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GIS-based methodology for culvert location evaluation on railways: a case study of the Qena–Safaga Track in Egypt

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ABSTRACT

Railway infrastructure plays a critical role in transportation networks, and ensuring its integrity and resilience is of utmost importance. Culverts are vital components of railway tracks, providing drainage and water management to prevent structural damage and disruptions. Identifying suitable locations for culverts requires careful evaluation and consideration of various factors. A study using GIS techniques was conducted on an existing commercial railway track in the Eastern Desert of Upper Egypt to assess the effectiveness of existing culverts in preventing flash floods. The culvert suitability index map revealed that areas with high slopes and large drainage areas were more susceptible to water accumulation, indicating the need for culverts. The study also highlighted areas where culverts could be installed without significantly impacting existing infrastructure. It was recommended to install culverts in 27 locations along the track where they intersect with watercourses. Existing culverts covered just 93 watercourses, while 5 specialized culverts needed to be relocated. The findings have significant implications for railway engineering, as using GIS techniques streamlines the process of culvert location evaluation, saving time and resources. The systematic approach ensures culverts are installed in the most appropriate locations, minimizing flooding risks and ensuring the safety and efficiency of railway operations.

Key words: culvert location, flash floods, GIS-based methodology, hydrological modeling, railway infrastructure

HIGHLIGHT

- The research aims to develop a GIS-based methodology for assessing culvert locations on Egyptian railways, specifically the Qena–Safaga Track. The methodology aims to improve decision-making and infrastructure development by enhancing efficiency and accuracy. It addresses traditional methods and uses GIS techniques for railway engineering.

ABBREVIATIONS

Ahp	Analytic hierarchy process
DEM	Digital elevation model
Fr	Frequency rate
Fra	Federal railroad administration
Fr–Ahp	Frequency rate and analytic hierarchy process approaches
Fsm	Flood susceptibility mapping
Gis	Geographic information system
Mca	Multi-criteria analysis approach
Mcdm	Multi-criteria decision-making
Rhhms	Railway hydraulic hazard monitoring system
Rs	Remote sensing
Sar	Saudi Railway Company

1. INTRODUCTION

Railway infrastructure plays a crucial role in the transportation sector, enabling the movement of goods and people across long distances. A key component is the culvert, a structure that allows water to pass under tracks, preventing water accumulation, erosion, and potential track damage, thus ensuring the integrity of the railway system.

The location of culverts along railway tracks is essential for the smooth operation and longevity of the infrastructure. It requires careful evaluation of factors like topography, hydrology, geology, and environmental considerations, traditionally requiring time-consuming and labor-intensive manual data collection and analysis methods.

Numerous studies have been conducted to address culvert location evaluation in various parts of the world. The earliest studies employed traditional methods such as field surveys and manual calculations to determine the most suitable locations for culverts on railway tracks (FHWA 1986; Cowherd & Perlea 1989; NCSPA 1991; FHWA 1995). The studies focused on factors such as topography, hydrology, and soil conditions to identify potential locations for culverts. While these studies provided valuable insights into the process of culvert location evaluation, it was limited by the time-consuming nature of the traditional methods used. Nevertheless, recent studies utilized advanced optimization techniques such as GIS techniques (Clement & Edward 2017; Olga *et al.* 2018; Altuwaijri 2019), the Hydrologic Engineering Center-River Analysis System (HEC-RAS) hydraulic model (Felix *et al.* 2022), the Railway Hydraulic Hazard Monitoring System (RHHMS) (William *et al.* 2012), hydrological modeling (Holgun & Sternberg 2018; Alqreai & Altuwaijri 2023), and the geographic multiple criteria decision analysis (Sharifi *et al.* 2006; Abdelkarim *et al.* 2020) to identify the optimal locations for culverts. They developed a comprehensive set of criteria, including factors such as flood risk, environmental impact, and construction feasibility. These studies utilized GIS techniques to integrate and analyze the spatial data, and a weighted scoring system was used to rank the potential culvert locations. In a more recent study, Abdelkarim's study (2021) revealed that railway tracks were damaged by direct runoff, which the existing culverts could not handle, leading to significant economic losses. While Abdelkarim *et al.* (2019) reported significant land use changes in the region, causing a shift in direct runoff water flow and its direct diversion toward the railway.

Additional studies used hydrological and morphometric GIS analysis to establish the locations, volumes, and directions of water networks (Bevan 2003; Bevan & Conolly 2004; Lee *et al.* 2013; Hu 2016). They have been applied to drainage-based watershed management (Sreedevi *et al.* 2013; Rai *et al.* 2018; Sayema & Adila 2023) and watershed prioritization (Javed *et al.* 2011; Arefin *et al.* 2020). Remote sensing and GIS have been successfully used to calculate morphometric parameters (Singh *et al.* 2014). Floods, a major natural disaster, pose a significant threat to urban development, population, and transportation due to their harmful effects (UNESCO 2014).

Heavy rains have caused flash floods in Upper Egypt governorates such as Assiut, Sohag, Qena, Aswan, and the Red Sea in 1990, 1994, 1996, 2010, 2012, 2013, 2014, 2016, and 2021, causing huge losses in life and property (Gabr & El Bastawesy 2015; Saber *et al.* 2018; Mohamed 2021). The Qena–Safaga Track, situated in the eastern desert, is frequently affected by heavy rains on the Red Sea mountain ranges, leading to severe flash floods and significant damage to the track infrastructure, as depicted in Figures 1 and 2.

Recently, many studies have been conducted in the study area, such as Nasr *et al.* (2022), which explored the integration of remote sensing and GIS methodologies to assess hydrologic characteristics and develop a flash model for flood risk assessment in the Wadi Queih area of Egypt. Moawad *et al.* (2016) examined flash floods in the Sahara, specifically the January 28 flood in Qena, Upper Egypt, by examining the spatial characteristics of poorly gauged drainage systems. Also, Taha *et al.* (2017) evaluated flash flood hazards in Wadi Qena using quantitative geo-morphometric parameters and tropical rainfall

Figure 1 | Subgrade failure of the Qena–Safaga Track due to flooding (Egyptian Railway and Abuzeid *et al.* 2022).

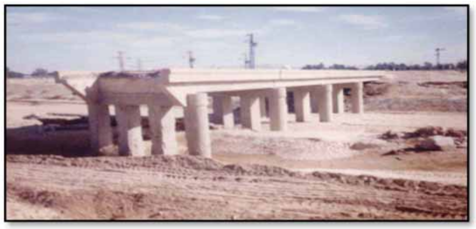

Figure 2 | Bridge damage on the Qena–Safaga Track due to 1996 flooding (Egyptian Railway and Abuzeid *et al.* 2022).

monitoring mission satellite data. Additionally, Mohamed (2019) investigated the application of satellite image processing and GIS-spatial modeling for mapping urban areas prone to flash floods in Qena Governorate, Egypt.

GIS technology can improve railway culvert location evaluation by integrating and analyzing spatial data. This allows engineers and planners to make informed decisions based on accurate information. The Qena–Safaga Track in Egypt serves as a case study for this research, a vital transportation link connecting Qena and Safaga. The track's diverse terrain presents unique challenges for culvert location evaluation, highlighting the potential of GIS in railway culvert location evaluation.

This study aims to create a GIS-based methodology for assessing culvert locations on railways, specifically the Qena–Safaga Track in Egypt. It considers hydrological conditions, topography, geology, and environmental factors. The methodology aims to enhance the efficiency and accuracy of the culvert location evaluation process, thereby promoting better decision-making and cost-effective infrastructure development. It addresses the limitations of traditional methods and proposes a more efficient and accurate approach using GIS techniques. The study will explore the role of railway culverts in track integrity and the potential benefits of integrating geographic information system (GIS) technology in railway engineering.

However, it is crucial to recognize the study's limitations, such as its context-specific nature, reliance on accurate data, the need for expertise in GIS and railway engineering, and financial and logistical constraints.

2. SITE DESCRIPTION AND LOCATION PROPERTIES

2.1. Case study area description

This section outlines the significance of understanding Egypt's Qena–Safaga Track's characteristics for efficient culvert location evaluation using GIS techniques.

2.1.1. Geographical location

The Qena–Safaga Track, a 232-km railway line in Egypt, was built to export phosphate from Abu-Tartor mines (Figure 3). It had 5 bridges, 12 exchange stations, 2 tunnels, and 93 culverts. However, it stopped in 2010 due to flash floods, and since then, phosphate has been transported by land to Safaga Port, which is more expensive and takes longer.

The railway study area is located between latitudes 25° 48′ and 26° 48′ north and longitudes 32° 48′ and 34° 12′ east, bordered by the Red Sea and Nile River. Also, the Qena–Safaga and Qena–Qussier roads border it (Figure 4). It is characterized by extreme geographic complexity and undulation due to its Red Sea chains.

2.1.2. Topography

The Qena–Safaga Track is an arid, flat plain with rolling hills and rugged mountainous terrain in the Eastern Desert. Its high levels in the middle decrease as you head east toward the Red Sea and Safaga port or west toward the Nile Valley and Qena City (Figure 4). This varying topography poses challenges in determining suitable culvert locations for proper drainage and water flow.

