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Integrating Hydrodynamic Modelling and Remote Sensing for Spatiotemporal Analysis of Wadi Thuwal Basin Flood Hazards Affecting the Haramain Train Pathway

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Abstract. Spatiotemporal analysis to create accurate flood simulations in arid environments and hydrological unmeasured valley basins is one of the most important challenges in flood risk studies. This study investigated the flood risks that the torrents of the Wadi Thuwal Basin pose to the Haramain Train Pathway in various time and space scenarios. It also examined the potential impacts of climate change and environmental alterations on flood risks. The research aims to develop a comprehensive risk management plan that mitigates the possible negative consequences associated with floods. To achieve these goals, remote sensing, and high-resolution data from LiDAR, geological, topographic, and soil maps were processed using GIS. The Hydrological Engineering Centre-Hydrologic Modelling System (HEC-HMS) was used to derive the hydrograph of torrential waters and the hydraulic model of the Hydrologic Engineering Centre-River Analysis System (HEC-RAS) to simulate the Wadi Thuwal flood. This involved creating maps of torrential waters' velocity, depth, and spread, and evaluating the hydraulic installations under the train pathway. This study presents important planning considerations for policymakers in the KSA, given the paramount importance of the two holy cities of Makkah and Al-Madinah and the crucial role of the Haramain Train Pathway in ensuring safe connectivity between them.

1 Introduction

In recent decades, natural disasters, especially floods, have become more frequent and severe. Floods are one of the worst tragedies (Joy and X.x., 2004). Because they destroy lives, property, and infrastructure, floods fascinate scholars and inspire them to study and develop prevention and control methods (Rimal et al., 2018). In dry and semi-arid environments, quick and strong rainfall causes flash floods. Flood prediction and management in dry, partially dry, or poorly monitored basins require adaptable hydrological and hydraulic models. Scientific advances have made spatiotemporal modelling more important in flood simulation and evaluation. Climate change, urbanization, and human interventions rapidly change processes, making flood map predictions, modelling, and assessment essential. Due to climate change in the previous decade, spatiotemporal models to simulate and predict flood maps in dry and semi-arid Arab basins are needed. Rainfall has increased as urbanization and building have increased (Elkarim et al., 2020). The best way to reduce flood risks is to employ spatial-temporal hydrodynamic modelling to create flood maps for land-use plans and flood risk prevention initiatives. Flood risk management involves identifying flood-prone locations and taking precautions to reduce damage. This comprises early warning and response systems.

High-resolution satellite imagery (Abdelkarim and Gaber, 2019; Billa et al., 2005, 2006) and geographic information systems (GIS) with maps and digital elevation models (Biswajeet and Mardiana, 2009; Pradhan and Youssef, 2011; Saleh and Al-Hatrushi, 2011; Youssef et al., 2011) have been used to identify flood-prone locations and assess flood damage. Remote Sensing and GIS technologies have helped store, analyse, process, and visualize geographical data (Hamdy et al., 2023; Haq et al., 2012). This helps hydrodynamic models like geomorphology, hydrology, land uses, and land cover assess water runoff and flood dangers (Masoud, 2011; Ologunorisa and Abawua, 2005; Subyani, 2011). Flood applications are more efficient with upgraded LiDAR technology, but due to high costs, many poor nations avoid LiDAR data sets (Muhadi et al., 2020). Although expensive, LiDAR is the most used method for DEM creation (Hashim et al., 2016). Most global studies show that flood damage to infrastructure is understudied and needs more research (Doll et al., 2014; Gil and Steinbach, 2008; Koks et al., 2019). Infrastructure failure can harm public health and economic security, reducing society's resilience (Arrighi et al., 2017, 2021; Fekete, 2019; Lhomme et al., 2013; Tarani et al., 2019). Many flood risk studies use hydrodynamic models to identify and assess risks. Other research examines indirect effects in time and space using aggregate flood failure models (Balijepalli and Oppong, 2014; Lyu et al., 2018; Pant et al., 2018; Singh et al., 2018).

Many researchers have used hydrologic and hydraulic methods and models to assess flood risks to infrastructure in recent years, but hydrodynamic modelling is the most widely used and reliable (Abdelkarim et al., 2019b, 2020; Werner, 2004). These models can be one-dimensional (1D), two-dimensional (2D), or one-dimensional river flow models with two-dimensional floodplain flow models (Van Ginkel et al., 2021). Much research has found that the HEC-RAS and HEC-HMS models utilized in this study are popular because they are simple, adaptable, and can incorporate spatiotemporal dimensions. These models help with flood prediction, simulation, and change tracking (Abdelkarim et al., 2019a). Data processing procedures are more efficient using RS and GIS with these models. This connectivity also makes model output monitoring and evaluation easier. Kellermann et al. (2016) examined Austria's Moor River Basin railway infrastructure using dynamic modelling. Rail Infrastructure flood damage model was employed. Carlino and Di Francesco (2018) examined how floods damaged a railway bridge on Sicily's Gornalonga River using a paired model 1D-2D approach using MIKE FLOOD software. Monsef (2018) applied the mitigation technique to mitigate flood risks on Egypt's Al-Quseir-Qena route using HEC-HMS. Abdelkarim et al. (2019b) used RS and HEC-HMS to determine how land use changes might increase flood risks on the Riyadh-Dammam train track in Saudi Arabia, while Abdelkarim (2019) used hydrological and hydrodynamic modelling to assess future flood risks on the Jazan-Abha highway. Büche et al. (2021) assessed German federal highway network flash flood risk using hydrologic and two-dimensional hydraulic modelling. Fathy et al. (2020) used HEC-HMS hydrological modelling to protect Saudi Arabia's new Tama road from floods, while Ogras and Onen (2020) analysed the floodplain between the Diyarbakir-Silivan highway and the historic El-Ayoun bridge using HEC-RAS. Aureli et al. (2021) employed a fully two-

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dimensional shallow water model (PARFLOOD) to model flood threats in northern Italy. Sadek et al. (2021) monitored flood hazards in Ras Gharib, Egypt, using modelling and remote sensing (RS) multi-source data.

The Kingdom Annual floods in Saudi Arabia harm and disrupt numerous locations (Youssef et al., 2015a, b; Youssef and Maerz, 2013). Flood planning and risk assessments can reduce these effects. In 2009 and 2011, floods in western Saudi Arabia, north of Jeddah, killed hundreds and destroyed buildings and infrastructure. The Haramain Train Pathway, which connects Makkah and Al-Madinah (Figure 1), changed land use in the study area, especially because it crossed valleys from east to west and the Red Sea. These concerns must be examined considering the changing landscape, as shown by the new land-use map.

Here is a description of the study challenge: The Wadi Thuwal drainage basin, which impacts the Haramain Train Pathway north of Jeddah, frequently experiences devastating torrents. The train pathway, culverts, and bridges changed the study area's land use map, flow, and flooding patterns. Most dry valleys in Saudi Arabia are not well defined because no hydrometric stations measure surface flow. To find torrential water hydrographs and immersion ranges, hydrologic and hydraulic models are used. A two-dimensional (2D) model is needed because topographic maps, aerial photos, and digital elevation models can't show the path and limits of Wadi Thuwal near the Haramain Train Pathway. Also, a one-dimensional (1D) simulation makes it hard to see the depth, speed, and flood spread. The study's goals are to create, test, and analyse a two-dimensional simulation of the Wadi Thuwal flood that affects the Haramain Train Pathway and to find out how well the existing floodwater drainage systems in the culverts and bridges below the pathway can handle high flows. Using hydrodynamic modelling, we will integrate RS and GIS to develop strategic recommendations aimed at mitigating and protecting the study area from torrential rains. Different satellite images were used to compare the changes in land uses and land cover during floods, and the modelling was built using high-resolution LIDAR data. Version 6.1 of the hydraulic model for Geological, Soil, and HEC-RAS can generate 1D and 2D models to replicate torrents' stable or time-varying movement.

Figure 1. The Haramain Train Pathway and the installations constructed below to protect against torrential rains.

2 Materials and methods

2.1. Study area

The drainage basin of Wadi Thuwal is located 100 km northeast of Jeddah between the latitudes 21° 53' 47.4'' and 22° 49' 28.9'' North and the longitudes 40° 14' 21.7'' and 39° 9' 54.6'' East. It covers 5,189.52 km^2. The source of the basin is Jabal al Libidah

