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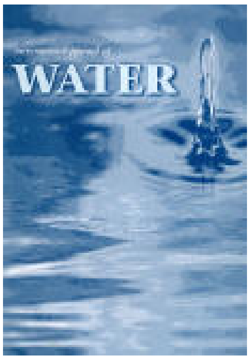

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Understanding and mitigating extreme rainfall events in Jeddah: a comprehensive analysis of the November 24, 2022, flash flood and historical trends

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Understanding and mitigating extreme rainfall events in Jeddah: a comprehensive analysis of the November 24, 2022, flash flood and historical trends

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Abstract: In November 2022, Jeddah, Saudi Arabia, faced a severe flash flood due to heavy rainfall. This research analyses the event, employing the Soil Conservation Service Curve Number (SCS-CN) model for runoff estimation and reviewing rainfall records from 1966 to 2022. Our findings reveal varied rainfall intensity across Jeddah, with the south and southeast experiencing the heaviest downpours. Historical analysis indicates a rising trend in daily maximum precipitation, suggesting an increasing flood risk. The study underscores the urgent need for enhanced early warning systems, drainage improvements, and strategic urban planning to mitigate future flood impacts. These insights are crucial for developing resilient infrastructures and adaptive strategies, contributing significantly to the city's preparedness for extreme weather events.

Keywords: Jeddah; runoff; Saudi Arabia; flash flood; runoff model.

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Biographical notes: Raied Saad Alharbi, PhD, is an Assistant Professor of Hydrology and Water Resources at King Saud University, specialising in remote sensing and GIS-based watershed modelling. Holding a PhD from the University of California, Irvine, he has a strong academic and research background, contributing significantly to water resources literature. His career spans from teaching assistant to UNDP expert, underpinning his vast experience in hydrology and water management. He leads important technical committees, further establishing his expertise and leadership in the field.

1 Introduction

In recent decades, there has been a noticeable increase in the severity and economic consequences of flood occurrences, making them extremely destructive and onerous natural catastrophes. These events are significant because of their enormous influence on property, infrastructure, and, most importantly, human lives (Dano, 2020). Floods are responsible for around 34% of all deaths caused by natural catastrophes, according to statistics. An extensive examination of natural catastrophe events from 1995 to 2015 reveals that floods accounted for 43% of all recorded incidences, causing harm to 2.3 billion people worldwide (Balogun et al., 2020). The occurrence of these disasters has caused significant economic damage, amounting to an estimated USD 662 billion, and has led to the unfortunate loss of 157,000 lives (Hussain et al., 2021).

When considering the future, forecasts indicate a worrisome pattern. It is projected that by 2050, the number of people vulnerable to flood occurrences would increase dramatically to 2 billion (Elsebaie et al., 2023). The heightened vulnerability may be ascribed to a combination of reasons, such as the consequences of climate change, rapid population expansion in flood-prone regions, widespread deforestation, the deterioration of wetlands, and the continuous rising in sea levels (Winsemius et al., 2018). The complex nature of this problem highlights the need for comprehensive approaches in disaster management, urban development, and climate mitigation to effectively tackle the increasing threat of worldwide flood occurrences.

Saudi Arabia, a country often linked to dry desert terrains, has regular occurrences of flooding in different areas on a yearly basis (Saud, 2010). The country's three main urban centres, Jeddah and Dammam, located on the coast, and Riyadh, surrounded by valleys, are especially prone to regular occurrences of flooding (Dano, 2020). The susceptibility to flooding, particularly in the form of sudden floods, is ascribed to a blend of geographical and topographical elements, in addition to both natural and human forces (Hussain Shah et al., 2023).

The combination of low elevation in some regions, together with the existence of mountains and inadequately sloping terrains, greatly enhances the likelihood of flash floods (Zaigham et al., 2021). These floods occur when heavy rainfall exceeds the ability of the local drainage basins to absorb the water. The outcome is a swift and substantial release of water, which forcefully flows into the nearby surroundings, often without prior notice (Dano et al., 2023). This situation highlights the need for improved flood control and urban development policies in Saudi Arabia, namely in its major cities, to reduce the effects of these natural calamities.

Over the past decade, Jeddah has faced recurrent flash flood events, resulting in tragic human losses and severe infrastructure damage (Youssef et al., 2016a). Due to its geographical location, Jeddah has witnessed similar incidents in its history, with notable occurrences in 2009 and 2011 (Tammar et al., 2020). On November 25, 2009, the city endured a deluge of 90 mm of rainfall, tragically claiming the lives of more than 161 individuals (Ameur, 2016). A similar event unfolded on January 26, 2011, when 111 mm of rain fell, resulting in more than ten fatalities and anticipated economic losses exceeding USD 2 billion (Abbot and Hammond, 2019; Tammar et al., 2020).

In response to these recurring challenges, numerous flash flood mitigation initiatives were launched, including the Jeddah Stormwater Drainage Projects (JSDPs), following the disastrous events of November 2009 (Atif et al., 2020). These initiatives involved the construction of water storage dams and stormwater drainage systems. However, it remains clear that an extreme precipitation event has the potential to overwhelm the urban drainage system, leading to flash flooding, as vividly demonstrated by the events of November 24, 2022 (Vorobevskii et al., 2020).

Jeddah, being a susceptible city prone to frequent flash flood dangers, has undergone more extensive research compared to other cities in Saudi Arabia. (Haggag and El-Badry, 2013) conducted a simulation of the intense rainfall that led to the flash floods in Jeddah in 2009. (Youssef et al., 2016) used statistical techniques to evaluate the vulnerability of Jeddah city to flash floods by considering variables such as precipitation, soil type, geological characteristics, slope, drainage, elevation, and proximity to streams. The study by Tekeli (2017) compared three methods of predicting floods in Jeddah using data from a satellite. They looked at Constant Threshold, Cumulative Distribution Functions, and Jeddah Flood Index to see which was best at forecasting floods. The study by Saud (2010) assesses flood risks in the Jeddah area of Saudi Arabia. It identifies flood-prone zones and the factors affecting them, using high-resolution images from the IKONOS satellite. Elfeki and Bahrawi (2017) developed an efficient methodology using random walk theory to map out areas likely to be inundated by floods. They applied this method to the flood that occurred in Jeddah city in November 2009, using a simplified model of the city. For additional studies can be found (Youssef et al., 2014, 2015, 2016a, 2016b; Daoudi and Niang, 2019; Abu Abdullah et al., 2019; Nidhi et al., 2017; Ghanim et al., 2023; Azeez et al., 2020; Bashir, 2023).

On November 24, 2022, the city of Jeddah experienced a catastrophic flooding event that resulted in significant human and economic losses. This fateful day, characterised by relentless heavy rainfall that persisted for several hours, unleashed a devastating flash flood, claiming the lives of two individuals and causing extensive damage to property and infrastructure (Saudi Arabia – Severe Floods Hit Jeddah After 179mm of Rain in 6 Hours – FloodList, n.d.). It is crucial to note that Jeddah, situated in the western region of Saudi Arabia, rests upon the escarpment of several Wadis within the Al Hejaz Mountains, rendering it susceptible to flash flooding. Unlike areas with perennial rivers and streams, Jeddah relies on a limited system of stormwater drainage channels to manage rainwater (Atif et al., 2020).