The Qena–Safaga Track, designed to match the region's topography, starts in Qena governorate at a low point (73 m) and ascends 85 km to its highest point (622.75 m) at 103.35 km, then descends parallel to the Red Sea coast and ends at Safaga port (Figure 5).

The Qena–Safaga Track in the Eastern Desert is divided into two zones, each with its own wadi. Zone 1 is between Qena city and the center, extending from 0 to 100 km and subject to Wadi Qena, a large, wide, arid valley. Zone 2 is between the center and the end of the area, extending from 100 to 232 km and ending at Safaga port (Figure 6). The drainage system in

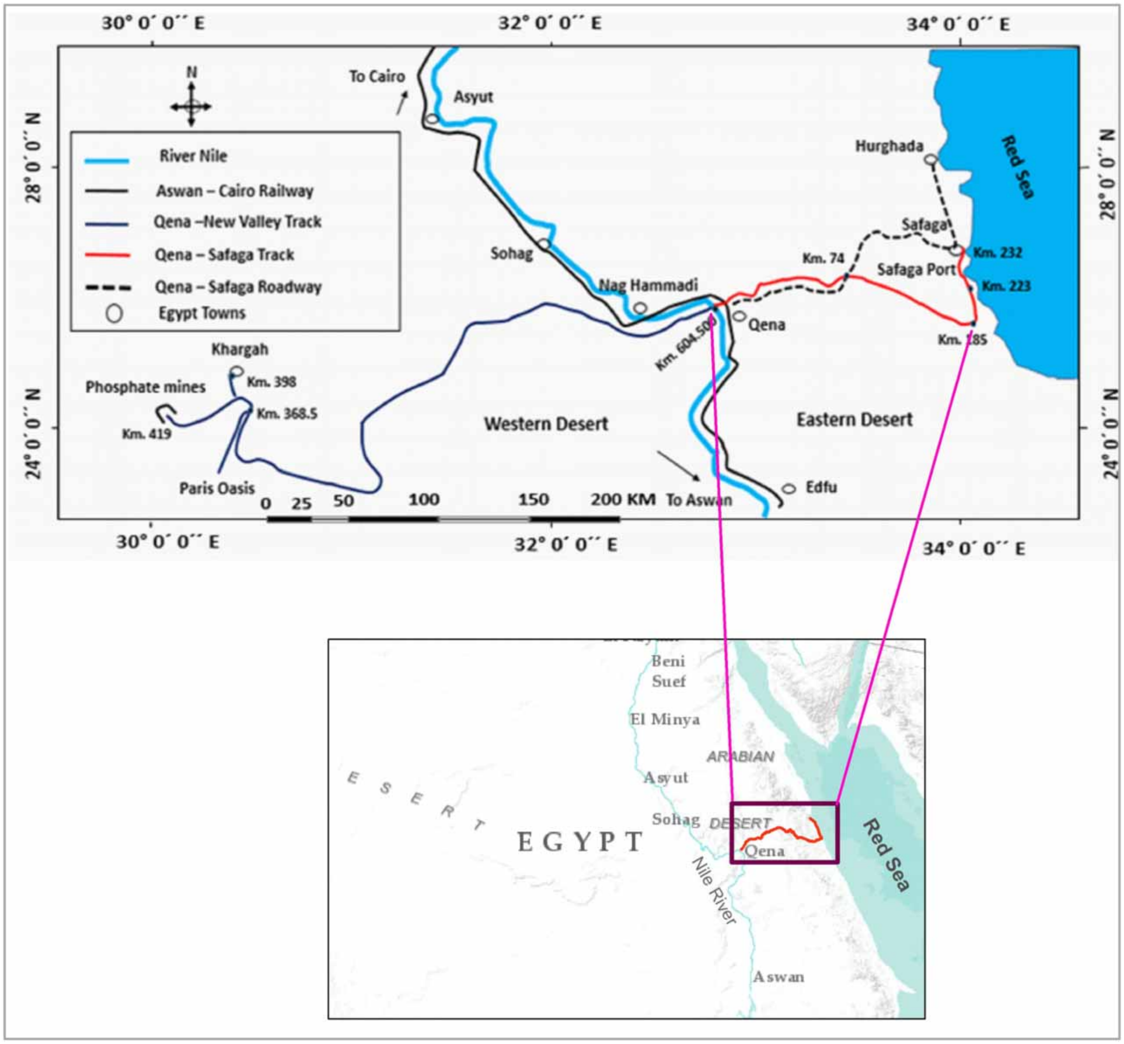

Figure 3 | Qena–Safaga Track within Egypt map (National Authority for Tunnels, Egypt).

Zone 2 includes 11 basins, including Ambagi, El Baroud, El Queih, Safaga, and smaller basins like Naqarah, Abu Sheqili, El Bahari, Abu Sheiqili, El Qibli, Gasous, Gawasis, El Hamraween, and Abu Hamra El Bahari. Most of these wadis flow west–east toward the Red Sea coast (Youssef *et al.* 2009).

2.1.3. Hydrology

The study area's hydrological conditions are influenced by its proximity to the Red Sea, lack of major rivers, desert climate, and limited rainfall, leading to flash floods and railway infrastructure damage.

2.1.4. Climate

The Qena–Safaga Track experiences a hot desert climate, with summers exceeding 40 °C and winters milder. Low annual precipitation, with most rainfall in winter, causes severe flash floods and infrastructure damage (Figures 1 and 2). Meteorological data from 1913 to 2022 reveal that arid climate conditions significantly impact the design and maintenance of culverts for efficient drainage and water-related issues (Weather & Climate 2022).

2.1.5. Vegetation

The study highlights the importance of proper culvert location in the study area due to its sparse vegetation, which increases the railway track's vulnerability to erosion and sedimentation.

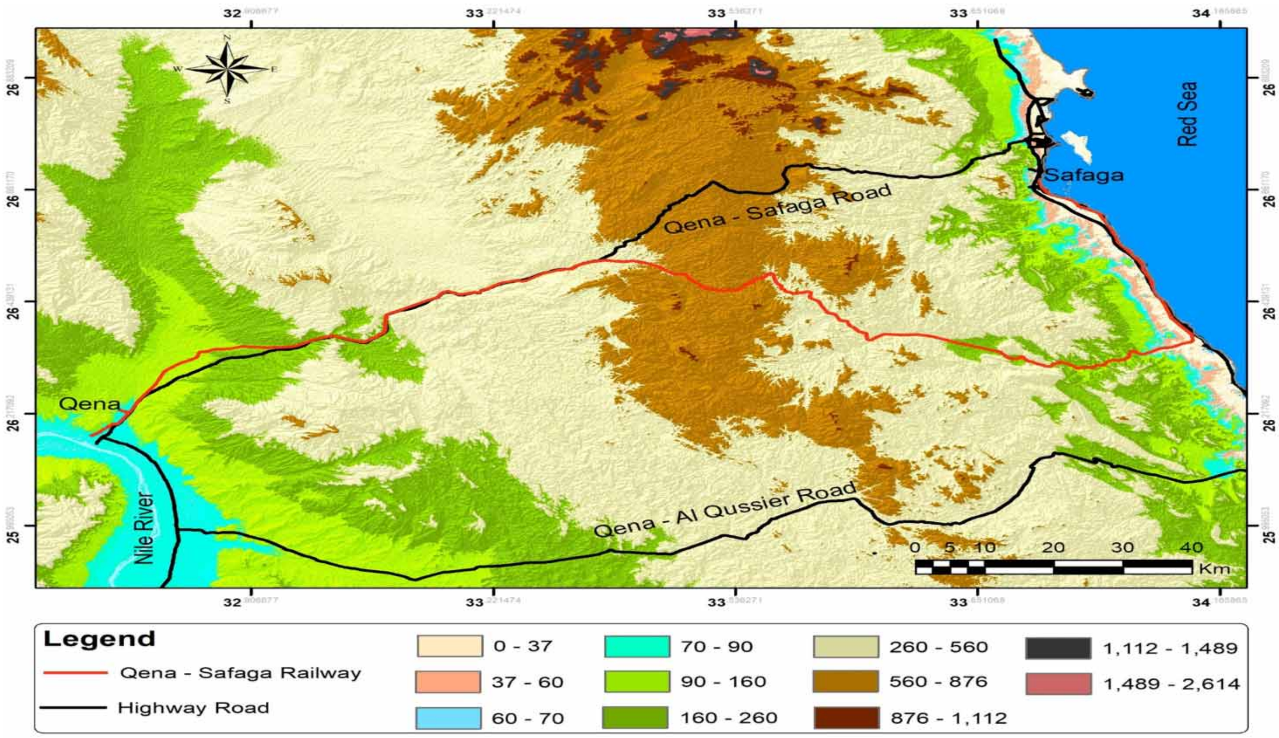

Figure 4 | GIS topographic map of the research area (Abuzeid *et al.* 2022).

