that avoid or mitigate landslide risks to ensure long-term safety and sustainability. The hybrid cost surface, integrating all three scenarios with equal weighting, emerges as the most comprehensive model. By balancing engineering feasibility, environmental preservation, and safety concerns, it provides a holistic framework for road alignment [29].

The hybrid cost surface showcases its utility in identifying routes that minimize overall costs, reduce environmental impacts, and enhance resilience against geohazards. Its integration of multiple criteria makes it a reliable tool for evaluating alignment options in complex terrains.

Route optimization

GIS-based Least-Cost Path Analysis (LCPA) generates multiple route alternatives based on the cost surfaces. The proposed hybrid least-cost path offers significant advantages over the existing road, reducing the length from 122 kilometres to 103.46 kilometres. This reduction translates into lower construction costs, decreased travel time, and improved connectivity [30]. Additionally, the shorter alignment minimizes environmental disruption by avoiding high-risk and ecologically sensitive zones.

Alternative routes generated based on individual cost surfaces vary in length and trade-offs [31]. For instance, the engineering cost surface results in a route of 104.3 kilometres, prioritizing stability and feasibility but with a moderate ecological footprint [32]. The environmental cost surface produces a slightly longer route of 105 kilometres, emphasizing minimal disruption to natural ecosystems but increasing construction costs. The landslide-specific cost surface results in the shortest route at 98.3 kilometres, but this alignment risks intersecting critical ecological zones and increasing engineering challenges.

The hybrid route balances these trade-offs by integrating engineering, environmental, and safety considerations. It avoids steep slopes and high-density drainage zones, aligns with stable lithological formations, and minimizes ecological impact by bypassing Chillimo Forest and densely forested areas. This route represents the most efficient and sustainable alignment option, addressing both technical and environmental challenges.

Validation of the landslide susceptibility map using Receiver Operating Characteristics (ROC) and Area Under the Curve (AUC) analysis confirms the reliability of the model, with an AUC score of 0.756. This score indicates good predictive accuracy, demonstrating the effectiveness of the susceptibility map in identifying high-risk zones [33]. The integration of these validated maps into the hybrid cost surface further ensures that the proposed route minimizes exposure to geohazards.

Discussion

The results highlight the effectiveness of integrating geospatial tools and multi-criteria decision-making methodologies for sustainable road planning. The thematic maps provide a detailed understanding of the terrain's physical characteristics, while the cost surfaces underscore the importance of balancing engineering feasibility, environmental considerations, and safety concerns [34].

The proposed hybrid route demonstrates significant improvements over the existing road, reducing its length by approximately 15%. This reduction not only lowers construction and maintenance costs but also enhances travel efficiency and safety. By avoiding landslide-prone zones and

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minimizing interaction with dense drainage networks, the hybrid route ensures long-term resilience against geohazards [35]. Moreover, its alignment through moderate slopes and stable lithological formations reduces construction complexity, making it both practical and sustainable.

The study's methodology also has broader implications for infrastructure planning in other geohazard-prone regions. By integrating thematic mapping, AHP, and LCPA, the study presents a replicable framework for evaluating alignment options in complex terrains [36]. This approach can guide policymakers and engineers in addressing similar challenges, ensuring that road infrastructure development aligns with environmental and socio-economic goals.

From a socio-economic perspective, the hybrid route offers enhanced connectivity to densely populated regions, reducing travel time and transportation costs for local communities. Additionally, it minimizes the displacement of agricultural activities, preserving livelihoods and fostering regional development [37]. By incorporating population density and land use into the decision-making process, the study underscores the importance of addressing social considerations in infrastructure planning.

While the methodology is robust, certain limitations remain. The reliance on remotely sensed data may introduce uncertainties in thematic maps, and subjective biases in AHP weighting could affect the reliability of the cost surfaces [38]. Future studies should consider incorporating additional factors, such as climate resilience and real-time geohazard monitoring, to refine the analysis further. Additionally, the use of more advanced machine learning algorithms for susceptibility mapping could enhance the precision of risk assessments.

Conclusions

This study demonstrates the effective integration of geospatial tools and multi-criteria decision-making methods to optimize road alignment in the Ginchi to Chullute corridor. By employing GIS-based Least-Cost Path Analysis (LCPA) and the Analytical Hierarchy Process (AHP), the research evaluates and prioritizes engineering, environmental, and safety factors to identify the most sustainable and cost-effective route. The integration of thematic maps, cost surfaces, and landslide susceptibility analyses provides a robust framework for addressing the complexities of road alignment in geohazard-prone regions. The proposed hybrid least-cost path, which reduces the road length from 122 kilometers to 103.46 kilometers, offers significant advantages over the existing alignment. This optimized route balances safety, cost, and environmental considerations by avoiding steep slopes, high drainage densities, and landslide-prone zones while minimizing disruptions to sensitive ecosystems such as Chillimo Forest. The integration of stable lithological formations and moderate slopes enhances the feasibility and sustainability of the proposed alignment. Validation of the landslide susceptibility model, with an AUC score of 0.756, further underscores the reliability of the methodology.

Beyond its technical contributions, the study highlights the socio-economic benefits of the optimized route. The hybrid alignment improves accessibility for densely populated areas, reduces travel time, and lowers transportation costs, thereby fostering regional development and economic opportunities. By preserving agricultural land and minimizing environmental disruption, the alignment supports sustainable land use while maintaining ecological balance. While the methodology effectively integrates multiple factors, limitations such as reliance on remotely sensed data and subjective weighting in AHP remain. Future research should explore advanced techniques, including machine learning-based susceptibility mapping and climate resilience assessments, to enhance the robustness of the analysis.

The study exemplifies the utility of geospatial technologies and decision-making frameworks in addressing complex infrastructure challenges. The proposed approach is replicable and adaptable, offering a model for sustainable road planning in geohazard-prone regions. Policymakers and planners are encouraged to adopt this methodology to ensure infrastructure development aligns with safety, sustainability, and socio-economic objectives.

Disclosure statement

No potential conflict of interest was reported by the authors.

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