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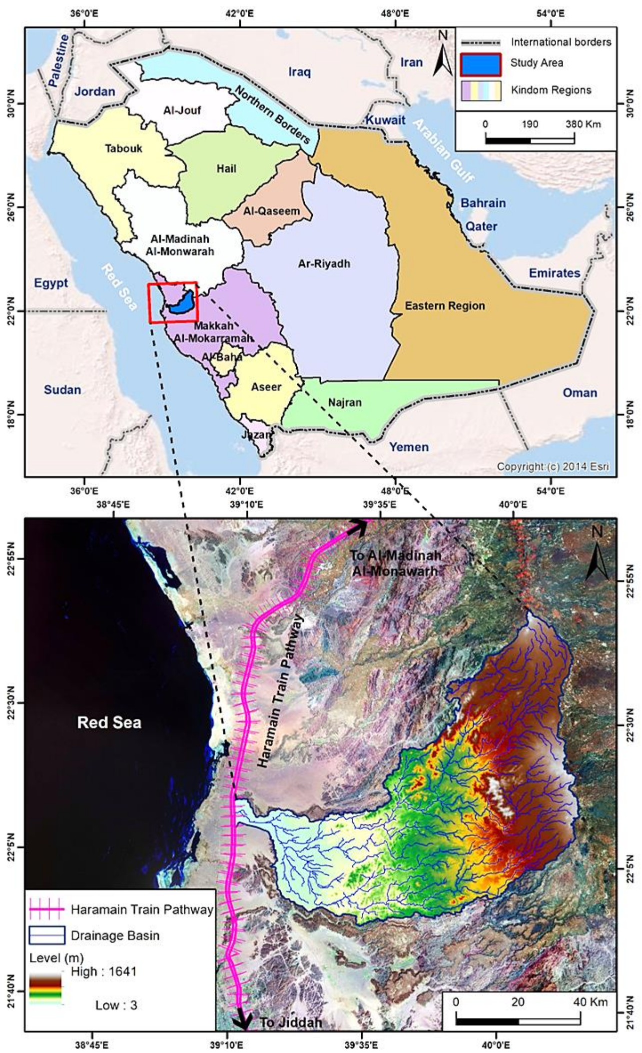
at 1662 meters, and the basin slope is 0.0086 m/m. The basin levels range from 1-1662 m. The basin outfall is 1 meter high at the Haramain Train Pathway. Khulays, Umm ad Dar, Ihala, Sayah, and Ghiran are the main sub-wadis Fed by Wadi Thuwal. Figure 2 depicts how the Wadi Thuwal basin affects the Haramain Train Pathway, which connects Makkah and Al-Madinah in 120 minutes through Jeddah. The 450-km Haramain Train Pathway connects Makkah and Al-Madinah in western Saudi Arabia. The project has 35 trains with 13 carriages and 417 seats apiece. It intends to improve transit between the two holy capitals and increase Saudi Arabia's railway network. The Haramain Express train project is the state's largest public transport system and one of its plans is to expand railway transportation to keep up with the growing number of pilgrims and Umrah pilgrims and relieve pressure on the roads between Makkah, Jeddah, and Al-Madinah while providing safe and fast transportation.



Source: (a) the official map, the geospatial portal, the General Authority for Survey, (b) the atlas of distribution maps of the results of the general population and housing census, the General Authority for Statistics, and Jeddah Municipality, (c) High-resolution LIDAR data, Ministry of Municipal and Rural Affairs and Housing.

Figure 2. A geographical overview of the Wadi Thuwal Basin and its proximity to the Haramain Train Pathway highlights the main sub-wadis contributing to the basin's hydrology.

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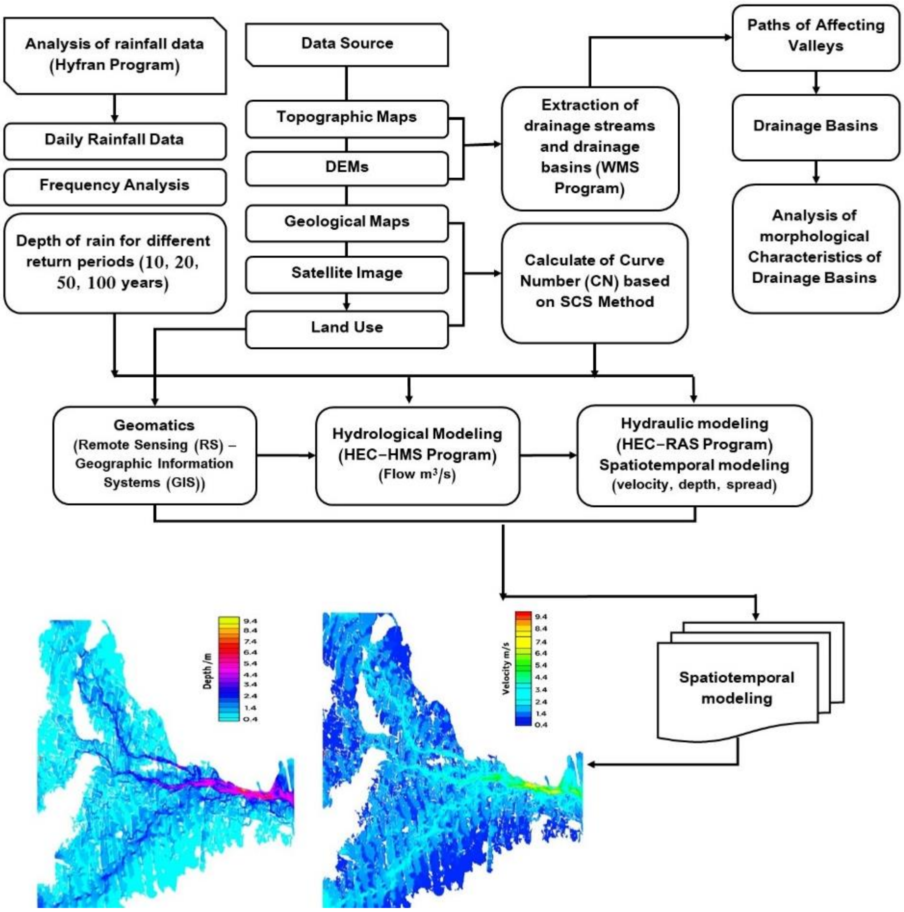
2.2. Methodology

Figure 3 illustrates the study methodology used in the spatiotemporal analysis of flood hazards for Wadi Thuwal basin affecting the Haramain Train Pathway, which relied on integrating RS and GIS with hydrodynamic modelling of both (HEC-RAS and HEC-HMS) models.



Source: Researchers' work

Figure 3. The comprehensive methodology employed in the study, integrating remote sensing (RS) and geographic information systems (GIS) with hydrodynamic modelling (HEC-RAS and HEC-HMS). The flowchart outlines the key processes involved in data collection, model calibration, and flood hazard analysis, illustrating the interconnectedness of various data sources and modelling techniques used.

2.2.1. Determining data sources:

Table 1 and Figures 4 and 5 show that this study's hydrological model (HEC-HMS) and hydraulic model (ECR-RAS) need topographic, geological, morphological, and climatic maps. To identify and extract the network of valleys affecting the Haramain Train Pathway, several sources were used, including high-resolution LiDAR data with 50 cm resolution from the Ministry of Municipal and Rural Affairs and Housing, topographic maps at a drawing scale of 1:50000, and Landsat 8/O. The

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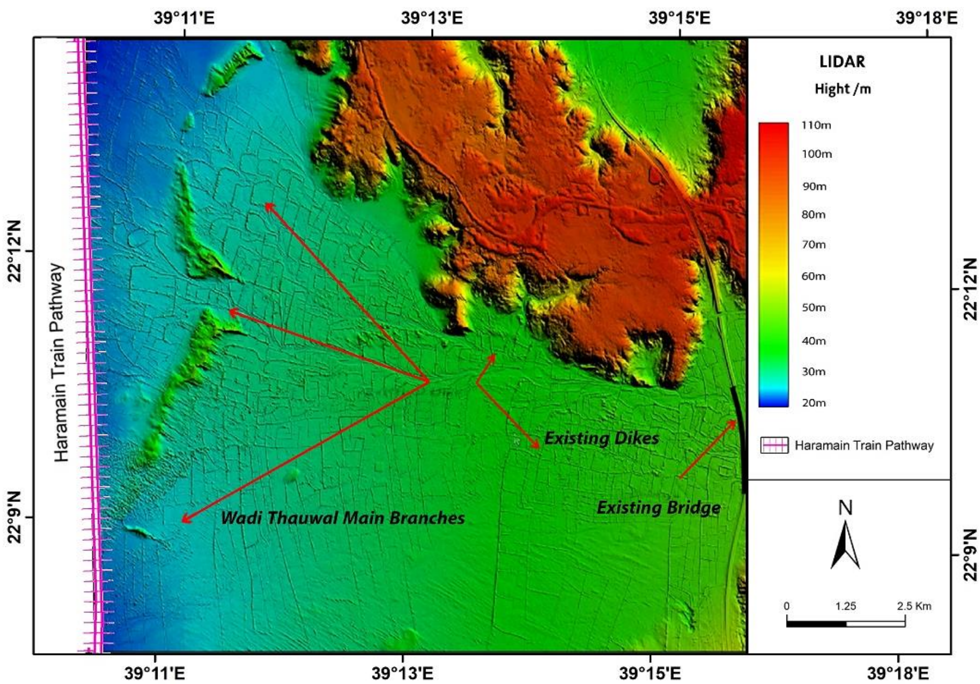
hydrological parameters of the soil were extracted from 1:250,000 Saudi Geological Survey geological maps. The Ministry of Environment, Water, and Agriculture data was analysed to determine rainfall amounts for various return periods and the intensity, density, and frequency curves (IDF curve) for the study area's major rain stations.

Table 1. Input data and spatial accuracy and their sources for the criteria used in the study

Criteria	The data used to extract the criteria		Commission/websites used to obtain the data
	Source	Scale/spatial accuracy	
Valleys	LiDAR data	50 cm	Ministry of Municipal and Rural Affairs and Housing
	Topographic maps	50.000:1	General Authority for Survey
slopes	LiDAR data	50 cm	Ministry of Municipal and Rural Affairs and Housing
Land Uses / Land Cover	Satellites visuals: Landsat-5/TM – Landsat-7/ETM+ - Landsat 8	30 meters	http://earthexplorer.usgs.gov
Rain stations	Khulais (J106), Madrakah (J214), Ain Al-Aziziya (J219), Al-Madhah (J220), Asfan (J221), and Al-Barza (J239)		Ministry of Environment, Water and Agriculture
Arrange the valleys	The network of valleys derived from LiDAR data	50 cm	Ministry of Municipal and Rural Affairs and Housing
Geological formations	geological maps	250.000:1	Saudi Geological Survey
Culverts, bridges, and Haramain Train Pathway	Survey mylar		Jeddah Municipality
	The researcher's field study		Visit the study area



Source: High-resolution LIDAR data, Ministry of Municipal and Rural Affairs and Housing.