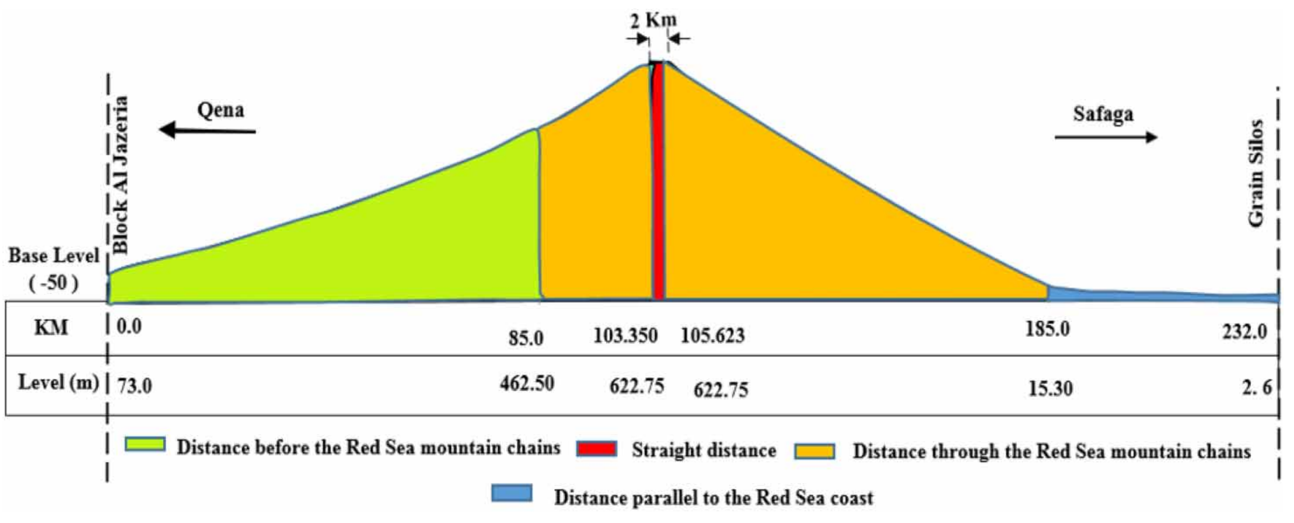

Figure 5 | Longitudinal section of Qena–Safaga Track within the study area (Abuzeid *et al.* 2022).

2.1.6. Land use

The Qena–Safaga Track's land is predominantly desert with few human settlements, but some small villages and towns serve as transportation hubs and access to mining and industrial areas. Understanding these patterns is crucial for identifying potential culvert locations that may intersect with existing infrastructure or affect local communities.

2.1.7. Existing railway infrastructure

The Qena–Safaga Track is a vital railway in Egypt, connecting Qena and Safaga. It is crucial for the transportation of goods and passengers. It is a single-track line with multiple stations, sidings, and 12 exchange stations. The railway also features 93 culverts, 2 tunnels, and 5 bridges to ensure water flow and maintain infrastructure integrity (Figure 7).

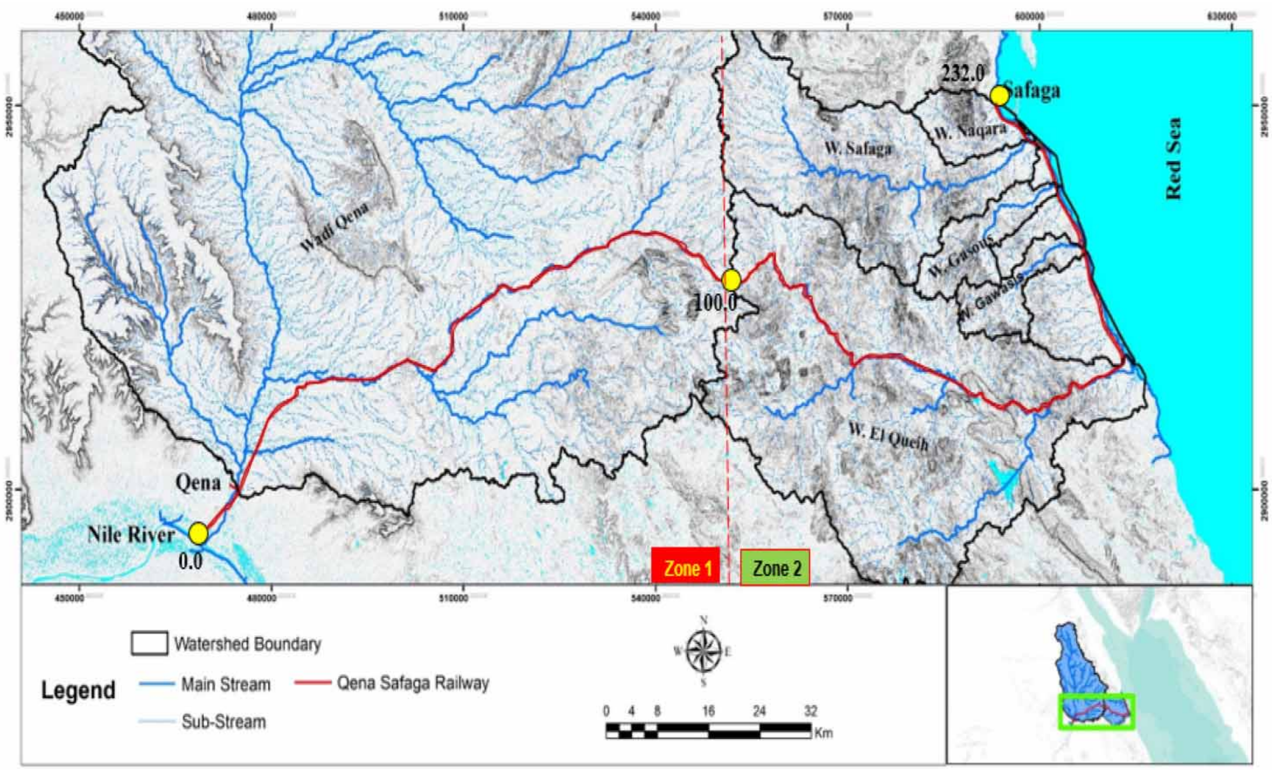

Figure 6 | GIS map of the drainage network of the wadis affecting the Qena–Safaga Track through Zones 1 and 2 (Abuzeid *et al.* 2022).

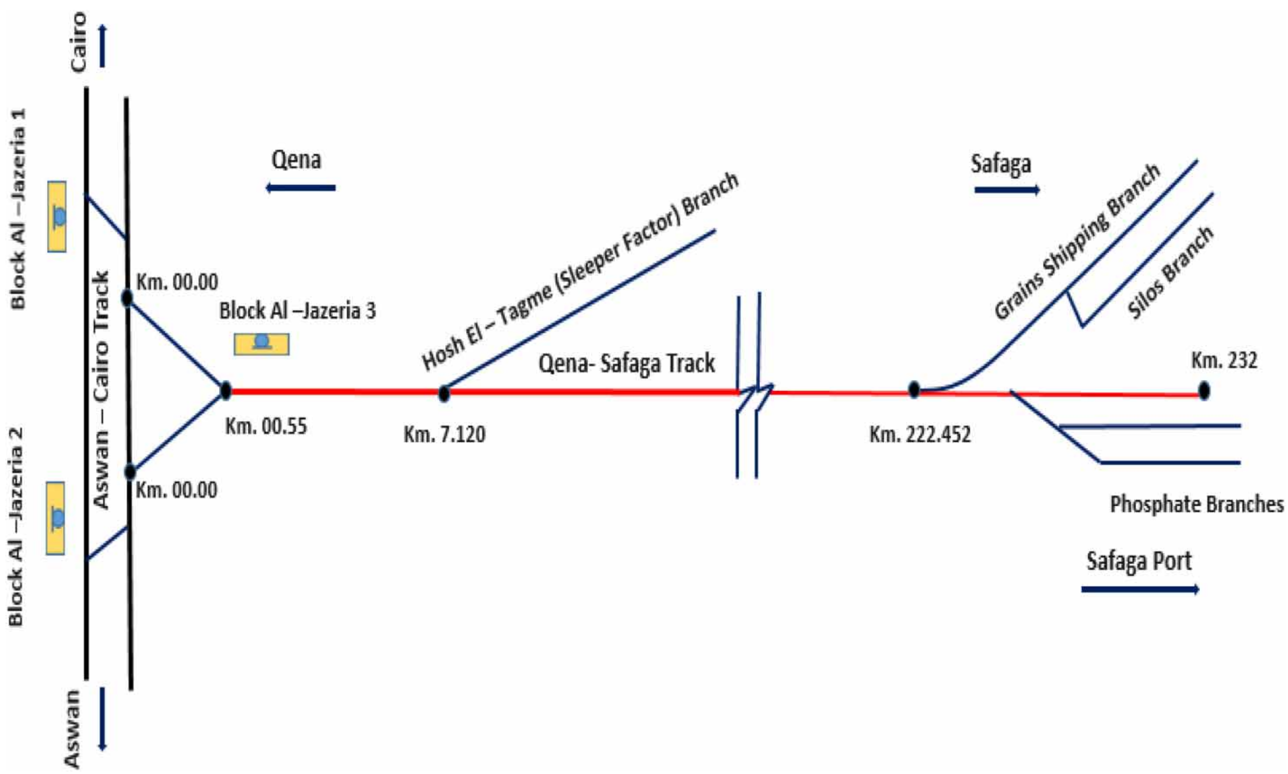

Figure 7 | A schematic diagram of the Qena–Safaga railway track.