To address these critical issues and foster the sustainable development of infrastructure capable of mitigating such anomalies, comprehensive studies of extreme events are imperative. Such studies must encompass an in-depth analysis of the temporal and spatial distribution of precipitation and runoff. This study represents a significant advancement in the field, setting itself apart from previous research by serving as a comprehensive reference for both scholarly inquiry and urban planning, rather than merely reconstructing past flooding incidents. It conducts a thorough investigation of spatial and temporal rainfall measurements related to the extraordinary rainfall event that occurred on November 24, 2022. This work not only forecasts flood rates for this particular incident but also imparts a distinctive insight into the rainfall dynamics in the Jeddah region. By comparing recent rainfall data with historical patterns, this study enhances understanding of evolving meteorological trends and their influence on flood risks in Jeddah. This approach marks a critical progression in hydrological research and urban planning, particularly within the context of changing climatic conditions. This research endeavours to achieve the following objectives.

- This paper's primary objective is to assess both the spatial and temporal patterns of precipitation during the extreme event of November 24, 2022, in Jeddah.
- Quantify the runoff generated because of this extreme precipitation event by employing the soil conservation service curve number (SCS-CN) model.
- Explore historical records of extreme rainfall events in Jeddah from 1966 to 2022, seeking any discernible trends in extreme precipitation patterns.

2 Data and methods

2.1 Study area

Jeddah, located along the Red Sea coastline in Saudi Arabia, occupies a geographical expanse between latitudes 20° 50′ N – 22° 20′ N and longitudes 39° 00′ E – 39° 40′ E. Nestled within a coastal plain, the city finds itself flanked by the imposing Al Hejaz Mountain ranges to the east and the expansive Red Sea to the west. Jeddah stands as the second-largest city in Saudi Arabia, and its vast urban footprint extends across approximately 1765 square kilometres.

The topography and location of the Jeddah region are visually represented in Figure 1. According to (Saud, 2010), the area east of Jeddah is home to 24 smaller Wadis, dry channels that occasionally channel water into the city. Despite its arid climate, Jeddah's weather is significantly influenced by the proximity of the Red Sea and the rugged terrain of the Al Hejaz mountains. Seasonal temperatures in Jeddah range from 28.2°C to 32.4°C during the summer and 20°C to 24.2°C in the winter, resulting in a mean annual temperature of 28.7°C (Almazroui, 2011a).

Annual rainfall in the Jeddah region is typically limited, fluctuating between 50–100 mm, with most of the precipitation occurring during the winter months (Almazroui, 2011b).

2.2 Data sources and analyses

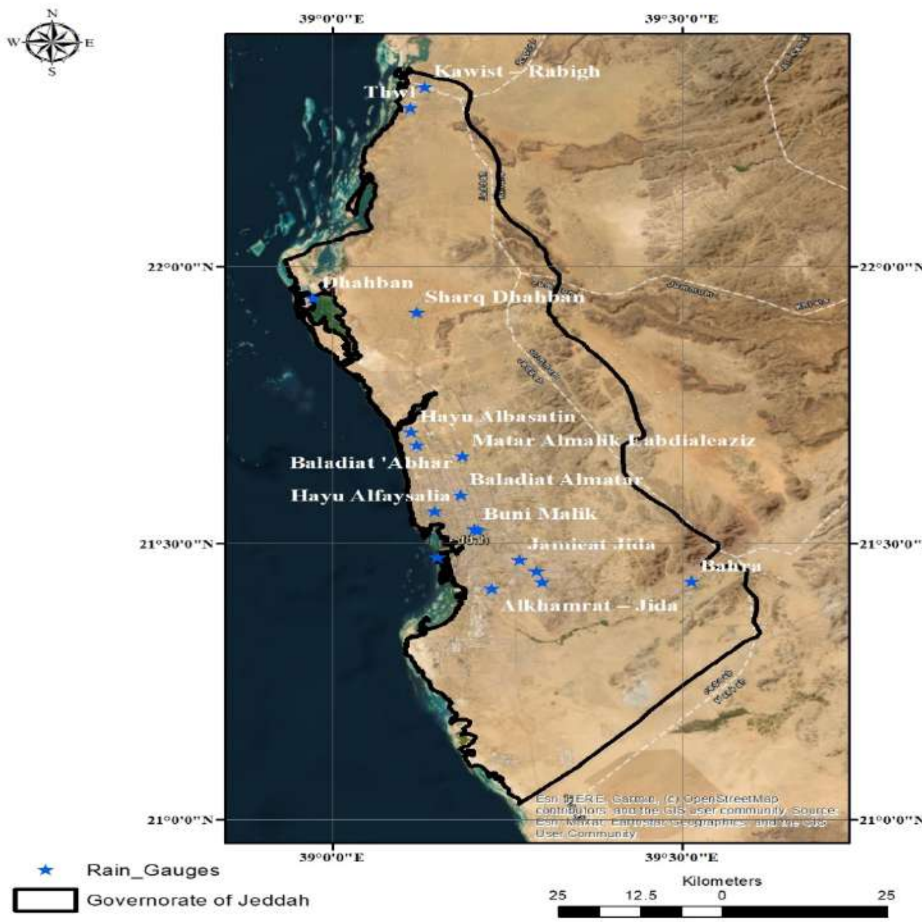
2.2.1 Ground-based precipitation dataset

In this investigation, the Ministry of Environment, Water, and Agriculture of Saudi Arabia graciously provided the primary source of daily and sub-daily rainfall data spanning the Jeddah Region.

2.2.2 PERSIANN-Dynamic infrared rain rate near real-time (PDIR-Now)

A high-resolution global precipitation product known as Persiann-dynamic infrared rain rate near real-time (PDIR-Now), developed by the Center for Hydrometeorology and Remote Sensing (CHRS) (Nguyen et al., 2020), plays a pivotal role in this study. Distinguished by its remarkable spatial resolution of 0.04° by 0.04°, PDIR-Now offers unparalleled advantages for monitoring precipitation events worldwide. One of its standout attributes is its minimal latency, ranging from a mere 15–60 min from the moment of rainfall incidence. To rectify errors and uncertainties stemming from infrared data usage, PDIR-Now employs dynamic shifts in (Tb-R) curves informed by rainfall climatology. This swift dataset proves particularly invaluable for near-real-time hydrological applications, notably flood forecasting. The daily and sub-daily rainfall data used in this study were sourced from https://chrsdata.eng.uci.edu/ and retrieved as of November 26, 2022.