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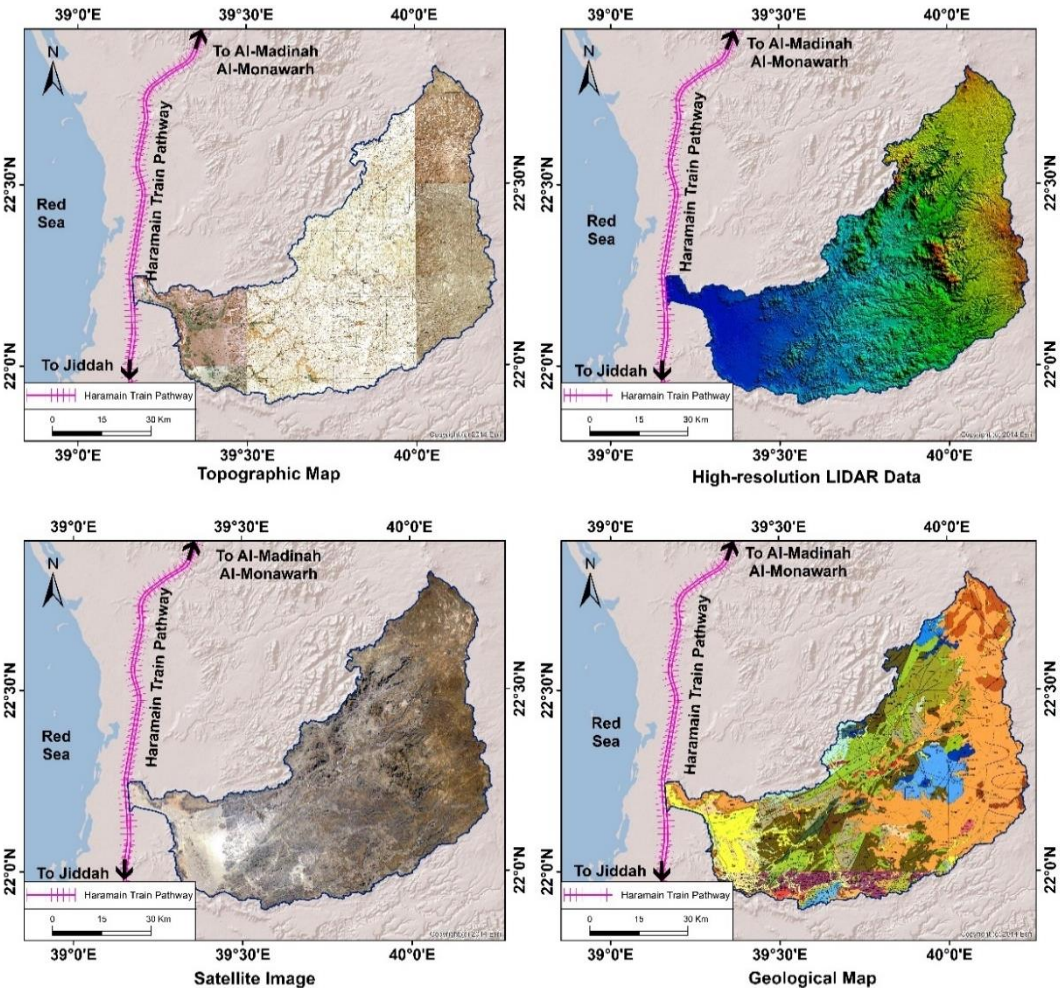
Figure 4. High-resolution LiDAR data that contributed to the construction of two-dimensional spatiotemporal models of the Wadi Thuwal Basin. The detailed topographical features enable the accurate simulation of flood dynamics and assess terrain influences on hydrological behaviour.



Source: Topographic maps at scale 1:50,000 - General Authority for Survey, Landsat 8/OLI satellite image - USGS, geological maps at scale 1:250,000 - Saudi Geological Survey, High-resolution LIDAR data - Ministry of Municipal and Rural Affairs and Housing.

Figure 5. The sources of data utilized for the study, including topographic maps, geological data, and satellite imagery.

2.2.2. Geometric Hydrological Model (HEC-HMS):

The hydrological model utilizing the Geometric System (HEC-HMS) employed in this study is recognized for its compliance with both local and global standards, and it has been extensively utilized in numerous research studies (Bajwa and Tim, 2002; Halwatura and Najim, 2013). The HEC-HMS program is a hydrological computer program that specializes in modelling and simulating the relationship between rainfall and surface runoff in water drainage basins. It is an updated and graphical version of the HEC-1 program. The program performs all hydrological calculations, and among its most significant outputs are groundwater

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discharge, infiltration, water movement in waterways, losses, total filtration, residual rain, and direct runoff values. The HEC-HMS demonstrated significant efficacy in determining hydrograph units in unmeasured basins, particularly in dry areas.

The Runoff Curve Number method was used to estimate the surface runoff, determine the maximum flows of torrential water, and calculate the hydrograph of the torrent after subtracting the various loss values from the rainwater falling on the drainage basin. A factor known as the Runoff Curve Number expresses these losses based on the characteristics of the soil, the activities conducted there, and the land uses. The maximum flow rate of the torrential runoff over the surface of the drainage basin is obtained using the following equation:

$$Q = qu * AB * R * F \quad \textbf{\textit{(1)}}$$

Whereas:

Q: The maximum flow of torrential water over the entire area of the drainage basin (m^3/s).
qu: Unit of maximum flow ($m^3/s/km^2/mm$).
AB: Area of drainage basin (km^2).
R: Depth of torrent water runoff (Runoff Depth) expected to occur per unit area of the drainage basin (mm).
F: Coefficient to correct the value of the surface runoff due to the presence of collection ponds in the drainage basin.

$$qu = (10C0 - 3.36609) * (TcC1 + C2\,log(Tc)) \quad \textbf{\textit{(2)}}$$

Whereas:

Tc: Time of concentration (hours).
C2, C1, C0: Constants whose value depends on the initial losses of rainwater and the initial absorption of the drainage basin (P/la).

The maximum loss or storage that can occur in the soil of the drainage basin (S), as well as the value of the initial loss (Ia) expected to occur in the drainage basin (Rahman et al., 2017), is determined using the following equation:

$$S = 25.4\,(1000/CN - 10) \quad \textbf{\textit{(3)}}$$

$$la = 0.2S \quad \textbf{\textit{(4)}}$$

Whereas:

S: Maximum storage depth in soil (mm).
CN: Curve number, which is estimated according to international standards.
La: Initial loss (at the start of the rainstorm) (mm).

The (WMS) program was used to determine the soil cover of the collection basins affecting the study points. This analysis relied on land use and soil cover maps provided by the Saudi Geological Survey (SGS). A file for land uses was prepared based on the latest aerial photos, and they were added to the program, which in turn calculated the (CN) for each area in the collection basins. Then the depth of runoff of the torrent water (Runoff Depth, R) expected to occur is calculated per unit area of the drainage basin (mm) (Ponce and Hawkins, 1996; Shrestha MN., 2003), using the following equation:

$$R = \frac{(P - I_a)^2}{(P + 0.8S)} \quad (5)$$

Whereas:

P: Maximum daily average rainfall corresponding to the design repetition period (mm).

The shape of the torrent hydrograph resulting from the curve number method depends on the area of the drain basin and the delay time (Lag Time, TL). Usually, the delay time is calculated as 60% of the concentration time in the drain basin.

There are five methods of channel routing in (HEC- HMS) (Sharif et al., 2016), two of them have been used here:

(1) The Muskingum directive method uses a simple estimation of the finite difference to solve the following equation

$$O_t = \left(\frac{\Delta t - 2KK}{2K(1-X) + \Delta t}\right) I_t + \left(\frac{\Delta t - 2KK}{2K(1-X) + \Delta t}\right) I_{t-1} + \left(\frac{2K(1-X) + \Delta t}{2K(1-X) + \Delta t}\right) O_{t-1} \quad (6)$$

Whereas:

O: The outflow.

I: The inflow.

t: Time.

K, and X: Parameters that depend on the channel and flow characteristics.

(2) The modified pulse method, also known as storage routing or plane pool routing method, is based on the approximation of the finite differences of the continuity equation and is coupled with an empirical representation of the momentum equation. The regular expression is given by:

$$\left(\frac{S_t}{\Delta t} + \frac{O_t}{2}\right) = \left(\frac{I_{t-1} + I_t}{2}\right) + \left(\frac{S_{t-1}}{\Delta t} + \frac{O_{t-1}}{2}\right) \quad (7)$$

Whereas:

S: The storage in the channel access.

A functional relationship between the storage and the outflow is required to solve this equation.

2.2.3. Two-dimensional hydraulic models used (HEC-RAS):

The Hydrological Engineering Centre of the US Army Department of Engineers used two-dimensional hydraulic models (2D) to calculate flows, their paths, and their impact on the infrastructure. The centre uses the well-known two-dimensional modelling programs, namely HEC-RAS (2D) and HEC-RAS, at this stage to evaluate flood problems for the infrastructure. The US Army Department of Engineers approved the program's current use in civil engineering projects, transforming it from HEC-2 to a newer version with enhancements like a graphical interface and the capability to share data with the GIS (ArcGIS) via HEC-GeoRAS. The program has also added capabilities for hydraulic calculations, with the most significant outputs being the two-dimensional maps of flood borders and areas of risk (Flood Extent Maps) (Abdelkarim et al., 2019b; Van Ginkel et al., 2021).

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2.2.4. Calibration of Hydrological and Hydraulic Models:

Before running the simulation and verifying the results, the hydrological and hydraulic models were calibrated to derive the parameters used in predicting the different return periods. The parameters were estimated using trial and error procedures (Trial & Error), and then the results were compared with actual measurements (precipitation as input, flow as output) until the minimum error between the calculated and measured results was achieved. Most of Saudi Arabia's basins are unmeasured and uncovered. An uncertainty analysis was performed (Abdelkarim et al., 2020) to determine the accuracy of the hydrological models used in the study.