2.1.8. Challenges and opportunities

The case study area presents challenges and opportunities for culvert location evaluation due to rugged topography, an arid climate, and limited hydrological conditions. Existing railway infrastructure and human settlements complicate the process. GIS techniques can help analyze and visualize spatial data, enabling informed decision-making for culvert location and ensuring long-term railway track sustainability.

3. METHODOLOGY

This section discusses the methodology for assessing and determining culvert locations on railways using GIS techniques, specifically applied to the Qena–Safaga Track in Egypt. GIS techniques analyze spatial and attribute data, enabling informed decisions and playing a crucial role in determining the most suitable locations for railway culverts, thereby improving the efficiency of railway infrastructure.

3.1. Data collection

The study used various data sources, including topographic maps, satellite images, official data from Egypt's National Railway Authority, and field surveys, to analyze the Qena–Safaga Track. Topographic maps provide valuable information on terrain, elevation, and hydrological characteristics (Figures 4–6). A Digital Elevation Model (DEM) was created using these maps, obtained from the Egyptian National Authority for Remote Sensing and Space Sciences (NARSS). Satellite and aerial photos from reliable sources like Google Earth and Landsat were used to identify the railway line's culverts, drainage patterns, and other important characteristics. Field surveys were conducted to gather additional information on the size and condition of existing culverts and any hydraulic structures or impediments that could affect their location (Figure 8). This on-site data collection process ensured the accuracy and dependability of the analysis.

3.1.1. Data preparation

The collected data underwent several preparation steps to ensure its suitability for analysis. These included data cleaning, integration, and conversion into a GIS-compatible format. Data cleaning removed errors, inconsistencies, and outliers to ensure accuracy and reliability. Integration combined different datasets into a comprehensive dataset, allowing for a holistic analysis and identification of relationships and patterns. Data conversion involved converting paper maps into digital formats, georeferencing satellite imagery, and assigning appropriate attribute data to spatial features. This process ensured the data could be effectively analyzed using GIS software.

3.1.2. Spatial analysis techniques

The study utilized spatial analysis techniques to identify suitable locations for culverts based on slope, proximity to water bodies, and drainage patterns. One of the primary spatial analysis techniques used in this study was overlay analysis. Overlay analysis, which combines multiple layers of spatial data, was used to identify areas with suitable slope gradients, proximity to water bodies, and minimal interference from existing infrastructure. Another spatial analysis technique used was proximity analysis. Proximity analysis, which measures the distance between features, was also employed to identify areas within a

Figure 8 | Examples of sediment accumulation: (a) inside and in front of culverts, and (b) in front of culverts (Egyptian Railway).

specified distance threshold. Both techniques were used to evaluate culvert locations and assess the impact of existing infrastructure on the area.

3.1.3. Attribute analysis techniques

In addition to spatial analysis, attribute analysis techniques were used to examine the non-spatial data related to the culvert location evaluation. Attribute analysis entailed investigating the research area's characteristics and traits, such as soil type, land use, and existing infrastructure. Statistical techniques like descriptive statistics and regression analysis were used to analyze the attribute data, providing insights into distribution and variability and identifying relationships and correlations between different attributes.

3.1.4. Terrain analysis techniques

Furthermore, the methodology uses terrain analysis to evaluate the slope and elevation of study areas, identifying suitable locations for culvert installation based on topographic conditions (Figures 4–6 and Figures 9–11). Steep slopes or areas with significant elevation changes may require additional culverts for effective water flow management.

3.1.5. Validation of results

The analysis results underwent validation to ensure accuracy and reliability. This involved comparing predicted culvert locations with existing ones along the Qena–Safaga Track (Figures 13–15). Any discrepancies were examined, and adjustments were made if needed. The process also involved examining flood impact sites from previous years (Figure 16) and seeking expert opinions from railway engineering professionals. Their insights helped validate the results and provide valuable input for improvement.

In conclusion, this study utilized data analysis techniques to collect, prepare, and analyze spatial and attribute data. GIS techniques were used to thoroughly analyze the study area, identify suitable culvert locations, and validate the results for accuracy and reliability, making them valuable for decision-making in railway engineering projects.

3.1.6. Criteria for culvert location evaluation

GIS analysis is a method used to evaluate potential culvert locations, considering factors such as hydraulic capacity, structural integrity, environmental impact, and cost-effectiveness. Hydraulic capacity refers to a culvert's ability to handle water flow without flooding or excessive buildup. Structural integrity is crucial for a culvert's ability to withstand the weight of moving trains and external forces. Environmental impact assessment considers potential effects on ecosystems like wildlife habitats, water quality, and vegetation. The process prioritizes locations, minimizing environmental disturbance. Cost-

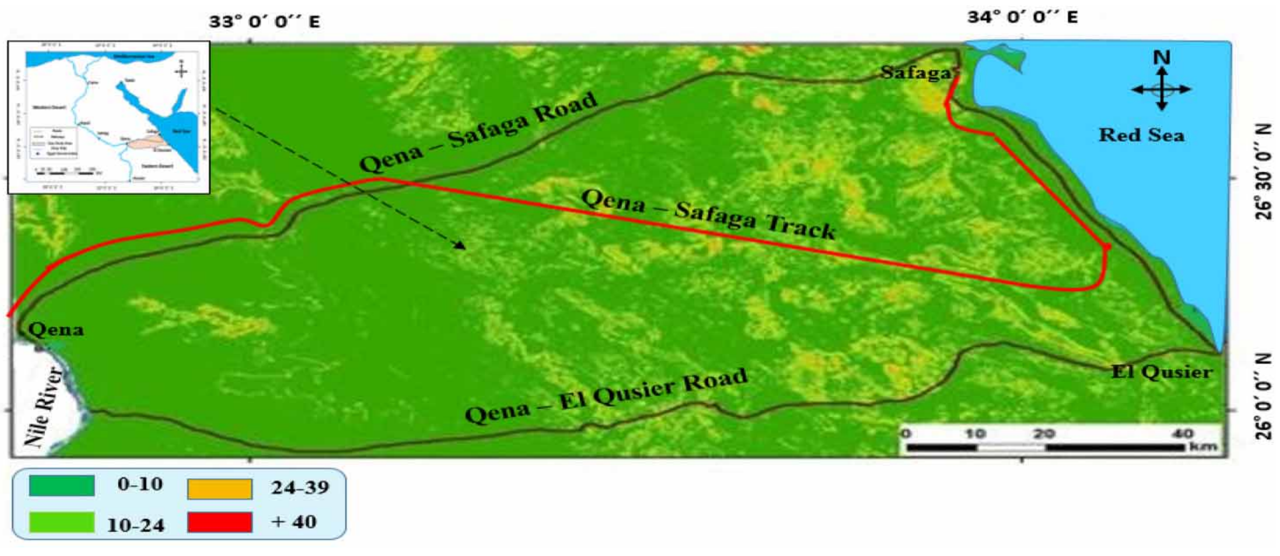

Figure 9 | Slope degrees in the case study area (Mamdouh 2014).

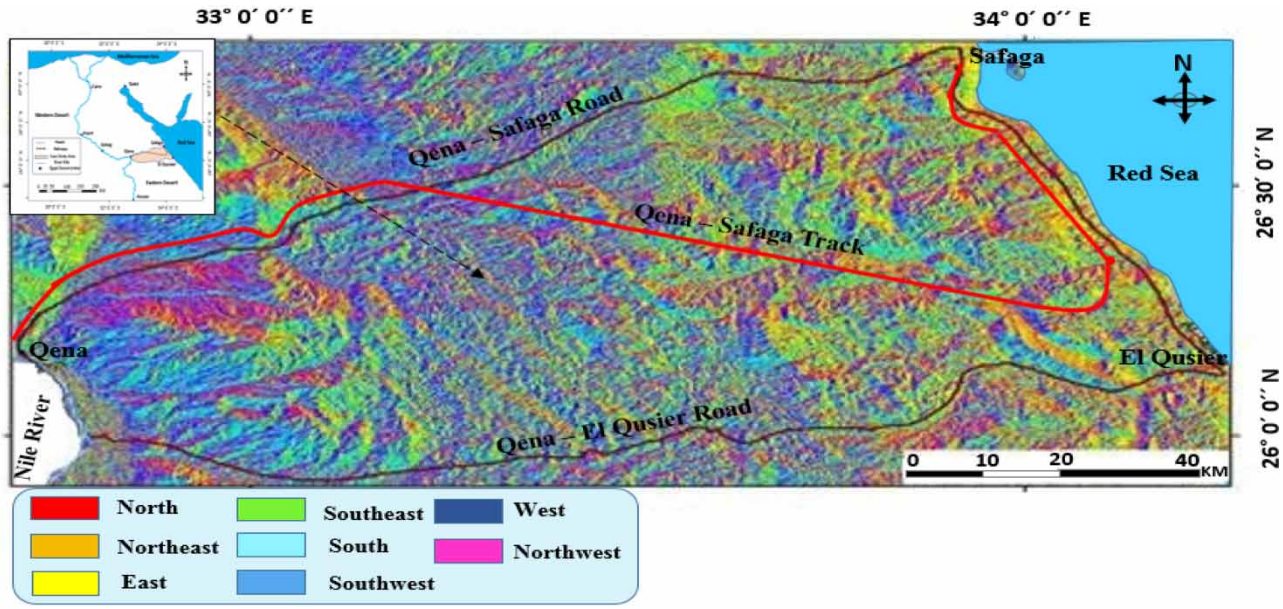

Figure 10 | Slope directions in the case study area (Mamdouh 2014).