Figure 1 The location of stations and the amount of rainfall that was measured over Jeddah governorate on November 24, 2022 (see online version for colours)

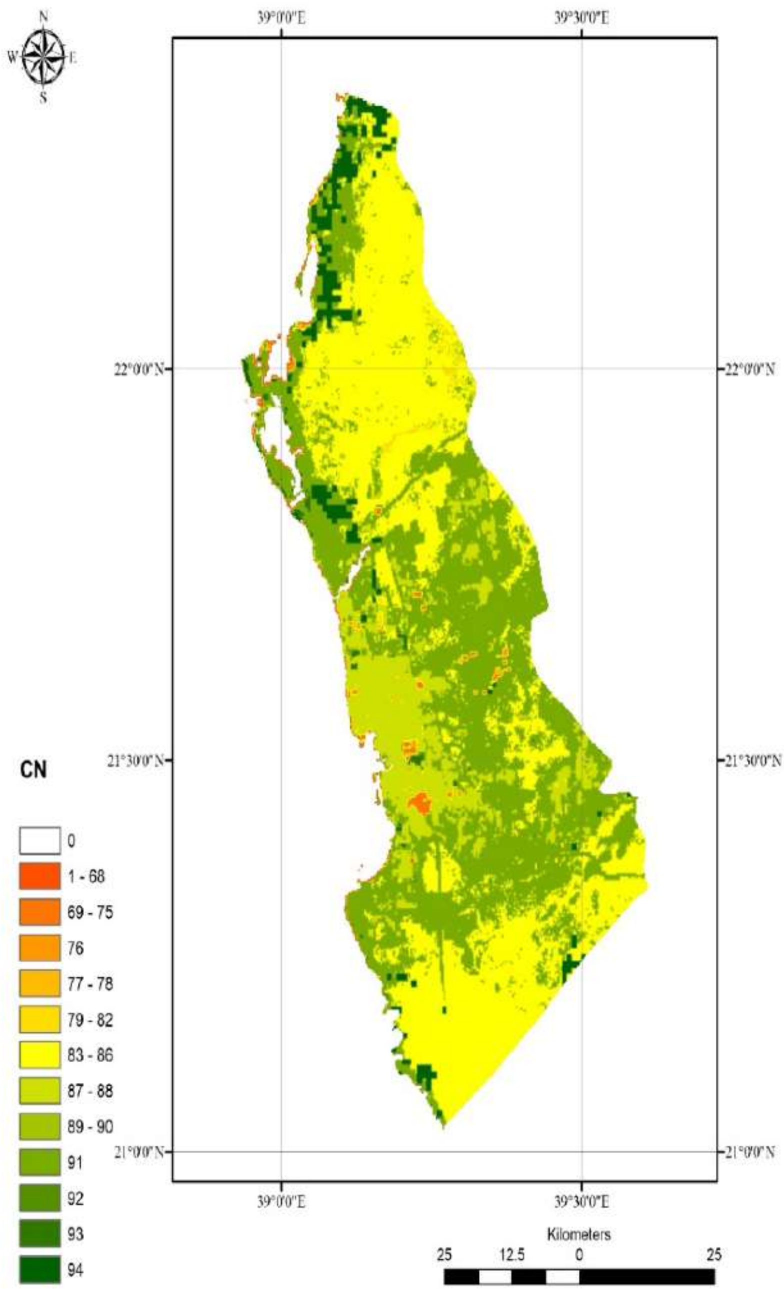


2.3 Global curve number (GCN) data

The global curve number (GCN) is an indispensable parameter in hydrological modelling, used to estimate runoff from precipitation events (Sishah, 2021). The initiative to create a gridded representation of GCN on a global scale was led by Jaafar et al. (2019), who meticulously compiled the dataset. This dataset was constructed utilising the 2015 ESA Land Cover Map combined with Hydrological Soil Group Data, applying the established USDA Curve Number methodology.

This comprehensive GCN dataset is characterised by a spatial resolution of 250 metres and accommodates different hydrological conditions, categorised into wet, dry, and average moisture scenarios. Such detailed resolution enhances the accuracy of runoff estimations across diverse terrain.

Figure 2 Spatial resolution of global curve number (GCN) data adapted for hydrological modelling (see online version for colours)



For the purposes of the current study, the relevant GCN dataset was procured at the specified spatial resolution from Figshare (https://figshare.com/). The dataset was then carefully calibrated to correspond with the geographical boundaries of the Jeddah Governorate, ensuring a precise overlay for the study's regional focus as shown in Figure 2.

The integration of the 250-m resolution GCN data is pivotal for simulating the hydrological impact of rainfall within the Jeddah Governorate. The alignment of the data with the region's topographic specifics underpins the modelling accuracy, aiding in flood risk prediction and water resource management.

2.3.1 SCS-CN runoff simulation model

The SCS-CN model has held its esteemed status as a widely employed hydrological tool for the simulation of runoff processes. It has been favoured by researchers and practitioners alike, as evidenced by noteworthy studies conducted by Barker and Chandrakantha (2022) and Batvari and Nagamani (2021). This modelling framework, originating in 1970, is a product of the U.S. Department of Agriculture's National Resources Conservation Service (NRCS), showcasing its enduring relevance in the field of hydrology.

At its core, the SCS-CN model integrates crucial input data derived from remote sensing technologies, including land use and soil type. This inherent adaptability to contemporary datasets enhances its applicability in modern hydrological investigations.

Curve number (*CN*): A fundamental concept within the SCS-CN model is the curve number (CN). The curve number represents a dimensionless parameter that quantifies the influence of soil properties and land usage on runoff generation. A lower CN suggests greater infiltration and lower runoff potential, while a higher CN indicates reduced infiltration and higher runoff potential (Fan et al., 2013).

Model equation (1):

The central equation of the SCS-CN model is expressed as follows:

$$Q = \frac{P - 0.2 * I}{P + 0.8 * S} \tag{1}$$

$$S = \frac{25400}{CN} - 254 \tag{2}$$

- Q represents the direct runoff, which is the portion of rainfall that flows over the land surface.
- P represents the total rainfall.
- I signifies the initial abstraction, a parameter that accounts for losses during the initial stages of a rainfall event. These losses include infiltration into the soil, interception by vegetation, and the storage of water on the canopy.
- S denotes the maximum soil water retention potential, which is a key parameter for understanding the capacity of the soil to retain water.

Estimation of maximum soil water retention (equation (2)):

The maximum soil water retention potential (S) is calculated using the curve number (CN) and is given by equation (2). This equation provides insight into the soil's ability to retain water, with higher CN values indicating lower retention potential and vice versa.

The SCS-CN model's versatility, historical significance, and compatibility with modern datasets make it an invaluable tool for hydrologists seeking to understand and simulate runoff processes across diverse hydrological contexts. By quantifying the complex interplay between land use, soil properties, and precipitation, the SCS-CN model continues to contribute significantly to the field of hydrological modelling and watershed management.

3 Results and discussion

3.1 Rain gauges

3.1.1 The cumulative rainfall based on rain gauges

On the 24th of November 2022, amidst adverse meteorological conditions, the Jeddah Governorate was systematically monitored by an array of 17 strategically positioned rain gauge stations. These instruments were engaged in the precise quantification of precipitation levels, as evidenced by Figure 1 which delineates the geographical positioning of these monitoring stations.

Table 1 The cumulative rainfall in the Jeddah governorate on November 24, 2022

Name of rain gauge	*Rainfall depth* (mm)
Amanat Janub Jada	182
Bahra	167.4
Baladiat 'Umi Alsalam	159.8
Almabnaa Alrayiysiu – Hay Alwurud	141.2
Buni Malik	97.4
Matar Almalik Eabdialeaziz	86.8
Baladiat 'Abhar	85.2
Hayu Albasatin	82.4
Madinat Almalik Eabdallah Alriyadia	81.2
Dhahban	80.2
Alkhamrat – Jida	78.4
Jamieat Jida	58
Hayu Alfaysalia	47
Sharq Dhahban	45.4
Baladiat Almatar	41.8
Kawist – Rabigh	34.4
Thwl	30.4

The quantified precipitation data from each station is exhaustively enumerated in Table 1. Notably, the station located in the Municipality of South Jeddah registered the highest precipitation, measuring a significant 182 mm. In contrast, the station in Thuwal recorded the minimal precipitation value of 30.4 mm. This data evidences a pronounced heterogeneity in precipitation across the various locales within the Jeddah Governorate.