2.2.5. Verify the accuracy of hydraulic modelling:

Modelling is a process of simulating natural phenomena as much as possible, so different scenarios can be anticipated, and practical solutions developed. Any model depends primarily on three basic elements: inputs, outputs, and coefficients. Inputs are the data used in a model's calculations. These are typically measurements of nature or values derived from other sources that remain unchanged during the analysis. Outputs refer to the results deduced from calculating the equations carried out by the model, whose values are compared with the existing values in nature to verify the accuracy of the model. If the outputs don't match the area's nature values, we adjust the coefficients. This process ensures consistency in the results, guarantees modelling accuracy, and verifies the outputs' conformity using the root mean square error equation.

3 Results

3.1. Geometric Morphometric Characteristics

The investigation of Figures 6, and 7 reveals that the length of the Wadi Thuwal basin is 189.53 km, and its size is approximately 5,189.52 km^2. The detailed analysis of the LiDAR data revealed that the ground elevations in the Wadi Thuwal Basin range from 2m above sea level at the lower end, primarily along the Haramain Train Pathway, to 1650m above sea level at the uppermost point of the basin's sources. The slopes in Wadi Thuwal Basin are inclined, ranging from 72.1 to 90 degrees, and the basin's total elevation difference is around 1648 meters. The terrain ratio was measured at 8.70 m/km, whereas the relative terrain was approximately 3.6 m/km. The ruggedness of Wadi Thuwal Basin was found to be 9 degrees, equivalent to 1.87. The gradient was around 8.70 m/km. The Wadi Thuwal basin's bifurcation rate was approximately 2.65. In the basin, the weighted branching rate was around 3.13. The basin had an elongation coefficient of approximately 0.21 and a rotation coefficient of approximately 0.30. Additionally, the Wadi Thuwal basin's relative circumference measures 11.2 km.
The average width of the basin in Wadi Thuwal was approximately 27.4 km, with a shape coefficient of about 0.14. The coefficient of integration was approximately 1.83, the buckling factor was about 1.73, and the hypometric integration value was 0.51 km^2/m. The Wadi Thuwal Basin contains approximately 6,274 sewers. The total length of the sewers was approximately 5898.1 km, with a sewage recurrence coefficient of approximately 1.21 $streams/km^2$, and a drainage density of

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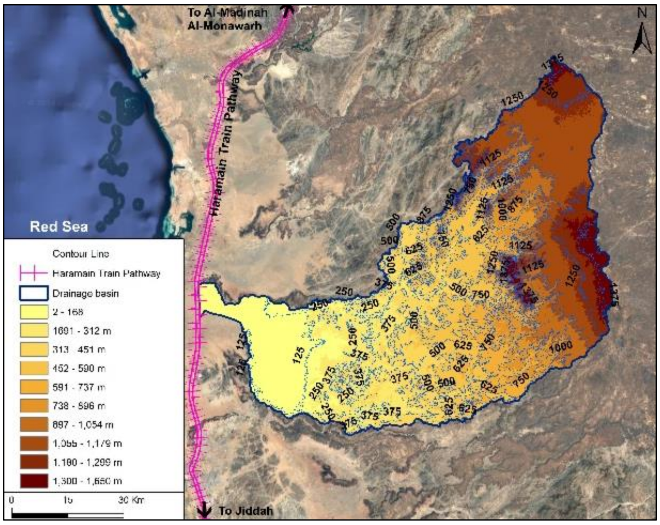
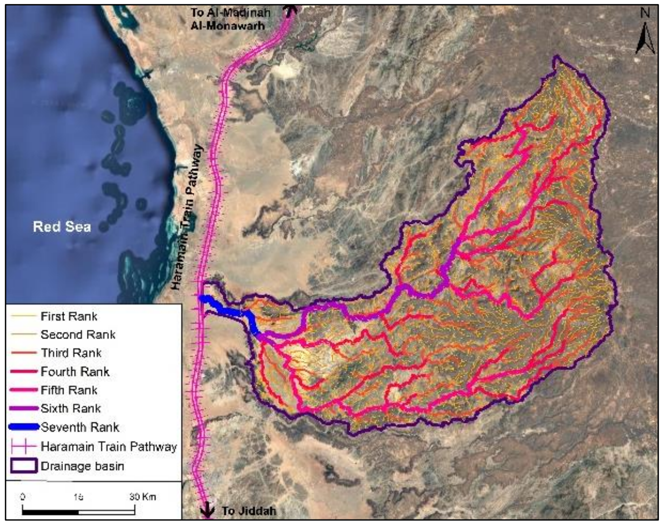
about 1.14 km/km². Wadi Thuwal is classified within the coarse density range of less than 5, indicating its coarse nature. The range of 13.7 to 155.3 is classified as soft, while values exceeding 155.3 are categorized as softer.



Source: High-resolution LIDAR data, Ministry of Municipal and Rural Affairs and Housing.

Figure 6. The contour lines illustrating the topography of the Wadi Thuwal Basin, revealing variations in elevation throughout the area from lower areas along the train pathway to the basin's sources.



Source: High-resolution LIDAR data, Ministry of Municipal and Rural Affairs and Housing.

Figure 7. Ranks of valleys within the Wadi Thuwal Basin based on hydrological characteristics, highlighting the primary waterways that influence flood dynamics.

3.2. Characteristics of rain affecting the study area:

The report on Saudi Arabia's climate state in 2050, which highlighted seven climate models, served as the basis for this study. The scenario (RCP 8.5) assumed the highest rate of change in the expected rainfall in 2050, representing 19% of the total expected rainfall. The impact of this percentage on the recurring storm of 100 years has been calculated, as the annual average for this scenario is 112 mm. Precipitation in a region plays a critical role in the hydrological cycle, which regulates the availability and supply of water, as well as water disasters worldwide. Meanwhile, rainfall and its amount are crucial factors in calculating torrential rains and accurately estimating the size of the resulting floods (Olawoyin and Acheampong, 2017). These factors serve as the correct foundation for water statistics and the probability of recurring floods.

The study area encompasses eight meteorological stations. However, two stations were excluded: Al-Oqla (J141) and Al-Kamil (J142) due to the lack of data for these stations. Since multiple rain stations influence the Wadi Thuwal basin, we established Thiessen polygons to identify each station's impact on the study area. The approach relied on segmenting the Wadi Thuwal basin into multiple sections, each directly impacted by a single monitoring station. Subsequently, the average rainfall height in each region was computed, subsequently dividing it throughout the entire region. If the distribution of rain stations is not uniform, the Thiessen polygons method was used to determine the average rain height (Arianti et al., 2018). Figure 8 shows where the rain stations are located, Figure 9 shows the lines of equal annual rainfall, and Table 2 shows the depth of

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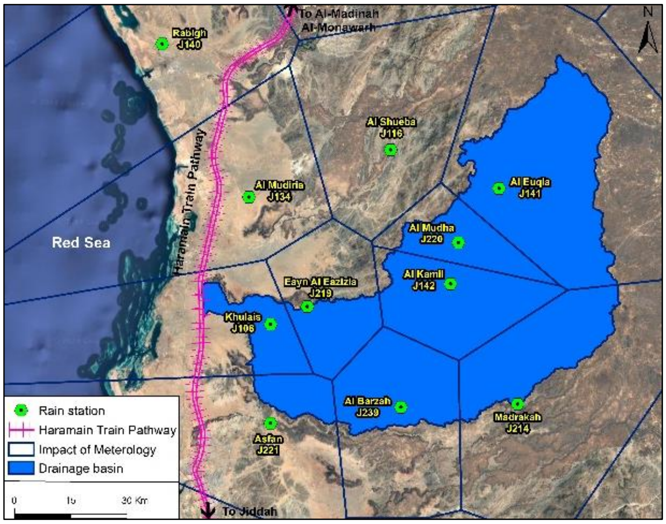
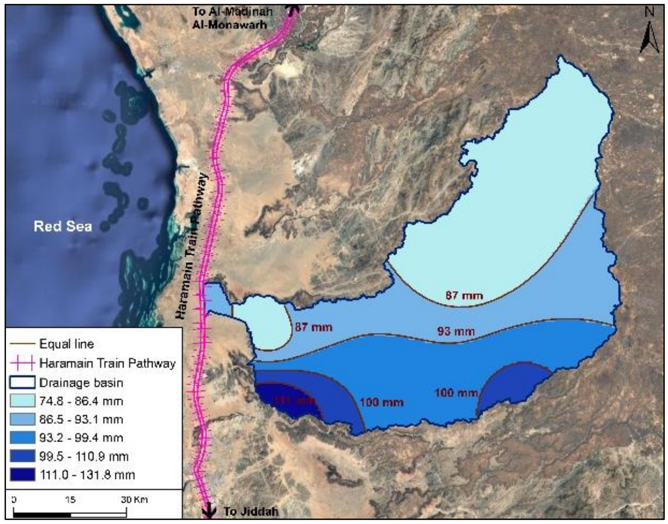
rain based on metrological stations and the Thiessen Polygon method in the WMS program. This method uses the relative weight of rain stations, also known as the precipitation gage weight.



Source: Rain stations Ministry of Environment, Water and Agriculture Using the Precipitation Gage Weight method within the WMS program.

Figure 8. The locations of the surrounding rain-gauging stations represented by the study area



Source: Rain stations Ministry of Environment, Water and Agriculture.

Figure 9. Lines of equal annual rain for Wadi Thuwal basin affecting Haramain Train Pathway

Table 2. Rain depth for Wadi Thuwal Basin during different return periods.

Basin data	Basin name	Wadi Thuwal
	Basin area (km^2)	5189.52
Areas affected by weather stations (km^2)	Khulais (J106)	375.34
	Madraka (J214)	766.35
	Ain Al-Aziziya (J219)	361.02
	Al-Madhah (J220)	2778.06
	Asfan (J221)	212.35
	Al-Barza (J239)	696.4
Rain depth for different return periods (mm)	2	20.59
	5	36.89
	10	48.09
	20	58.93
	50	73.01
	100	83.64

220 **3.3. Characteristics of Soil Hydrological Group and Curve Number:**

Wadi Thuwal basin geological maps at 1:250,000 scale were used (Figure 10). The Wadi Thuwal drainage basin has 87.1% volcanic rocks, 11.8% sand and gravel, and 1.1% valley sediments. The drainage basin of Wadi Thuwal is divided into three soil hydrological groups: A (137.3 km², 2.6%), B (476.83 km², 9.2%), and C (4575.39 km², 88.2%) (Figure 11).