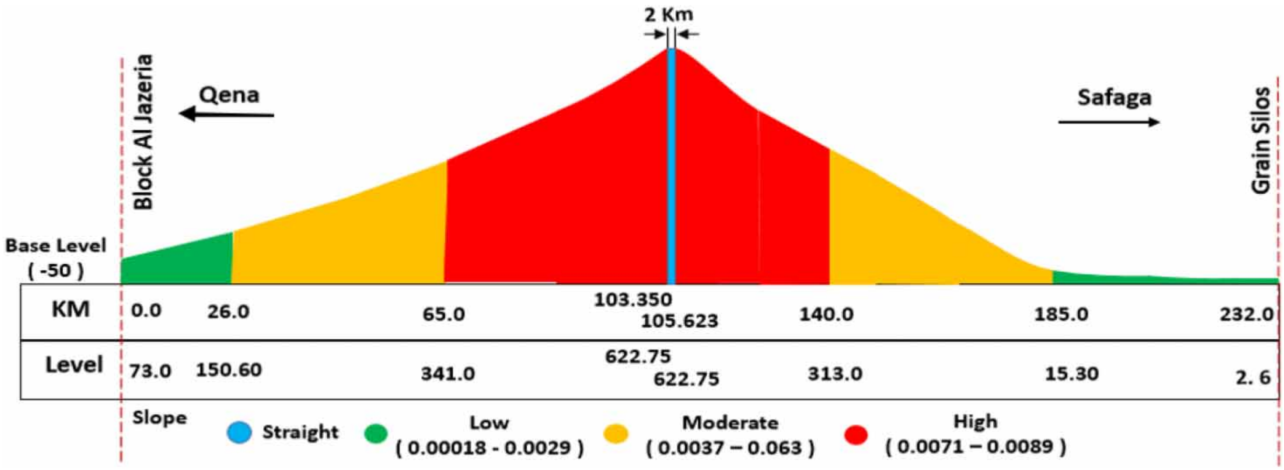

Figure 11 | Slopes of Qena–Safaga Track within its longitudinal section (Egyptian Railway).

effectiveness is also a key factor, considering construction and maintenance costs. The goal is to find locations that balance functionality and affordability, considering financial implications.

3.1.7. Methodology for culvert location evaluation

Based on the data collection, GIS analysis techniques, and evaluation criteria outlined above, the methodology for culvert location evaluation is as follows:

1. Identify potential culvert locations through spatial overlay analysis, considering factors such as topography, hydrology, and proximity to the railway track.
2. Conduct proximity analysis to determine the optimal spacing between culverts and identify areas where additional culverts are required.
3. Perform terrain analysis to assess the slope and elevation characteristics of the study area and identify suitable locations for culvert installation.

4. Evaluate potential culvert locations based on criteria such as hydraulic capacity, structural integrity, environmental impact, and cost-effectiveness.
5. To select the most suitable culvert locations that meet the evaluation criteria and ensure efficient drainage along the railway track. This study uses GIS techniques to assess the compatibility of wadi streams with installed culverts along the railway track and to determine the locations of suggested culverts to mitigate flood impacts on the track, utilizing the following steps:
   (a) Delineating watersheds based on a DEM from the Japan Aerospace Exploration Agency (ALOS Global Digital Surface Model 2022)
   (b) Defining the DEM georeferencing using the GIS tool, the reference for Egypt is UTM Zone 36 N.
   (c) Derivation of the drainage network by computing: (1) fill basins (2) flow direction, (3) flow accumulation, (4) stream definition, (5) stream segmentation, (6) catchment grid delineation, (7) catchment polygon processing, (8) drainage line processing, (9) adjoint catchment processing, and finally (10) extracting the watershed model for the study area.
   (d) Computing the watershed surface areas of wadis affecting the track under study.
   (e) Determining the locations of existing culverts along the track under study within the watershed delineation model and aligning their locations with the wadis streams.
   (f) Specifying the culvert's locations that must be installed along the track to face wadi streams within the watershed delineation model extracted from GIS analysis.

4. RESULTS ANALYSIS AND DISCUSSION

4.1. Results of culvert location evaluation

This section presents the results of the culvert location evaluation conducted using the GIS-based methodology on the Qena–Safaga Track in Egypt. The results provide valuable insights into the optimal location of culverts, which can significantly enhance the efficiency and safety of the railway infrastructure.

4.1.1. Data analysis

The study utilized GIS to analyze topographic maps, hydrological data, and satellite imagery to identify potential locations for culverts. Spatial analysis techniques like overlay, proximity, and terrain were employed to identify areas with steep slopes that could cause water accumulation and flooding. Proximity analysis was used to locate areas near water bodies where culverts could facilitate water passage under the railway line. Hydrological analysis was employed to identify natural drainage patterns in the area, aiming to ensure efficient water flow and prevent disruptions to railway operations.

4.1.2. Results

The watershed delineation model extracted from GIS revealed that six major wadis, including Wadi Qena, Wadi El Queih, Wadi Safaga, Wadi Gawasis, Wadi Gasous, and Wadi Naqara, affect the track. Some of these wadis drain into the Nile River, while others drain directly into the Red Sea. According to Table 1, Wadi Qena has the biggest watershed surface area, followed by Wadi El Queih and Wadi Safaga. Also, it was found that the railway crosses these wadis in various locations between 0 km in Qena Governorate and 232 km in Safaga Port (Figure 12). The part of the track between 8 and 34 km interacts with the Wadi Qena basin and drains it to the Nile River, while the section between 34.0 and 100.0 km intersects with the streams of Wadi Qena descending from east to west. Moreover, the segment from 100 to 185 km intersects the main basin of Wadi El-Queih. The portion along the Red Sea coast from 202 to 232 km intersects with the basins of Wadis: Safaga, Gawasis, Gasous, and Naqara. These wadis drain directly into the Red Sea.

To verify the accuracy of the alignment of the installed culverts with wadis streams, 93 locations along the track were marked on the GIS streams map (Figure 13). The track reach exposed to Wadi El-Queih had the most number of installed culverts, with 41 culverts, followed by the reach exposed to Wadi Qena, which had 22 culverts, and the reach exposed to the wadis that drain into the Red Sea, which had 30 culverts. It was also found that most of the culvert sites matched the

Table 1 | The watershed surface areas of wadis affecting the under-study track

Wadi name	Qena	El-Queih	Safaga	Gawasis	Gasous	Naqara
Watershed area (km^2)	15,561.9	1,846.7	738.0	112.1	141.7	114.8