Specifically, the station at Amanat Janub Jada documented the apex of precipitation at 182 mm, closely followed by the Bahra station at 167.4 mm and the Baladiat ‘Umi Alsalam station at 159.8 mm. These localities experienced the zenith of rainfall, potentially implicating critical concerns for hydrological resource management, augmented flood risk, and infrastructural burden.

Conversely, the stations at Almabnaa Alrayiysiu - Hay Alwurud, Buni Malik, and Matar Almalik Eabdialeaziz recorded precipitation levels of 141.2 mm, 97.4 mm, and 86.8 mm respectively, indicating a moderate precipitation scenario. This suggests that while these areas were subjected to significant rainfall, it was quantitatively less severe compared to the aforementioned locales with the highest recordings.

Further, the stations at Thuwal, Kawist – Rabigh, and Baladiat Almatar reported minimal rainfall levels of 30.4 mm, 34.4 mm, and 41.8 mm respectively, as detailed in Table 1. This minimal precipitation may indicate a lesser impact from the meteorological event in terms of hydrological accumulation and potential flooding.

The observed variance in precipitation across the stations points to an asymmetric distribution of rainfall within the Jeddah Governorate. This disparity may be attributed to factors such as geographical localisation, topographical elevation, extent of urbanisation, and localised atmospheric conditions.

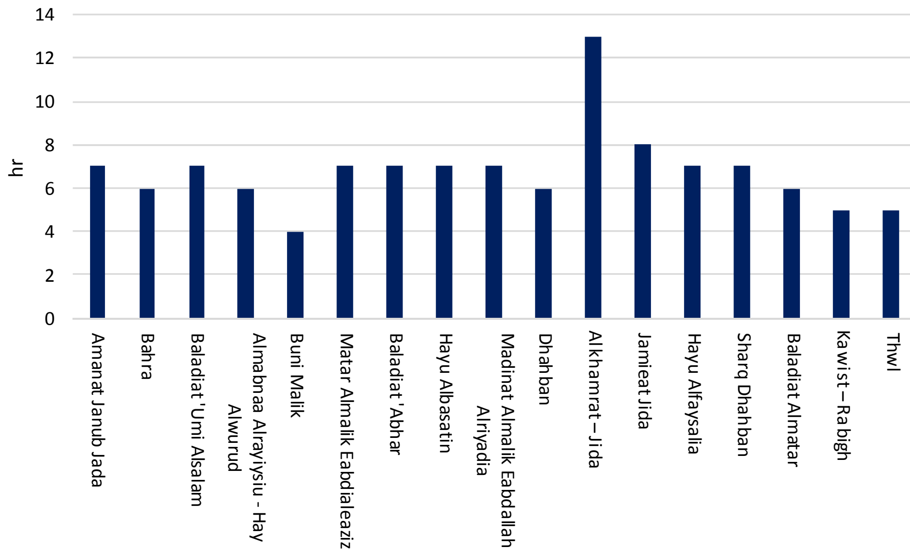
This dataset is of paramount importance for urban developmental planning, particularly in the design and implementation of effective drainage systems, flood mitigation strategies, and emergency response protocols. Specifically, areas like Amanat Janub Jada, which witnessed the highest rainfall, necessitate robust infrastructural adaptations to accommodate such intense hydrological events.

The accumulated rainfall data, as collected and presented from the rain gauges in the Jeddah Governorate on November 24, 2022, and as systematically tabulated in Table 1, underscores a varied and disparate distribution. This data is indispensable for a plethora of applications, encompassing urban developmental planning, disaster management, agricultural strategising, and environmental conservation endeavours. The diversity in precipitation levels across the different stations accentuates the need for tailored regional strategies to effectively mitigate and manage the ramifications of such meteorological phenomena.

3.1.2 Duration analysis of rainfall event using rain gauge data in Jeddah governorate

The duration of the rainfall event that occurred on November 24th has been analysed using data collected from a network of rain gauges distributed throughout the Jeddah Governorate. As demonstrated by Figure 3, an average duration of 6.7 h was calculated for the rainfall across the region. It should be noted, however, that significant variation in duration was observed between the different stations. Durations ranged from as little as 4 h at the Bani Malik station to as much as 13 h at the Al-Khumra station.

Figure 3 The duration of the event for each station (see online version for colours)



The spatial distribution of event duration is further detailed in Figure 4. A pronounced disparity is seen, with southern stations such as Al-Khumra, Dhahban, and Madinat Almalik Eabdallah Alriyadia experiencing longer rainfall durations ranging from 8 h to 13 h. This is in contrast to the central and northern stations, including Bani Malik and Hayu Alfaysalia, where rainfall events were recorded for shorter durations of 4–6 h. Such spatial patterns suggest that the southern portion of the governorate may have been in closer proximity to the storm system's core, leading to more prolonged precipitation events.

The risk of flooding is directly impacted by the duration of rainfall, as evidenced by the data. In areas like Al-Khumra, where longer durations were recorded, a higher risk of flooding is expected compared to regions with shorter rainfall events. Additionally, the timing of peak rainfall intensity within the event's duration is a critical determinant of the potential for flooding. A concentrated bout of intense rainfall, especially if it occurs early in a lengthy event, could significantly heighten flood risks.

A thorough comparison between the durations observed and those predicted by weather forecasting models is suggested to evaluate the accuracy of the models in reflecting the event's spatial variability. Furthermore, the influence of local factors, such as topography, the proximity to the Red Sea, and urban heat island effects on the duration of rainfall, ought to be examined to elucidate the observed patterns. The correlation of rainfall duration with other hydrological parameters, like intensity and ground moisture saturation, would also contribute to a fuller understanding of the event's impact.

This meticulous analysis, which incorporates both spatial and temporal data from rain gauges, offers critical insights into the complexities of the extreme rainfall event in the Jeddah Governorate. Such detailed information is fundamental to improving flood risk assessments, refining weather forecasting techniques, and formulating more effective mitigation strategies against the adverse effects of future extreme weather phenomena. The value of this analysis lies in its capacity to inform and guide the strategic decisions of those responsible for community safety and environmental management.

3.2 Spatial and temporal distribution of rainfall depth in Jeddah governorate

The comprehensive analysis of the extreme event on November 24, 2022, unveils a diverse spatial and temporal distribution of rainfall depth within the Jeddah Governorate. Rainfall depth measurements during this event ranged from 30 mm to 180 mm, reflecting the dynamic nature of the precipitation patterns observed as shown in Figure 5.

Northward Rainfall Depths: As depicted in Figure 4, the northern reaches of the Jeddah Governorate experienced rainfall depths predominantly estimated between 30 mm and 50 mm. These areas witnessed a comparatively milder impact from the extreme event, characterised by moderate to light rainfall.