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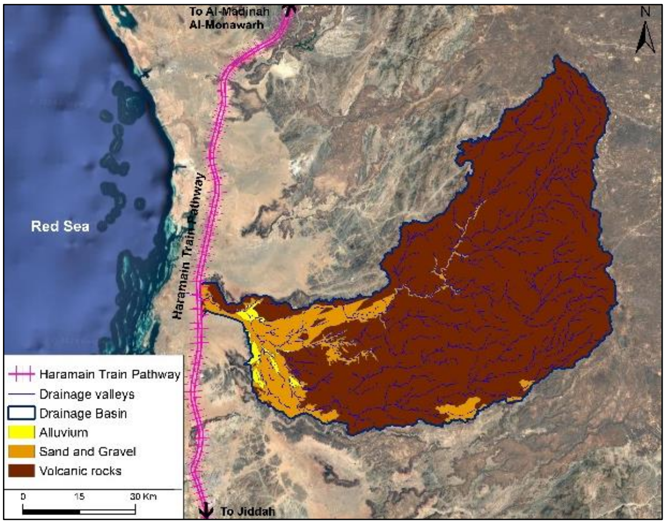
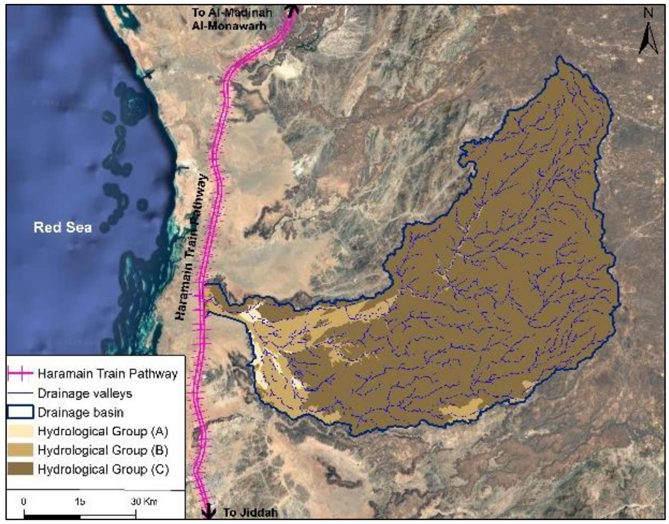
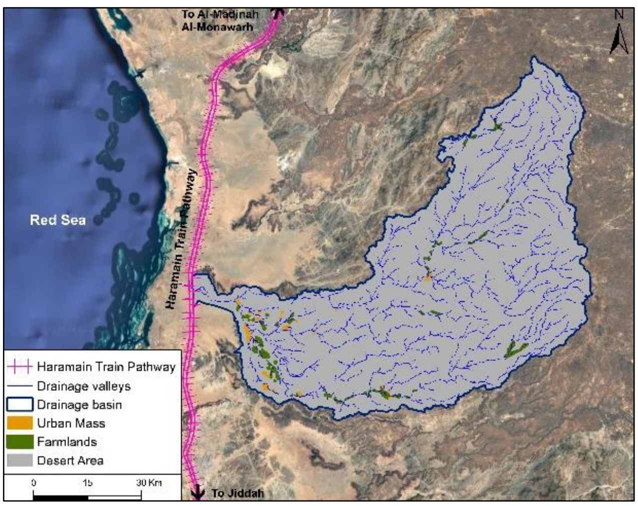


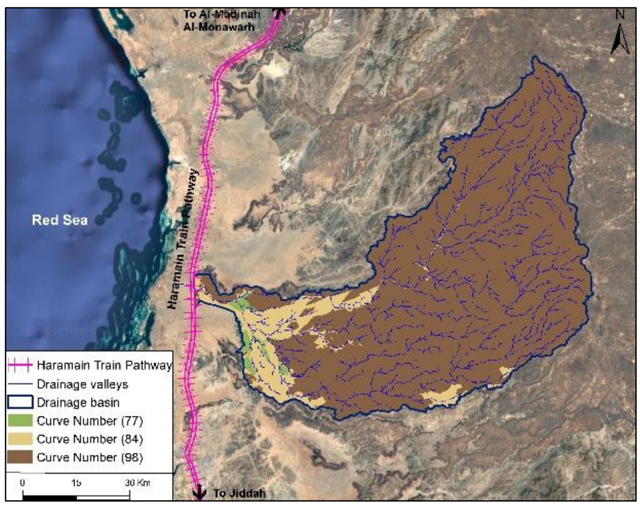
Source: Geological maps at scale 1:250,000 - Saudi Geological Survey.
Figure 10. Geological map of Wadi Thuwal Basin showing the predominance of volcanic rocks, sand and gravel, and valley sediments.



Source: Geological maps at scale 1:250,000 - Saudi Geological Survey.
Figure 11. Soil Hydrological Group of Wadi Thuwal Basin indicating their respective runoff characteristics and infiltration capacities.

Changes in land use affect rainfall interception, infiltration, groundwater intrusion, evaporation, and transpiration, reducing soil rainwater absorption and increasing flood risk (Huong and Pathirana, 2013; Tang et al., 2021). Figure 12 illustrates the three main land uses. Urban areas, encompassing 14.84 km², represent 0.3% of the basin area and constitute the initial category of land use. The second land type encompasses 30.26 km², representing 0.6% of the basin, whereas the third and final type, desert, spans 5144.42 km², accounting for 99.1% of the basin. The curve number values for the Wadi Thuwal Basin range from 77 to 98 (Figure 13).





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Source: Landsat 8/OLI satellite image - USGS

Figure 12. The land uses of Wadi Thuwal Basin showing urban areas, agricultural land, and desert.

Source: Watershed Modelling System (WMS) software

Figure 13. Curve Number across different land use categories of Wadi Thuwal Basin, where lower CN values indicate better infiltration and less runoff potential, while higher values are associated with urbanized areas with greater runoff.

3.4. Characteristics of the torrential waters of Wadi Thuwal Basin:

The massive water flows in the Wadi Thuwal drainage basin were analysed using a hydrograph. Table 3 shows that the sizes of the torrents ranged from 86434070 to 229166850 m^3 over the course of 10 to 100 years, and the highest flow rate in the Wadi Thuwal Basin was between 1161.63 and 3120.23 m^3/s over those same time periods. Figures 14 and 15 demonstrate the characteristics of the torrential waters using HEC-HMS.

Table 3. Wadi Thuwal secondary drainage basin floodwater characteristics during different recurring times.

Periods	10	20	50	100
Total rain (mm)	48.09	58.93	73.01	83.64
Total losses (mm)	31.43	34.50	37.61	39.48
Residual rain (mm)	16.66	24.43	35.40	44.16
The size of the torrents (1000 m^3)	86434.07	126761.67	183723.21	229166.85
Maximum flow (m^3/s)	1161.63	1713.12	2495.20	3120.23

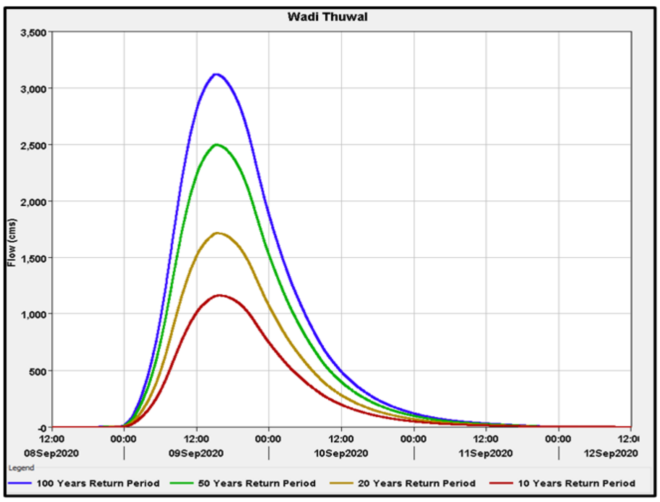

Figure 14. Hydrography of the torrential waters for the return periods (10, 20, 50, 100 years), helping to visualize how flood conditions may evolve during significant storm events. This analysis is crucial for understanding potential flood risks associated with extreme weather scenarios in the Wadi Thuwal Basin.

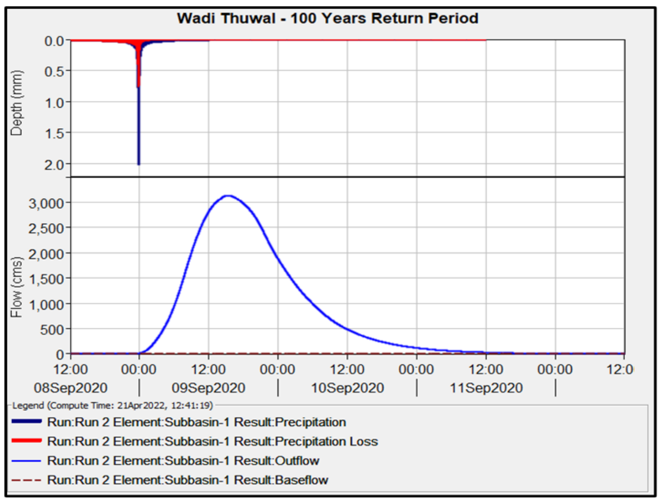

Figure 15. Hydrograph of the torrential waters for the return periods of 100 years highlights the intensity and duration of potential flooding events, providing essential data for flood risk management towards infrastructure planning, especially under the Haramain Train Pathway.