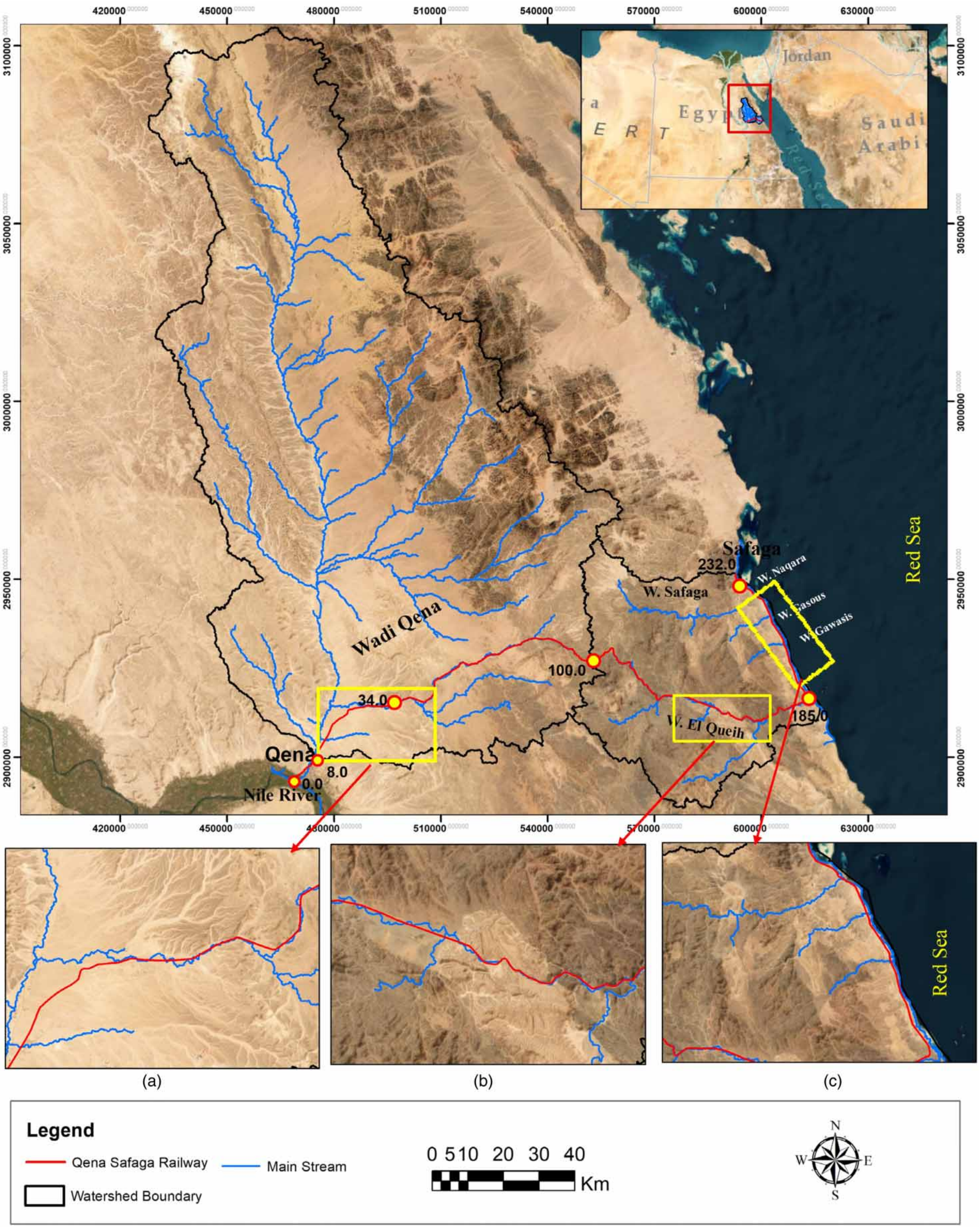

Figure 12 | GIS map of wadi streams intersecting with the track under study

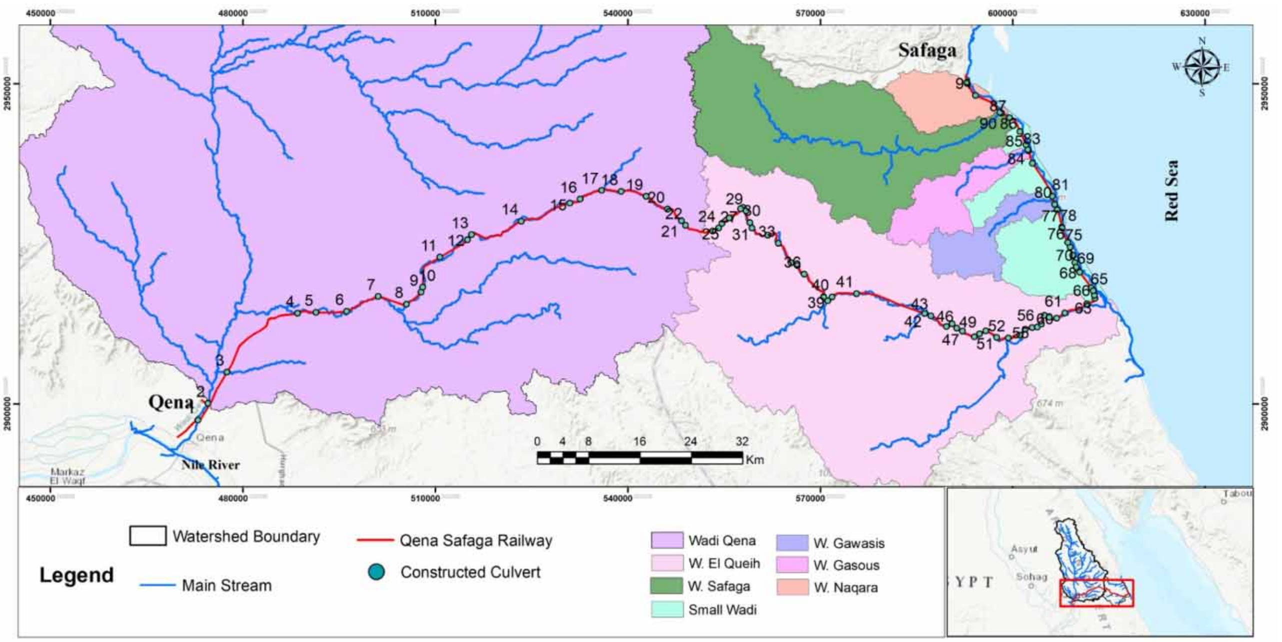

Figure 13 | Locations of the constructed culverts along the track under study are indicated within the GIS map of wadis streams.

streams, except for five culverts whose locations were not compatible with the streams. These culverts represent about 5% of the total installed culverts, all of them extending within Wadi El-Queih (Figure 14). Despite this, it has been found that the existing culverts do not cover all streams. As a result, it is recommended to install 27 culverts at the locations where the railway crosses the streams (Figure 15). The locations of the culverts that need to be installed along the study track are shown in Table 2, as measured from the study track's starting point at Qena Governorate. The table shows that the track segment intersecting with Wadi El-Queih (20 culverts) had priority in the culvert installation, followed by the track section intersecting with the wadis draining into the Red Sea (6 culverts), and then the track section intersecting with Wadi Qena (1 culvert).

Additionally, for validation of the study results, documented flood impact sites in 1990, 1994 (Gabr & El Bastawesy 2015), and 1996 (Egyptian Railway) and related culverts along the track under study were delineated on the GIS stream map. It was discovered that several of the impacted sites had culverts (Figure 16). Most of these culverts on the track under study are clogged by sediment accumulation, reducing their capacity to discharge flood water and damaging the track infrastructure (Figure 8). As a result, culvert locations and track sections intersecting with wadi streams are more likely to sustain damage than other locations, necessitating greater attention to flood mitigation and preventative measures. So, regular maintenance and the installation of a grid in front of track culvert openings are recommended to prevent sediment from accumulating inside culverts. Also, on the railway tracks that are periodically exposed to such flooding cases, more care and importance must be given to efficient methods and techniques of quick drainage and getting rid of any water that may submerge the line foundation, base layer, and grout under the flanges of the rails. In order to preserve the railway and mitigate flooding, it is also recommended to establish check dams in the outflows of the sub-basins at appropriate sites. Additionally, the quantity and capacity of culverts will increase. All of these suggestions could be useful for managing water during rainstorms.

4.2. Discussion of results

The study evaluates GIS-based culvert locations on the Qena–Safaga Track in Egypt to ensure efficient drainage, minimize flooding risks, and prevent track instability, considering factors like topography, hydrology, geology, and railway alignment.

The results of the culvert location evaluation revealed several key findings. Firstly, the analysis identified specific areas along the Qena–Safaga Track that were prone to water accumulation and flooding. These areas were primarily located near rivers and streams, where the natural drainage patterns intersected with the railway line. By placing culverts in these locations, the flow of water was effectively managed, reducing the risk of flooding and associated damage to the railway