In stark contrast, the southern and southeastern regions of the Jeddah Governorate bore the brunt of this extreme event, encountering notably heavier rainfall. Rainfall depths in these areas surged considerably, with measurements ranging from 70 mm to 180 mm as shown in Figure. 5. This concentrated intensity of rainfall underscored the localised nature of the event, wherein specific geographic pockets experienced substantially more substantial precipitation.

This spatial heterogeneity in rainfall depth distribution serves as a critical component of the extreme event's characterisation. Understanding these variations is pivotal for assessing flood risk, urban planning, and emergency response strategies. Further analysis of the temporal evolution of this rainfall pattern, in conjunction with geographical factors, can provide valuable insights into the dynamics of extreme precipitation events in the region.

A crucial facet of this meteorological narrative lies in the temporal evolution of rainfall intensity as seen in Figure 6. It is discerned that the intensity of precipitation was far from uniform throughout the event's duration. Rather, it exhibited a dynamic temporal rhythm. Remarkably, the zenith of rainfall intensity materialised between the hours of 10 and 11 in the morning. During this concise time frame, the heavens bestowed their most formidable deluge, signifying these 2 h as the epicentre of meteorological vigour.

Figure 4 The start and end times of the extreme event for each rain gauge (see online version for colours)

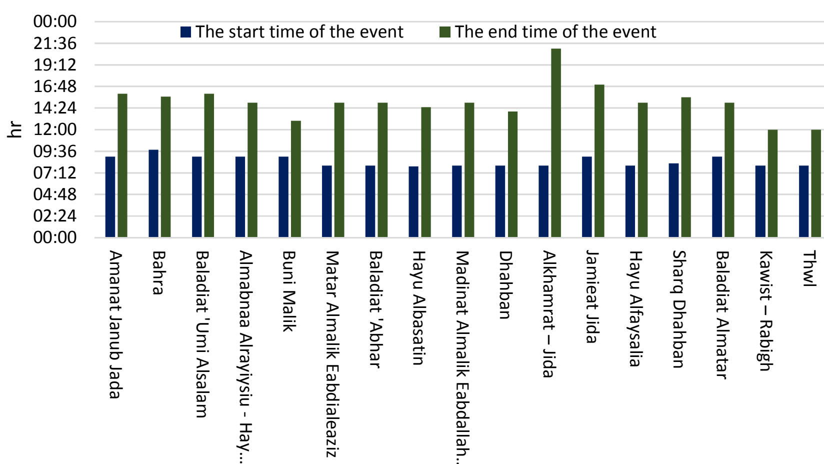
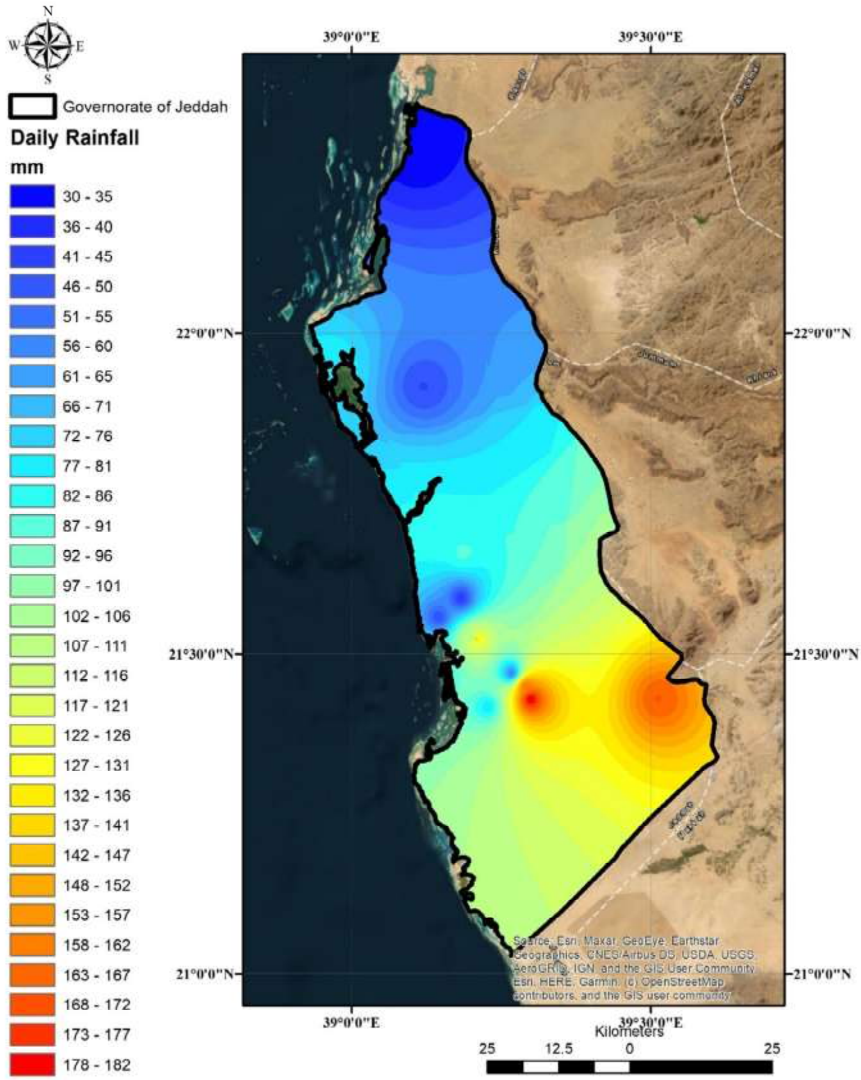
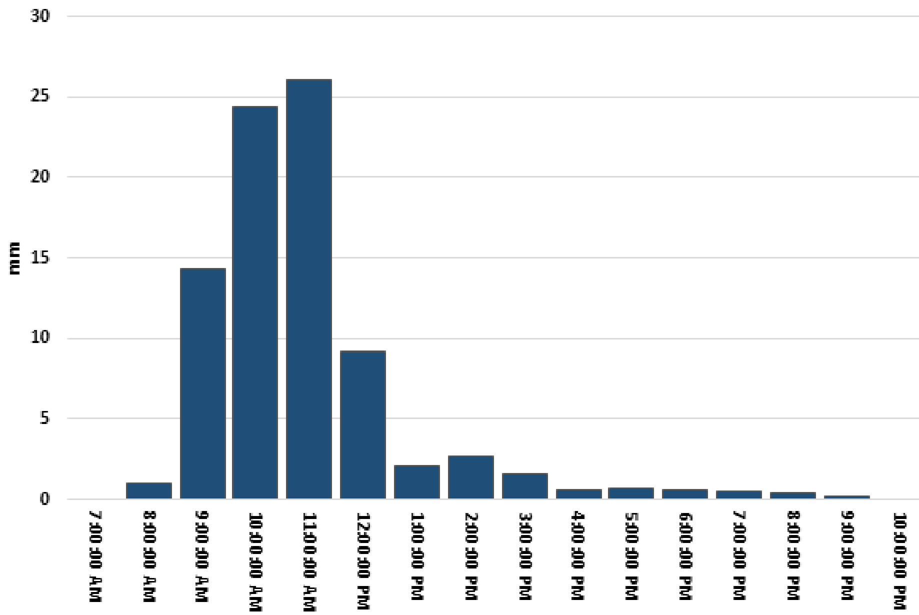


Figure 5 The spatial depth of rainfall (see online version for colours)



This comprehensive understanding of both spatial and temporal dimensions of rainfall intensity enhances our scientific grasp of the event's multifaceted nature. The precise identification of the temporal peak in rainfall intensity provides invaluable data for hydrological modelling, flood risk assessment, and emergency response planning. Moreover, the spatial variations underscore the potential influence of local geographic features on precipitation gradients. Further scientific inquiry into the interplay between precipitation patterns and geographical factors will contribute to enhanced flood mitigation strategies and improved resilience against extreme events in the Jeddah Governorate.