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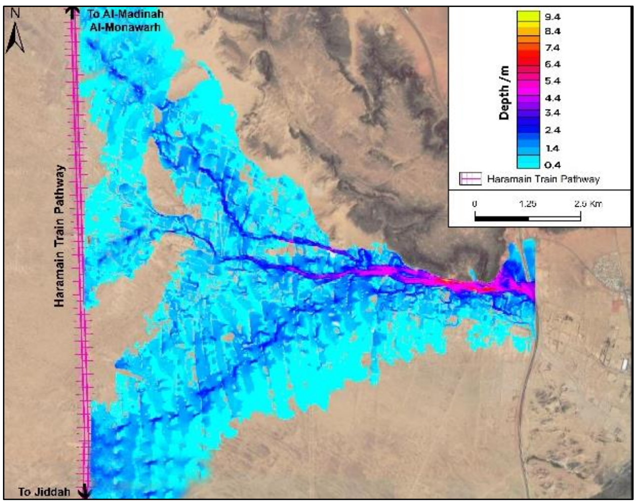
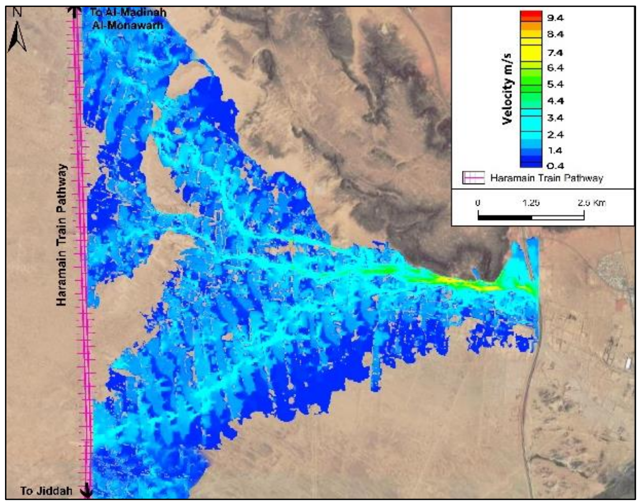
3.5. Characteristics of two-dimensional hydraulic modelling of Wadi Thuwal Basin:

To build spatiotemporal models of Wadi Thuwal flooding and deduce maps of torrential waters' depth, velocity, and spatial spread, the peak flow of 3120.23 m^3/s during the 100th maximum storm and 50 cm accurate LiDAR data were used to construct valley cross sections. Figures 16 and 17 show that the spatiotemporal modelling splits Wadi Thuwal into three main portions, suggesting the flow disperses. 20.65% concentrate medium depths (2.4-5.4 m) north and south of Wadi Thuwal, encompassing 8.28 km^2, and 16.78% concentrate high depths (5.4-9.4 m) west of Makkah-Al-Madinah Road at As Sawati. The Haramain Train Pathway covers 25.09 km^2 (62.57%) with modest depths (0.4-2.4 m). The velocity map shows high velocity (5.4–9.4 m/s) west of Makkah-Al-Madinah Road near As Sawati, spanning 4.80 km^2 by 11.97%, and medium velocity (2.4–5.4 m/s) north and south of Wadi Thuwal, covering 7.30 km^2 by 18.21%. The Haramain Train Pathway emphasizes low velocity (0.4-2.4 m/s) over 28.00 km^2 (69.82%).



Source: 2D hydraulic modelling using Hydrologic Engineering Centre-River Analysis System (HEC-RAS)

Figure 16. Results of the two-dimensional hydraulic modelling (depth (m)). Different colour gradients illustrate varying depths, with the model showing concentrated areas of medium (2.4-5.4 m) and high depths (5.4-9.4 m). This information is essential for identifying zones at greater risk of inundation.



Source: 2D hydraulic modelling using Hydrologic Engineering Centre-River Analysis System (HEC-RAS)

Figure 17. Results of two-dimensional hydraulic modelling (velocity (m/s)). High-velocity regions (5.4–9.4 m/s) are shown in specific colours, indicating areas prone to faster water flow, particularly west of Makkah-Al-Madinah Road near As Sawati.

3.6. Validation of flood risk models

This study uses statistical and spatially intensive fieldwork to validate spatiotemporal flood simulation estimates and compare historical flood events in the studied area to current models. Most prevalent and trustworthy in this sector are the frequency ratio (FR) and Shannon's entropy (SE) models (Jaafari et al., 2014; Sahana and Patel, 2019). The model verification results, FR and SE, show that spatiotemporal modelling of the Wadi Thuwal flood is 89% successful and 99% dependable. Figure 18 shows how this prominent level of verification and reliability verifies Wadi Thuwal's spatiotemporal modelling.

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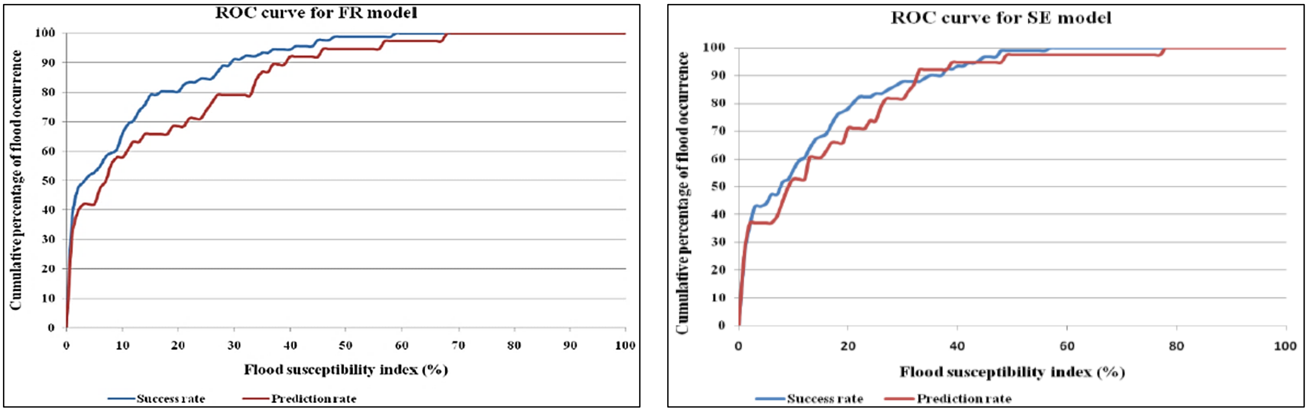
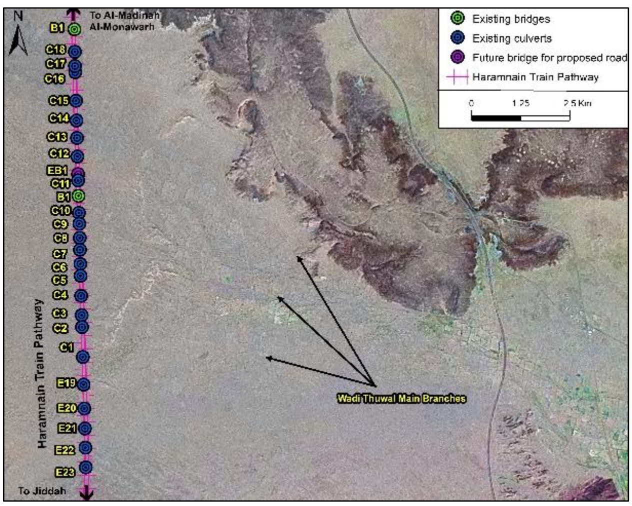


(A) (B)

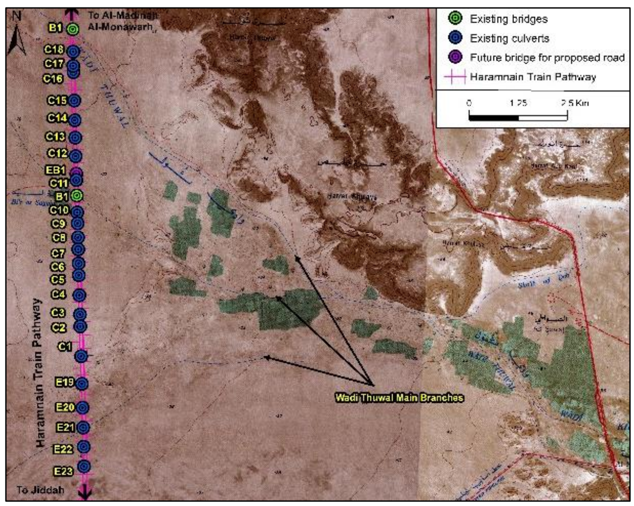
Figure 18. ROC curve for (a) FR model and (b) SE model, which validate the success and reliability of spatiotemporal flood modelling. The curves illustrate true positive rates against false positive rates, emphasizing the effectiveness of the models in predicting flood occurrences accurately.

One important scientific method used to check the accuracy of the projected time and space models of the Wadi Thuwal floods was to check the presence and condition of culverts and bridges below the Haramain Train Pathway. There are about 23 culverts and 2 bridges below train pathway. An important question arises: Why were these facilities constructed beneath the Haramain Train Pathway, specifically in the section traversing Wadi Thuwal? The topographic flatness and dispersed flows, as depicted in Figures 19, 20, and 21, obscure the path of Wadi Thuwal on topographic maps and satellite images in this area, particularly near the Haramain Train Pathway.



Source: Landsat 8/OLI satellite image - USGS

Figure 19. A recent satellite image of the study area provides a geographical context for the flood modelling study. It serves as a visual reference for assessing the terrain's influence on hydrological processes and flood dynamics as viewed from an aerial perspective.



Source: Topographic maps at 1:50,000 scale - General Authority for Survey

Figure 20. A topographic map of 1:50000 scale of the study area illustrates elevation variations across the Wadi Thuwal Basin and surrounding areas. The contours reveal the region's physical characteristics, essential for understanding how topography affects water flow and flood risks.