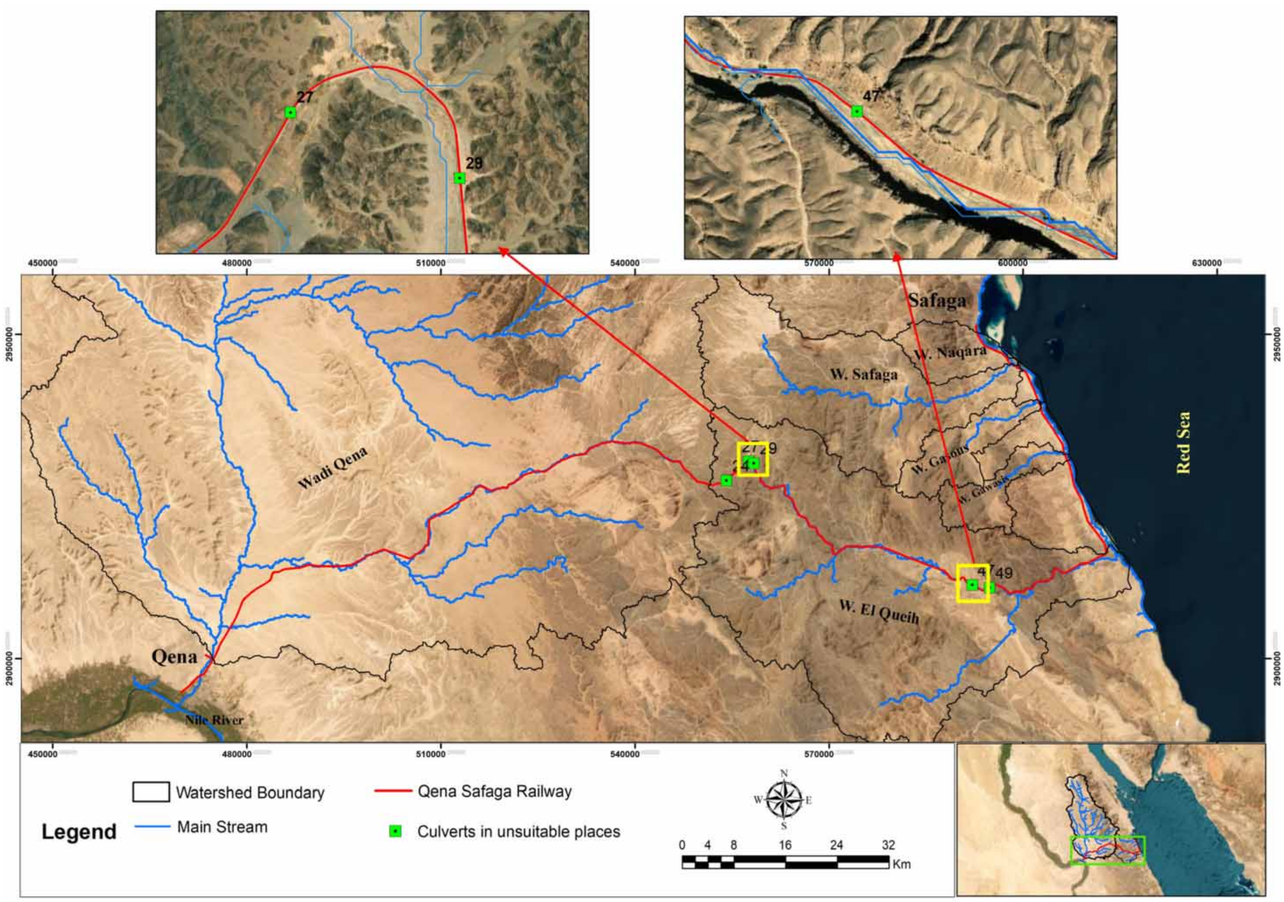

Figure 14 | Locations of the five culverts in unsuitable places along the track under study are indicated within the GIS map of wadis streams.

infrastructure. Furthermore, the analysis highlighted the importance of considering the topographic characteristics of the study area. Areas with steep slopes were found to be potential trouble spots, as water could accumulate and cause erosion or landslides. By strategically placing culverts in these areas, the excess water was efficiently channeled away from the railway line, mitigating the risk of slope failure and ensuring the stability of the track.

The accessibility analysis revealed that the majority of the identified culvert locations were conveniently situated near existing roads and infrastructure. This factor significantly facilitated the construction and maintenance of the culverts, reducing costs and minimizing disruptions to railway operations. Moreover, the proximity to populated areas was taken into account to minimize any potential adverse impacts on local communities. Also, the study underscored the significance of considering local climate and rainfall patterns and using historical data to identify high-precipitation areas for effective drainage during heavy rainfall. The culvert locations were designed to handle expected water flow and prevent disruptions to railway operations.

The study uses a GIS-based approach to assess culvert locations on the Qena–Safaga Track in Egypt, integrating spatial data layers and analysis techniques. Although not applicable to other railway tracks or regions, this methodology can serve as a framework for similar evaluations.

4.3. Limitations of the study

Although the culvert location evaluation provided valuable insights, it is crucial to acknowledge the limitations of this study. Firstly, it relied heavily on the availability and accuracy of data, which could have influenced the results. Additionally, the evaluation was only focused on the Qena–Safaga Track, which may not apply to other railway lines with different topographic and hydrological characteristics. Furthermore, the criteria for culvert location evaluation were specific, not considering factors like environmental impact or cost-effectiveness. Future research could explore integrating additional criteria to improve

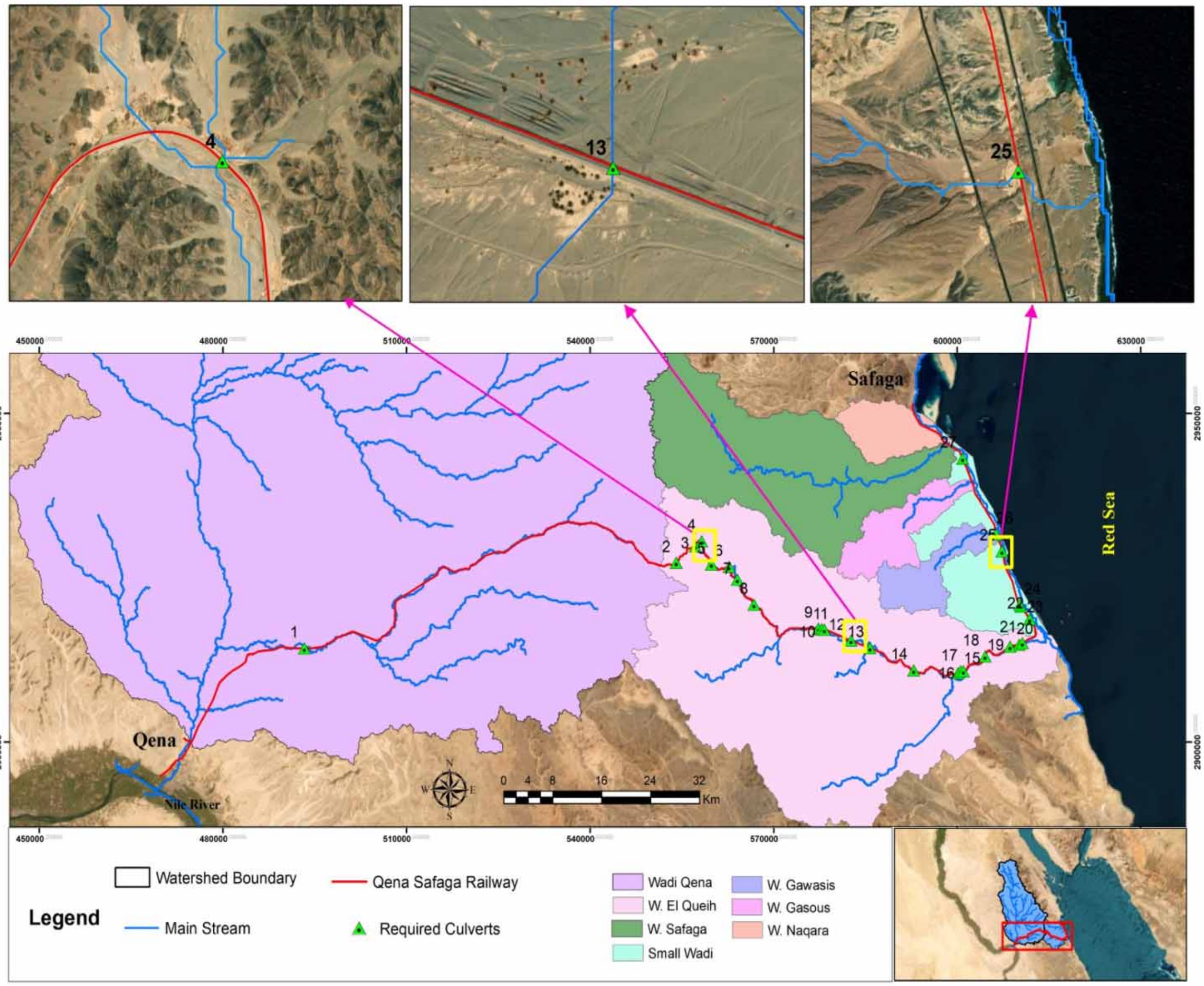

Figure 15 | Locations of the suggested culverts according to the GIS stream map.

the methodology. Despite these limitations, the study provides a solid foundation for future improvements and research in this field, serving as a starting point for refining criteria for culvert location evaluation on railways.

4.4. Implications for railway engineering

The use of GIS-based methodology in railway engineering significantly impacts culvert location evaluation, offering benefits in the planning, design, and maintenance of railway infrastructure, thereby enhancing the field's efficiency.

4.4.1. Enhanced decision-making process

GIS technology aids railway engineers in evaluating culvert locations by integrating spatial data like topography, hydrology, and land use with engineering criteria. This comprehensive analysis helps identify suitable locations that minimize environmental risks like flooding and erosion. The visualization and analysis of spatial data enhance decision-making, resulting in more efficient and effective railway infrastructure development.