Figure 6 The average rainfall intensity during the extreme event over Jeddah governorate (see online version for colours)



3.3 Temporal distribution of precipitation depth: a satellite analysis

This section undertakes a meticulous analysis of the temporal distribution of precipitation depth, leveraging satellite imagery as delineated in Figure 7. This examination provides a critical spatiotemporal perspective on the extreme event that unfolded on November 24, 2022, within the Jeddah Governorate. It is imperative to elucidate this multifaceted narrative to advance our scientific understanding of the event's intricacies and its implications for hydrological modelling and flood risk assessment.

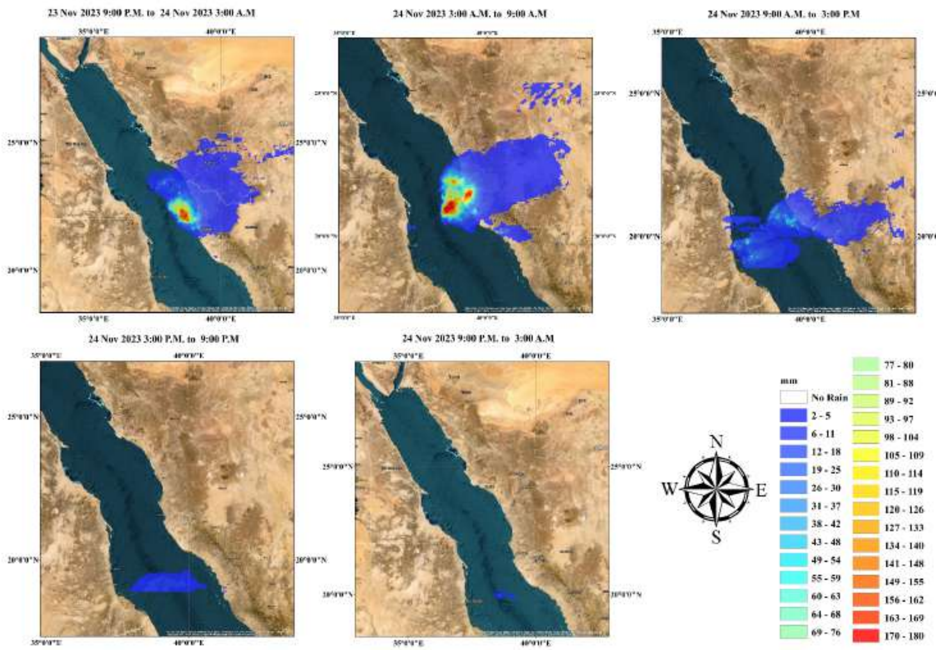
The extreme event began at an early hour, precisely at 3 o'clock in the morning. The event's origin may be traced back to the northwest of the Jeddah Governorate, namely in the Red Sea. The event gradually progressed and eventually came to an end at 3 o'clock in the evening. The time trajectory of this event is crucial for comprehending the spatial and temporal distribution of precipitation.

The map in Figure 7 has been instrumental in capturing the temporal evolution of precipitation depth during the event. This analysis offers a compelling visual representation of how precipitation unfolded over time. As we scrutinise this map, several key facets come to light:

The map's visual narrative reveals a clear progression of the event from its inception to culmination. It portrays the expansion of precipitation areas and the shifting patterns of intensity as the event unfolds.

The event exhibited a distinct directionality, emanating from the northwest of the Jeddah Governorate. Understanding this directional flow aids in tracing the origins of precipitation clusters and identifying regions more susceptible to heightened rainfall.

Figure 7 Temporal distribution of precipitation depth: a satellite analysis (see online version for colours)



By examining the map, we can discern temporal peaks in precipitation intensity. These peaks, which may coincide with specific geographic areas, offer critical insights into the event's dynamics.

The map also provides information on the duration of precipitation in different regions, allowing us to discern areas with prolonged rainfall and those experiencing more fleeting episodes.

This satellite-based temporal analysis not only enhances our scientific comprehension of extreme events but also underscores the potential for utilising remote sensing data for real-time monitoring and forecasting. By scrutinising the spatial and temporal dimensions of precipitation, we can uncover critical patterns that inform flood risk assessments, emergency response strategies, and urban planning considerations within the Jeddah Governorate and similar regions prone to extreme weather events.

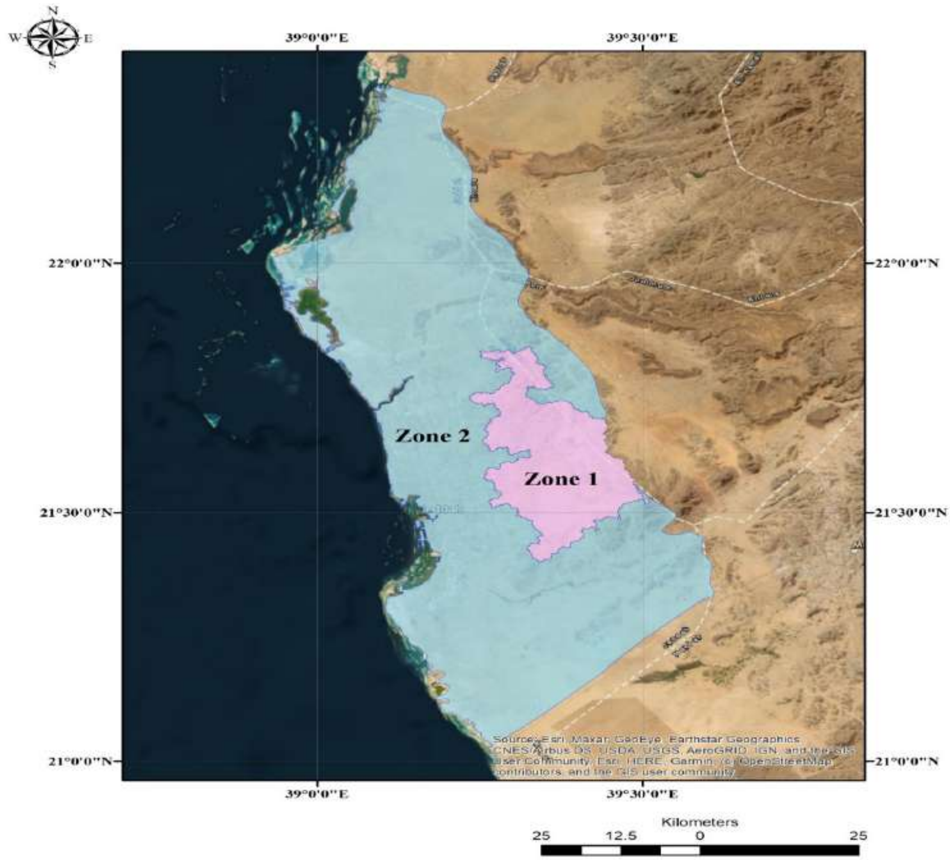
3.4 Runoff volume estimation

3.4.1 Spatial distribution of rainfall depth and estimated runoff volume for Zone No. 1

The assessment of torrential phenomena triggered by the extreme event of November 24, 2022, in the Jeddah Governorate necessitated the application of the SCS-CN Methodology. To facilitate a comprehensive analysis, the study area was thoughtfully partitioned into two distinct zones, as delineated in Figure 8: Zone No. 1, encompassing the watersheds protection by 15 dams serving as pivotal flood defenses for Jeddah, and