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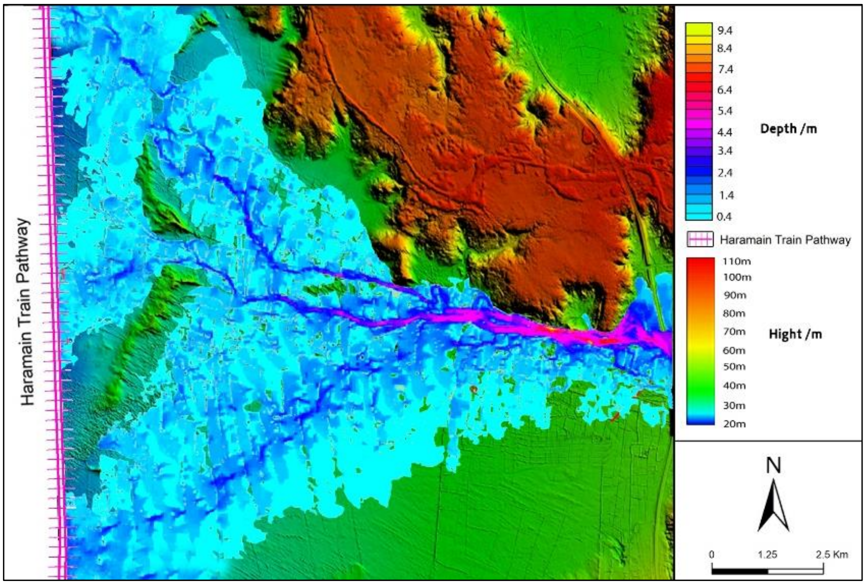
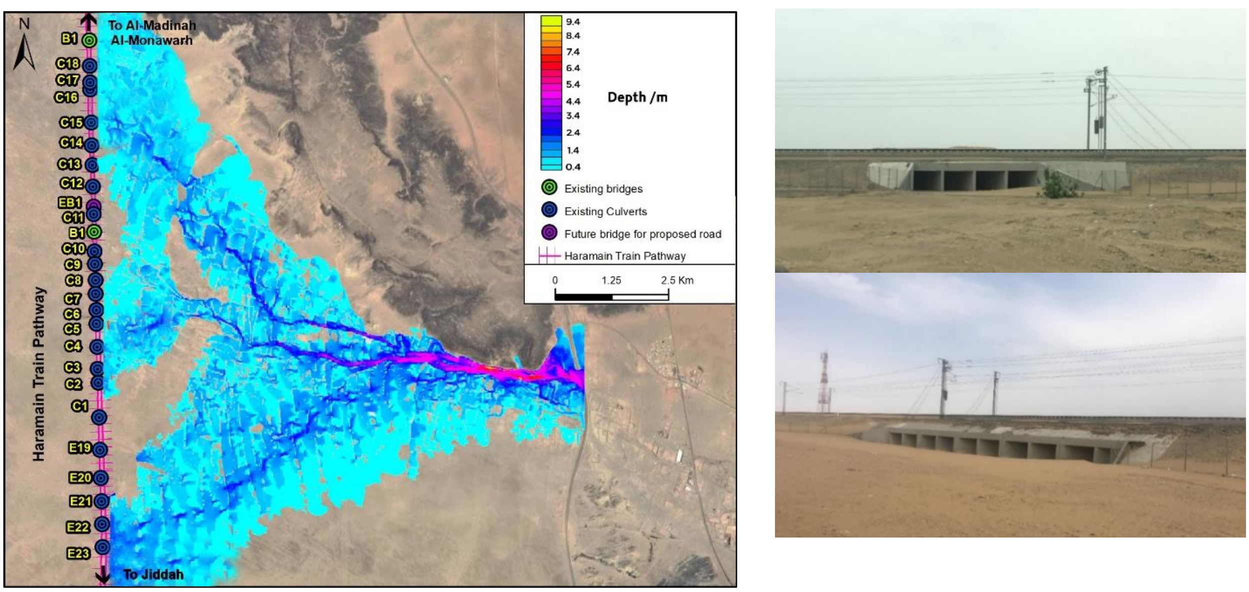


Source: (a) 2D hydraulic modelling using Hydrologic Engineering Centre-River Analysis System (HEC-RAS), (b) High-resolution LIDAR data, Ministry of Municipal and Rural Affairs and Housing.

Figure 21. 2D spatiotemporal modelling derived from LiDAR with a resolution of 50 cm and indicating the spread of flood waters to three main branches in front of Haramain Train Pathway. This spatiotemporal analysis provides critical insights into flood dynamics, allowing for better infrastructure planning and risk assessment.

Thus, detailed field research and hydraulic analysis of the facilities underneath the Haramain Train Pathway support their construction. Figures 22 and 23 and Tables 4 and 5 show that all these culverts and bridges can pass flow. Before building the Haramain Train Pathway, these hydraulic installations were planned, and their existing geographical distribution validated the HEC-RAS program's two-dimensional spatiotemporal modelling for Wadi Thuwal floods.



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Source: (a) 2D hydraulic modelling using Hydrologic Engineering Centre-River Analysis System (HEC-RAS), (b) Jeddah Municipality and Visit the study area

Figure 22. Verification of the existing hydraulic installations and two-dimensional hydraulic modelling verifying their capacity to handle expected peak flows. This assessment confirms the effectiveness of the hydraulic installations in managing floodwaters.

Figure 23. Examples of the installations to prevent the risks of the existing floods provides insights into engineering approaches taken to protect infrastructure from flooding events, illustrating the practical application of hydraulic modelling results.

Table 4. Characteristics and hydraulic analysis of the existing bridges

Bridge name	Maximum flow (m^3/s)	free clearance	number of slots	Slot width (m)	Slot height (m)
EB1	A bridge to a future road that does not pass any flow				
B1	1155.2	4.23	7	26.1	6.20
B2	1155.2	2.3	10	26.1	4.50

Table 5. Characteristics and hydraulic analysis of the existing culverts

No.	Type	No of slots	Slot width (m)	Slot height (m)	Flow velocity at the exit of the culvert (m/sec)	Water height at culvert entrance (m)	Maximum flow (m^3/s)
C1		2	2	2	3.62	1.8	4.9
C2		2	2	2	3.2	1.8	5.0
C3		1	1.5	1.5	3.2	1.8	5.0
C4		1	1.5	1.5	3.36	1.8	6.3
C5		1	1.5	1.5	3.71	1.8	6.5
C6		1	1.5	1.5	3.66	2.4	37.5
C7		1	1.5	1.5	4.71	2.4	50
C8		1	1.5	1.5	3.73	2.4	50
C9		1	1.5	1.5	3.69	2.4	77
C10		1	1.5	1.5	3.69	2.4	77
C11		1	1.5	1.5	3.75	2.4	60
C12	Box	3	2	2	3.71	2.4	52
C13		3	2	2	3.71	2.4	52
C14		1	1.5	1.5	3.70	2.4	51.5
C15		2	2	2	3.71	2.4	52
C16		1	1.5	1.5	3.71	2.4	78
C17		1	1.5	1.5	3.69	2.4	77
C18		1	1.5	1.5	3.69	2.4	77
E19		3	2	2	3.65	2.4	52
E20		3	2	2	3.60	2.4	52
E21		3	2	2	3.72	2.4	52
E22		3	2	2	3.73	2.4	52
E23		1	1.5	1.5	3.70	2.4	77

The assessment of the facilities to prevent the risks of torrential rains below the Haramain Train Pathway confirmed their capacity to pass the peak flows of Wadi Thuwal Basin. These culverts and bridges can pass the flow and transfer it from the east to the west under the Train Pathway in complete safety without having negative impacts on the Train Pathway, which is confirmed by modelling. However, it should be noted that there are risks resulting from the encroachment of sand and sediments carried by the valley towards the existing facilities, as many of these facilities were affected by sand burial, in addition to the presence of some environmental problems.

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4 Discussion

Mapping and assessing flood exposure is essential for determining adequate protection measures to ensure the safety of the area or infrastructure (Ata et al., 2023; Madi et al., 2023). Flood risk maps are used for various purposes, such as visualizing risk assessments, developing flood risk management strategies including spatial planning, and prioritizing required measures (De Bruijn and Klijn, 2009). These maps are also used for insurance purposes (de Moel et al., 2009) and have been developed based on hydrodynamic models that simulate the flood characteristics of potential flood events. Hydrodynamic models are widely used for this reason. The main objective of this study is to build, develop, assess, and analyse a spatiotemporal two-dimensional simulation of the Thul Valley flood affecting the route of the Haramain Train, where predicting, simulating, and assessing flood maps is critical due to rapid changes in processes primarily arising from climate change, urban expansion, and human interventions (Koks et al., 2019).

In this study, the hydrological model with an engineering system (HEC-HMS) was used. The chosen and applied hydrological model (HEC-HMS) in this study is one of the hydrological models that meet local and global standards and has been widely used in various studies (Bajwa and Tim, 2002; Halwatura and Najim, 2013). The program is used for all hydrological calculations, where the HEC-HMS model has achieved widespread acceptance in deriving the unit hydrograph for unmeasured basins in arid regions (Abdelkarim et al., 2019b, 2020). The Runoff Curve Number method was used, which is employed to estimate surface runoff, determine peak flow rates for flash floods, and calculate the flood hydrograph after subtracting various loss values from the rainfall falling on the catchment area according to soil characteristics, land use activities, and land uses. These losses are expressed by a coefficient known as the Curve Number. This method is commonly used in arid and semi-arid areas (Abdulrazzak et al., 2019; Elsebaie et al., 2023; Khan et al., 2022).