4.4.2. Improved safety and reliability

Railway engineering prioritizes infrastructure safety and reliability. GIS-based methodology helps identify and mitigate potential risks and vulnerabilities in culvert locations. Factors like flood-prone areas, soil stability, and hydraulic capacity are

Table 2 | Locations of the required culverts measured from the track's beginning

The name of wadi intersecting with the railway track	Numbering the culvert locations	The locations of the culverts that need to be installed along the study track, as measured from the track's beginning at Qena Governorate (km)
Wadi Qena	1	33.6
Wadi El-Queih	2	106.1
	3	110.5
	4	112
	5	116.1
	6	119.4
	7	122.3
	8	127.2
	9	141.1
	10	141.6
	11	142
	12	146.7
	13	150
	14	158.7
	15	167
	16	167.5
	17	168
	18	172.7
	19	177.9
	20	179.4
	21	180
Wadis draining into the Red Sea	22	185.2
	23	187.6
	24	187.9
	25	196.7
	26	199.4
	27	212.4

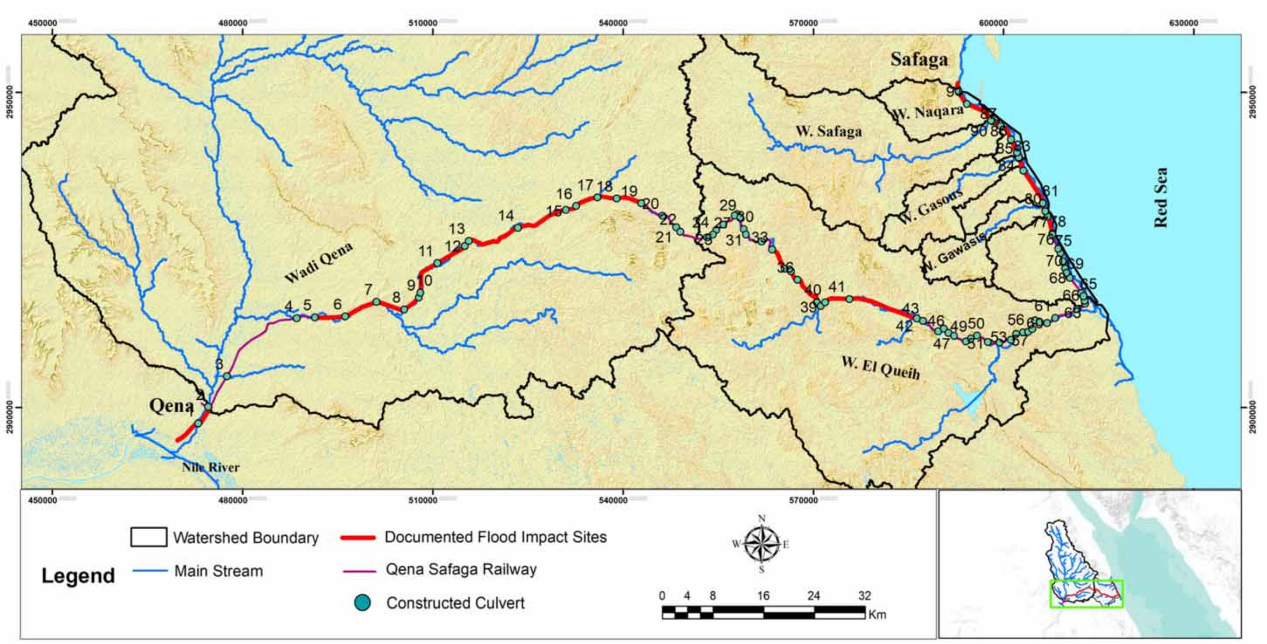

Figure 16 | Track culverts and documented flood impact sites in 1990, 1994, and 1996 delineated within a wadi stream GIS map.

considered. This minimizes culvert failure, which can cause track damage, disruptions in train operations, and accidents. Thus, implementing GIS-based methodology enhances the safety and reliability of the railway network.

4.4.3. Cost-effective infrastructure development

Railway projects require efficient infrastructure development due to significant investment. GIS-based methodology for culvert location evaluation optimizes resource use by identifying locations with minimal construction and maintenance efforts. This reduces construction costs and ensures optimal resource utilization. The methodology also considers factors like flood-prone areas and erosion risks, preventing costly future repairs and maintenance.

4.4.4. Environmental sustainability

Railway infrastructure development should prioritize environmental sustainability. GIS-based methodology helps engineers evaluate culvert locations' environmental impacts, making informed decisions to minimize disruptions. Factors like water quality, habitat fragmentation, and ecological connectivity are considered. Railway projects can contribute to sustainability goals by selecting locations that minimize disruption to watercourses and ecosystems.

4.4.5. Streamlined project planning and design

GIS technology enhances railway infrastructure project planning and design by integrating spatial datasets, allowing engineers to visualize existing conditions and constraints, and identifying potential challenges and opportunities early in the planning phase. This methodology also allows for efficient evaluation of multiple culvert location scenarios, reducing the time and effort required for project planning.

4.4.6. Scalability and transferability

The GIS-based methodology for culvert location evaluation is scalable and transferable to various railway projects, allowing engineers to learn from previous experiences. It can be applied to different geographical locations, ensuring the knowledge gained from the Qena–Safaga Track in Egypt can be applied to other global railway projects. This scalability and transferability ensure the effectiveness of the methodology.

4.5. The economic analysis of flood mitigation schemes

Flood mitigation is crucial in flood-prone regions to minimize the devastating impacts of flooding. Balancing the degree of flood control required and associated costs is essential. Economic analysis helps assess the feasibility and viability of flood control measures by considering expenses and benefits. The primary objective is to reduce flooding risk and safeguard lives, infrastructure, and the environment. However, eliminating flooding entirely is often impractical and financially unfeasible. Decision-makers and stakeholders must evaluate the costs and benefits of various flood control measures to determine the acceptable degree of flood control. There are several flood control measures that can be implemented in flood-prone regions to mitigate the risks associated with flooding. These measures can be broadly categorized into structural and non-structural measures. Here are some examples:

1. **Structural measures:**
   a. **Levees and floodwalls**: These are physical barriers constructed along rivers, coastlines, or around communities to prevent floodwaters from entering vulnerable areas.
   b. **Dams and reservoirs**: These structures are built to control the flow of water, store excess water during heavy rainfall, and release it gradually to prevent downstream flooding.
   c. **Channelization**: It involves modifying natural or artificial channels to increase their capacity and improve the flow of water, reducing the risk of overflow and flooding.
   d. **Detention basins**: These are large storage areas designed to temporarily hold excess water during heavy rainfall or flood events, reducing the peak flow downstream.
   e. **Flood diversion channels**: These channels are constructed to divert floodwaters away from populated areas and direct them to less vulnerable or designated flood zones.
2. **Non-structural measures:**
   a. **Floodplain zoning and land use planning**: These measures involve regulating land use in flood-prone areas, restricting construction in high-risk zones, and encouraging development in safer locations.

b. **Early warning systems**: These systems use real-time monitoring, weather forecasting, and communication networks to provide advance warning of potential flooding, allowing residents to evacuate or take precautionary measures.
c. **Flood insurance and financial incentives**: Encouraging individuals and businesses in flood-prone areas to obtain flood insurance coverage and providing financial incentives for implementing flood-resistant building techniques.
d. **Public awareness and education**: Raising awareness about flood risks, disseminating information about preparedness and response measures, and educating communities on flood safety and evacuation procedures.
e. **Natural flood management**: Utilizing natural processes such as restoring wetlands, constructing green infrastructure, and implementing measures to enhance water absorption and retention in the landscape, reducing runoff, and flood risks.

It's important to note that flood control measure selection and effectiveness are influenced by factors like local topography, hydrology, community needs, resources, and long-term planning. A combination of structural and non-structural measures is often used to enhance flood protection and resilience in flood-prone areas.

Economic analysis is a crucial tool in flood control decision-making. It helps assess the financial implications and feasibility of implementing flood control measures, including construction, maintenance, land acquisition, engineering studies, and monitoring. The analysis also considers the direct and indirect profits gained from flood control efforts. Direct benefits include reduced property damage, insurance claims, emergency response costs, and protection for critical infrastructure. Indirect benefits include avoided business disruptions, preserved agricultural productivity, and enhanced environmental conservation. By evaluating these benefits, decision-makers can gauge the overall economic returns of flood control measures. The economic analysis of flood mitigation schemes provides a framework for determining the acceptable level of flood control, ensuring efficient allocation of resources, maximizing benefits from investments, and considering the economic sustainability of such measures.

5. CONCLUSIONS

In conclusion, the results of the culvert location evaluation using GIS techniques on the Qena–Safaga Track in Egypt demonstrated the effectiveness of the methodology in identifying suitable locations for culverts. The GIS analysis provided valuable insights into the spatial distribution of potential culvert locations, considering factors such as topography, hydrology, geology, and railway alignment. The findings from this study can contribute to the improvement of culvert location selection processes on railways, leading to enhanced drainage efficiency and reduced risks of flooding and track instability. Also, the culvert suitability index map revealed that areas with high slopes and large drainage areas were more susceptible to water accumulation, indicating the need for culverts. The study also highlighted areas where culverts could be installed without significantly impacting existing infrastructure. It was recommended to add culverts at a total of 27 locations along the track where they intersect with watercourses. Existing culverts covered just 93 watercourses, while 5 specialty culverts needed to be relocated. Furthermore, regular inspections and technical maintenance are required to safeguard culverts from sand or rocks deposited and accumulated debris caused by floodwater or strong winds. Additionally, the GIS-based methodology for culvert location evaluation on railways has significant implications for railway engineering. It enhances the decision-making process, improves safety and reliability, offers cost-effective infrastructure development, promotes environmental sustainability, streamlines project planning and design, and provides scalability and transferability. By adopting this methodology, railway engineers can optimize the selection of culvert locations, leading to the development of robust and resilient railway infrastructure systems.

Overall, our research contributes to the growing body of knowledge on GIS applications in railway engineering and provides a foundation for further advancements in this field. We hope that our methodology and findings will inspire future research and practical implementations, ultimately leading to safer and more sustainable railway systems worldwide.

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AUTHOR CONTRIBUTIONS

H. M. A. designed, collected the observed data, wrote the first draft, and edited the document. T. S. A.-Z. collected, processed, guided writing, and reviewed. M. A. A. guided the writing and review. All authors have read and agreed to the published version of the manuscript.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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