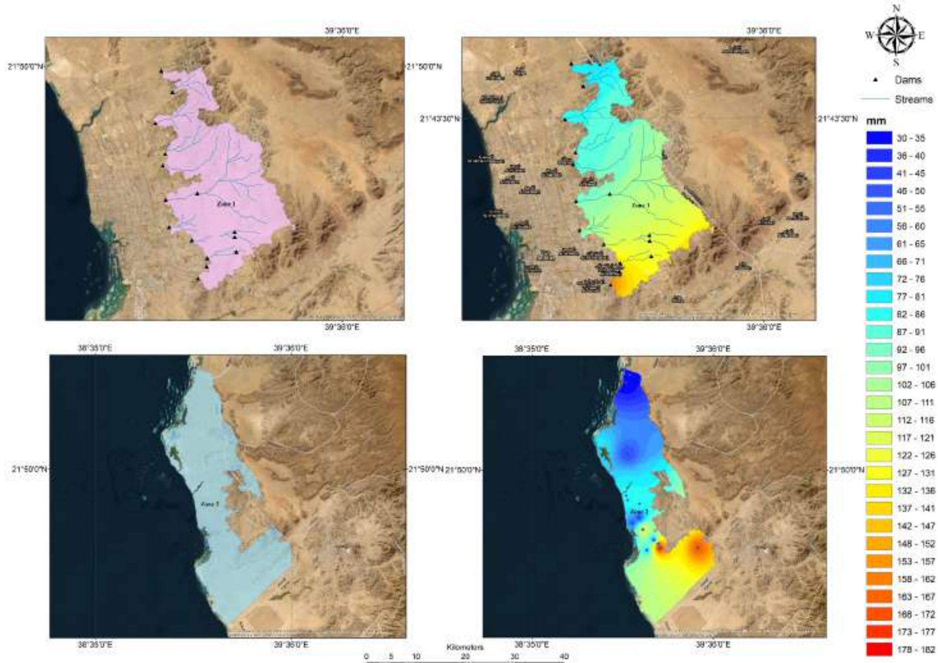
Zone No. 2, representing the broader expanse of the Jeddah Governorate, excluding the dam-protected zones.

Figure 8 Maps of the two zones (see online version for colours)



Focusing our analytical lens on Zone No. 1, the spatial distribution of rainfall depth within the dam basins unveils a compelling spectrum of variability, as vividly portrayed in Figure 9. Rainfall depth measurements oscillate within the range of 40–182 mm. The southeastern precincts of Jeddah emerged as the epicentre of precipitation, with several dams registering significant rainfall accumulations. Noteworthy among these are Qaws 3, Qaws 2, Qaws 1, Mathob 1, Mathob 2, Ghaleel Al Janoubi, and Ghaleel Al Shamali dams, which reported rainfall depths ranging from 120 mm to 180 mm. The Northern Ghalil Dam's water basin, in particular, bore witness to the most substantial rainfall during the study period. Remarkably, despite the concentration of dams' water basins in the northern and central sectors of Zone No. 1, the rainfall depth exhibits a range spanning from 40 mm to 120 mm.

Figure 9 The distribution of rainfall depth in Zone No. 1 and Zone No. 2 (see online version for colours)



Hydrological analysis culminates in the estimation of an average spatial rainfall depth of 90 mm for Zone No. 1. Furthermore, the computed volume of torrents detained behind dam gates, in response to the extreme event, is anticipated to fall within the range of 36–44 million cubic metres. It is imperative to underscore that this volumetric estimate is contingent upon the selection of a specific curve number, reflecting the inherent variability within hydrological modelling approaches.

3.4.2 Spatial distribution of rainfall depth and estimated runoff volume for Zone No. 2

Shifting our analytical focus to Zone No. 2, the investigation continues with a meticulous examination of the spatial distribution of rainfall depth, as graphically portrayed in Figure 9. Our rigorous analysis discerns an estimated average spatial rainfall depth of 74.4 mm for this region.

The runoff volume accumulation behind dam gates, attributed to the extreme event within Zone No. 2, is forecasted to be approximately 92.2 million cubic metres. It is imperative to emphasise that, akin to Zone No. 1, this volumetric projection is subject to variability predicated on the specific curve number chosen in the hydrological modelling process.

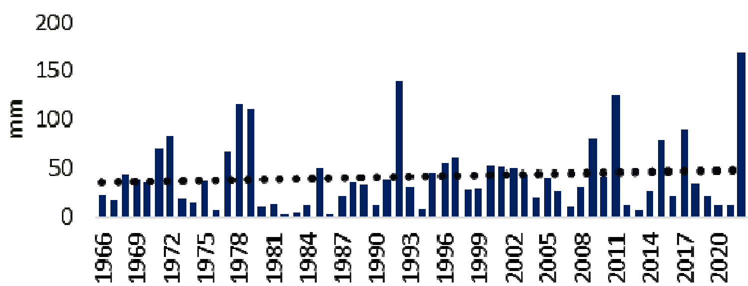
These findings, deeply rooted in hydrological science, underscore the intricate interplay between meteorological dynamics, geographic features, and the engineered infrastructure represented by dams. The judicious application of the SCS-CN Methodology has enabled the quantification of runoff volumes, a cornerstone of flood risk assessment. It is unequivocal that these volumetric insights have profound implications for flood mitigation, urban planning, and the sustainable management of water resources within the Jeddah Governorate. Furthermore, they underscore the necessity for continued academic inquiry to comprehensively comprehend the multifaceted hydrological phenomena underpinning extreme events.

3.5 Analysis of historical records of extreme rainfall

The investigation extends to an examination of historical rainfall records within the Jeddah Governorate, spanning the substantial timeframe from 1966 to 2022. This analytical endeavour aims to unravel and comprehend the potential recurrence of extreme rainfall events. The findings of this analysis are pivotal, as they offer valuable insights into the temporal evolution of extreme precipitation within the region.

Figures 10 and 11 eloquently present the historical records of rainfall stations in Jeddah, painting a chronological landscape of meteorological data that spans nearly six decades. This extensive dataset encapsulates the nuances of precipitation patterns, enabling a meticulous study of long-term trends and the identification of any notable anomalies.