Rainfall station analysis for various return periods was relied upon, covering the study area with eight meteorological stations. This study also relied on the Climate Change Projections Report for the year 2050 in Saudi Arabia, which presented seven climatic models, relying on the scenario (RCP 8.5), which gives the highest rate of change in the expected rainfall value in 2050, reaching 19% of the anticipated rainfall rate. The impact of this percentage was calculated on the 100-year return storm, where the annual average for this scenario was 112 mm. Hydrodynamic modelling, represented in this study by the models (HEC-RAS & HEC-HMS), is among the most used models for this purpose, attracting researchers' interest due to its simplicity, flexibility, and ability to integrate spatiotemporal dimensions according to numerous studies (Birendra Pandit et al., 2023; Namara et al., 2022; Ongdas et al., 2020; Yu and Zhang, 2023). It is applicable in various topics such as flood prediction, simulation, and assessing changes. The integration of remote sensing (RS) and Geographic Information Systems (GIS) with these models has significantly contributed to faster and increased data processing, as well as critical monitoring and evaluation of results. Two-dimensional hydraulic models (2D) were used to calculate flows, their paths, and their impacts on infrastructure represented by the Haramain Train route, as one-dimensional models (1D) are insufficient for simulating the flow, depths, or resultant velocities. Two-dimensional modelling is easier and more widely used with increasing computational capacity, the quality of data based on geographic information systems, and the availability of digital information with elevation data.

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Therefore, two-dimensional modelling is considered a solution for evaluating flood problems concerning infrastructure. In this phase, the well-known two-dimensional modelling software HEC-RAS (2D) was utilized.

The studies confirm that flood risk assessment in urban areas and infrastructure cannot be addressed by traditional methods, which cannot build a spatiotemporal two-dimensional model for the movement, depth, and speed of floodwaters. Most studies affirm that using appropriate models to perform spatiotemporal two-dimensional modelling helps develop appropriate strategies for mitigating flood risks (Farooq et al., 2019; Mignot et al., 2006; Tamiru and Dinka, 2021). Urban flood modelling (two-dimensional) in the literature poses a challenge due to the complexity of the area, the accuracy of the digital elevation models used, the lack of land use maps, the scarcity of rainfall data and blockage effects, and the presence of obstacles and interaction between buildings and surface flow (Hunter et al., 2008; Mignot et al., 2006).

In general, one of the main limitations of this study and the approach used is that flood prediction and management in most basins in arid and semi-arid areas, or unmeasured ones, require a significant degree of flexibility in using hydrological and hydraulic models. Most dry valleys in Saudi Arabia, including Wadi Thul, lack hydrometric stations to measure surface flow, resulting in most of these valleys being unmeasured. This necessitates the use of hydrological and hydraulic models when determining the flood hydrograph and inferring inundation ranges. The hydrological model (HEC-HMS) and hydraulic model (HEC-RAS) used in this study, like other hydrodynamic models, require the provision of various data sources, primarily accurate digital elevation models. The research relied on LiDAR technology, which facilitated and improved applications used for floods, and it is one of the preferred techniques for deriving DEM despite its high cost. Other limitations include the inability to determine the path and boundaries of Wadi Thul near the Haramain Train route on topographic maps, aerial photos, digital elevation models, and the difficulty of knowing the depth, speed, and spread of the flood in Wadi Thul using a one-dimensional (1D) model, which necessitates the construction of a two-dimensional (2D) modelling approach and enhances the chances of using this approach applied in this study in other areas.

Notably, the current study distinguishes itself by providing a robust approach for identifying, monitoring, simulating, modelling, and assessing the floods in the Thul Valley catchment and their impact on one of the strategic projects between the two holy cities of Mecca and Medina, the Haramain Train project, using an integrated approach combining remote sensing (RS) represented by satellite imagery, LiDAR data, spatial analyses, and integrating it with hydrodynamic modelling approaches for the models (HEC-RAS & HEC-HMS). To the authors' knowledge and the reference census, this is the first study to use this approach to assess flood risks to infrastructure in Saudi Arabia. The hydrodynamic modelling approach for simulating, modelling, and assessing flood risks to infrastructure is among the most used and reliable, and these models can be classified into one-dimensional (1D), two-dimensional (2D), and one-dimensional river flow models coupled with two-dimensional floodplain flow models. Moreover, the integrated approach of remote sensing (RS) combined with the hydrodynamic modelling approaches for the models (HEC-RAS & HEC-HMS) provides an easy environment for understanding complex issues, which can be utilized by officials and authorities in developing countries to reduce time and cost (Peker et al., 2024), handle large amounts of complex geographic data, and connect them (Dimri et al., 2023; Xafoulis et al., 2023), serving as an effective tool for detecting changes that can provide a better understanding of accurate and realistic outcomes for planners and decision-makers through graphical representation (Yusuf et al., 2023).

The proposed methodology in this study offers policymakers and planners an opportunity to formulate developmental plans and policies concerning flood risk maps for infrastructure, and that these models are applicable in similar geographical environments. This helps in mapping mitigation and integrated management of infrastructure, as the correct understanding of current climate changes and rainfall scenarios in arid and semi-arid environments, and their connection to flood risks is crucial for mitigating environmental, planning, social, and economic issues that challenge sustainability and community development. The approach used in this study can also serve as a model for assessing and monitoring flood risk maps for other areas with similar environmental and geographical conditions.

5 Conclusions

The infrastructure in the Kingdom of Saudi Arabia has witnessed rapid development, through extensive government spending and allocation of a large part of the budget of the Ministry of Transport for infrastructure. Whereas the Saudi government has allocated $7 billion to construct railway projects and provide safe, efficient, and sustainable railways until 2040, however, the exposure of road and railway tracks to frequent flooding and the poor distribution of facilities under these tracks, constituted a particularly important concern for both the Ministry of Transport and Ministry of Municipal and Rural Affairs and housing. Therefore, the study of spatiotemporal modelling, simulation, and evaluation of flood risks in the Kingdom has become of significant importance in the past years, especially with the climate changes in the region, the change in land uses, and the expansion of urban and infrastructure projects.

This current study dealt with monitoring, simulation, modelling and evaluation of the torrents of Wadi Thuwal Basin, and evaluating their impact on one of the strategic projects between the two holy cities of Makkah and Al-Madinah, which is the Haramain Train Pathway project, using the integration approach between remote sensing (RS) which is represented in satellite images, the use of LiDAR data, and spatial analysis, and its integration with the hydrodynamic modelling approach of both (HEC-RAS and HEC-HMS) models. The study examined whether building spatiotemporal models in the study area is applicable and can help in an integrated mitigation and management map. The correct understanding of current climate changes and rainfall scenarios in arid and semi-arid environments and linking them to flood risks is critical to mitigating environmental, planning, social and economic issues that challenge sustainability and community development. The assessment of the flood risks of railways in the Kingdom of Saudi Arabia, especially in the area between the two holy cities of Makkah and Al-Madinah, is of great importance to the political and planning decision-maker. This comes from the location of the two holy cities, which throughout the year witness the turnout of millions of Muslims from all parts of the world for Hajj, and Umrah, which is in line with the National Transformation Program and the Kingdom's vision, as the Kingdom targets 6 million pilgrims and 30 million Umrah pilgrims by 2030, and this is of great importance to this study.

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The results of the spatiotemporal modelling of Wadi Thuwal flood based on the hydrodynamic modelling approach and its integration with remote sensing (RS) and geographic information systems (GIS) revealed that Haramain Train Pathway in the part facing the valley is completely safe from flood risks, through the construction of 23 culverts and 2 bridges under Haramain Train Pathway. These facilities helped pass the entire flows of Wadi Thuwal Basin of 3120.23 m^3/s within 100 years, and its geographical distribution is fair, appropriate and in line with the flood plain produced through hydrodynamic modelling, which clearly confirms what the Kingdom Saudi Arabia, represented by SAR Company and the Ministry of Transport, has done in well planning Haramain Train Pathway despite the rugged topography and complex ecology of this region.

Based on the study's recommendations, four key points stand out: The primary recommendation addresses the issue of unauthorized farms established along both sides of the Haramain Train Pathway. These farms, often built on natural drainage paths, disrupt the natural flow of rainwater. Farmers divert floodwater away from valleys and towards their fields for irrigation. This diversion redirects torrential waters away from the flood drainage culverts constructed beneath the Haramain Train Pathway along these natural courses. This practice could compromise the safety of the railway during operation. Therefore, the recommendation advocates enforcing stricter penalties for these unauthorized farms and allowing a reasonable timeframe for existing farms to relocate. The second recommendation pertains the unauthorized quarry and borrow pit operations situated along both sides of the Haramain Train Pathway. These activities, frequently conducted by contractors without permits, are often located within natural valley streams flanking the railway tracks. This unauthorized excavation disrupts established floodwater flow patterns within these valleys. As a result, floodwaters are diverted away from the designated inflow and outflow points of the drainage culverts constructed beneath the Haramain Train Pathway. This disruption poses a safety hazard to the railway during periods of heavy rain. To mitigate this risk, it is recommended to enhance monitoring effort by the Saudi Arabian Railway Company (SAR) to identify and deter unauthorized operations, and to implement strict penalties to serve as a deterrent. The third recommendation relates to the blockage of most of the existing facilities represented by culverts and bridges under Haramain Train Pathway, through the encroachment of sand in some places or the transfer of sand and stone deposits transported by torrential water through the valleys. This requires maintenance and cleaning of these facilities by the Ministry of Transport and the Ministry of Municipal and Rural Affairs and Housing regularly. The final recommendation focuses on adopting the approach of integrating remote sensing and geographic information systems with hydrodynamic modelling represented by the (HEC-HMS) hierological model and the (HEC-RAS) hydraulic model. This powerful combination would enable the creation of detailed flood water hydrographs, including two-dimensional spatiotemporal modelling of floodwater velocity, depth, and spread over time. This information would be particularly valuable for assessing flood risk in critical areas, especially for critical areas along the Haramain Train Pathway where floodplains are absent, or the terrain is flat.

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Competing interests: The authors declare that they have no conflict of interest.

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