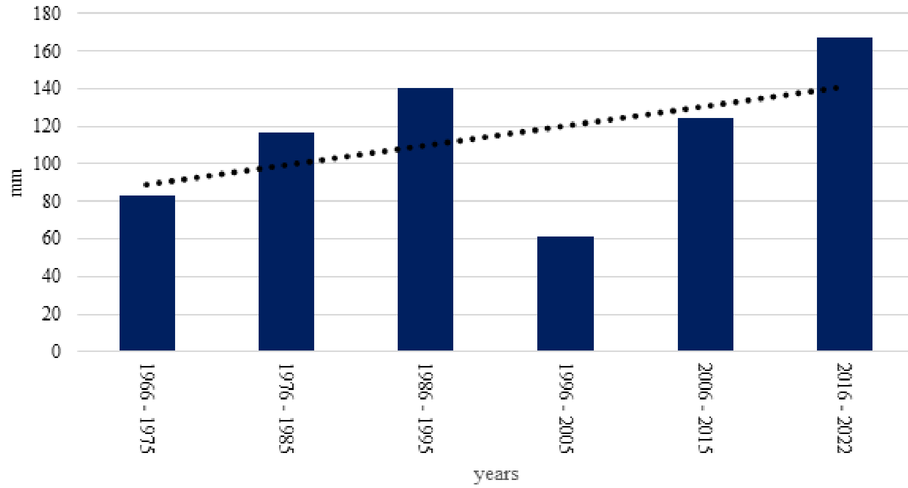
Figure 10 Annual maximum daily rainfall over Jeddah governorate (see online version for colours)



Of particular significance is the analysis of the highest annual daily precipitation. This analysis, derived from the historical records of monitoring stations, signifies a noteworthy trend. Specifically, our findings reveal an upward trajectory in the highest daily annual precipitation levels over the course of the analysed period. This upward shift in extreme precipitation events raises critical questions regarding the region's vulnerability to intensified rainfall and its implications for flood risk assessment and mitigation.

These historical records underscore the imperative nature of studying long-term meteorological trends. The observed increase in extreme rainfall events necessitates further investigation to ascertain the driving factors behind this trend. Climate change, urbanisation, and geographical features all play integral roles in shaping precipitation patterns. Considering these findings, proactive measures for flood preparedness, infrastructure resilience, and sustainable urban planning are warranted. Moreover, continued scientific inquiry into the intricate interplay between climate dynamics and regional precipitation patterns is essential for informed decision-making and adaptive strategies in the face of evolving meteorological challenges within the Jeddah Governorate.

Figure 11 The maximum daily rainfall observed in Jeddah city over a ten-year period (see online version for colours)



The hydrological analysis presented in this study is fundamental to understanding the impact of extreme rainfall events on Jeddah's water infrastructure and urban landscape. Here, we'll explore this aspect in greater detail:

The use of the SCS-CN model is a robust approach for estimating runoff in response to precipitation events. This method incorporates factors such as soil type, land use, and antecedent moisture conditions to quantify runoff. This study effectively demonstrates how this model can be applied to the different zones within the Jeddah Governorate, dividing the region into two distinct regions (Zone No. 1 and Zone No. 2).

The spatial variability in rainfall depth within these areas is crucial for understanding local hydrological responses. By presenting a detailed analysis of this variability, this study underscores the importance of considering microclimate effects and geographical factors in runoff estimation. The significant differences in rainfall depths between the northern and southern parts of Zone No. 2, for example, highlight the need for region-specific flood mitigation strategies.

Estimating runoff volumes provides actionable insights into potential flood hazards. This study estimates runoff volumes for both Zone No. 1 and Zone No. 2, emphasising the sensitivity of these estimates to the selection of curve numbers. This sensitivity underscores the importance of refining curve numbers through local calibration and considering uncertainties in hydrological modelling.

The event of November 24, 2022, marked a pivotal moment in Jeddah's history, with recorded rainfall levels doubling historical norms. This deluge had profound implications, not only in terms of immediate damage and disruption but also in highlighting the city's susceptibility to increasingly severe meteorological occurrences. The study's findings align with historical data trends, pointing to a rising trend in extreme precipitation events in the region.

Satellite technology has emerged as a critical tool in enhancing our ability to comprehend and respond to extreme events. In this study, we harnessed the power of satellite data to gain valuable insights into the dynamics of the November 24, 2022, flash flood event. These insights have far-reaching implications for our understanding of extreme events in Jeddah and beyond.

Satellite imagery enables real-time monitoring of extreme events, providing timely information that is instrumental in emergency response planning and flood forecasting. The ability to track the progression of the event as it unfolded was indispensable in this study.

Satellite data allows for the mapping of precipitation patterns with high spatial resolution. This helps identify localised areas of intense rainfall, which is crucial for assessing flood risk on a finer scale. Our analysis revealed stark spatial variations in rainfall depth, underscoring the localised nature of the event.

Satellite archives provide a valuable historical record of extreme events, facilitating long-term trend analysis. This historical perspective is vital for understanding the changing nature of extreme rainfall events in Jeddah and for making informed decisions regarding infrastructure and flood preparedness.

The integration of satellite technology into hydrological modelling and meteorological studies has vast potential. Future research can leverage satellite data to develop more accurate predictive models and enhance flood preparedness. This includes the ability to anticipate extreme events with greater precision and lead time.

The flood risk assessment and mitigation strategies discussed in this study are central to reducing the vulnerability of Jeddah to extreme rainfall events. Let's explore these aspects in more detail:

The use of GIS technology for spatial analysis is a powerful tool for identifying vulnerable regions. Going beyond identifying areas at risk, a detailed analysis can assess the criticality of infrastructure and the potential consequences of flooding. This information can guide prioritisation in mitigation efforts.

The creation of flood hazard maps is a critical step in visualising the potential risks. These maps can inform land use planning, emergency response preparedness, and infrastructure development. More detailed maps can differentiate between various flood severities, helping communities and authorities make informed decisions.

Effective emergency response and mitigation strategies are vital for minimising damage and loss of life during extreme rainfall events. While this study outlines several strategies such as early warning systems, improved drainage infrastructure, land use planning, evacuation plans, and community engagement, deeper discussions on the implementation challenges, costs, and timelines would be beneficial.

While this study has shed light on the vulnerabilities posed by extreme rainfall events in Jeddah, it is imperative to stress the need for continued climate research. The outcomes of this research underscore the importance of accurate predictions, informed policy-making, and strategic planning to bolster the city's resilience against evolving meteorological challenges.

4 Conclusion

The findings emphasise that Jeddah is increasingly susceptible to intensified and more frequent extreme meteorological occurrences. This vulnerability extends beyond immediate damage and disruptions, calling for a sustained commitment to climate research, infrastructure resilience, and urban planning.

Jeddah must prepare for a future marked by complex and unpredictable extreme events. Accurate predictions, informed policy-making, and strategic planning are essential to enhance the city's resilience.

Moreover, the use of satellite data and remote sensing technologies, as demonstrated in this study, can play a pivotal role in monitoring and forecasting extreme weather events in real-time. This integration of advanced technologies with hydrological modelling offers valuable insights for flood risk assessments and emergency response planning.

In summary, the lessons learned from the November 24, 2022, event in Jeddah serve as a stark reminder of the urgent need to address climate vulnerabilities and enhance preparedness. As the climate continues to change, research, innovation, and collaborative efforts will be essential to protect the city and its inhabitants from the growing challenges posed by extreme events.

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Conflict of interests

The author declares no conflict of interest

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