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Review

Flood Risk and Vulnerability from a Changing Climate Perspective: An Overview Focusing on Flash Floods and Associated Hazards in Jeddah

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Abstract: Natural hazard threats have grown as a result of climate change, fast demographic development, and major urbanization. Devastating floods have occurred in several areas of the world recently, including the Kingdom of Saudi Arabia, which is located in a region with a dry environment. In arid or semi-arid regions, rapidly forming flash floods associated with debris flowing down over dry water courses leading to a potential threat to both lives and property. Being located at the coastal plain of western Saudi Arabia, Jeddah City has witnessed an unexpected amount of rainfall events in recent years. Such extreme rainfall events, integrated with other factors, namely topography, land use, surface runoff, etc., have led to flood generation, which is alarming indeed. Herein, this paper addresses the varying climatic classifications of the Kingdom, its risk and vulnerability, followed by reasoning about the impact of flash flood events and the associated casualties and property losses. Further, it reports about the existing strategies of the government and proposes a systematic way forward on how to alleviate such events in future. Thus, risk variables have been discovered and integrated in the context of climate change and rising anthropogenic strain on coastal communities to give planners and decision makers tools to assure effective and appropriate flood risk management.

Keywords: floods; flash floods; Jeddah City; hazards; climate change; SDG6

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1. Introduction

With a very fragile and sensitive desert environment, the Kingdom of Saudi Arabia has been mainly affected by human activities [1–3]. Floods, being the most devastating and fatal among natural disasters [4], are accounted responsible for almost 34% of human loss. According to [5], floods were claimed to be the most common natural disaster and to have harmed the greatest number of people in the Kingdom. Additionally, it was noted that between 1980 and 2020, floods made up 44% of the natural hazards in Saudi Arabia, with epidemics and storms coming in second and third, with percentage values of 6% and 4%, respectively. Studies showed that between 1995 and 2015, 43% of all the documented natural disasters were caused by floods, killing almost 157,000 people, disrupting around 2.3 billion people and causing damages of about USD 662 billion. By 2050, these statistics are expected to rise drastically mainly due to sea-level rise [6], loss of wetlands, deforestation, climate change and urbanization in flood-prone regions [7,8]. Urban areas have been contributing much when it comes to greenhouse gas emissions. The contribution from global dwellers has been excessive. According to the World Bank, buildings and transportation as the major contributors of the CO_2 emission are estimated to have been the said cause [9]. This leads to the occurrence of natural disasters such as floods. To make cities resilient, safe and sustainable, urban development stakeholders must ensure alternative flood risk reduction approaches to reduce the death toll and economic loss caused by water-related disasters such as floods [7]. The sudden occurrence of flash floods has been destructive when it comes to human lives, properties and infrastructure [10,11]. Generally, due to long-term aridity, residents in flood plain regions are unaware of their consequences. Thus, such regions are built for settlement and other infrastructure developments [12]. Rapidly occurring flash floods move down over dry water courses [13–16]. Such floods are rather complex since their intensity depends on several other parameters. Among morphological and geological characteristics of the basin, they relate to the rock type, slope, elevation, area, etc., whereas concerning hydrological parameters, they mainly deal with evaporation, surface runoff, infiltration, ground water storage, etc. [17]. Additionally, manmade changes play a vital role when it comes to the behavior of flash flood occurrence [12,18].

Flash floods pose a significant threat to the city of Jeddah, and their frequency and intensity are increasingly linked to changing climate patterns. These hazardous events not only endanger lives and property but also disrupt the socio-economic fabric of the region. Therefore, there is a need to comprehensively understand the evolving flood risk and vulnerability dynamics in Jeddah, particularly in the context of a changing climate. This motivation arises from the critical necessity to enhance the city's resilience and preparedness against flash floods and their associated hazards. Therefore, the primary objective of this research was to provide an in-depth overview of flood risk and vulnerability in Jeddah, focusing on the perspective of changing climate conditions.

2. Bibliometric Analysis

A worldwide issue with the environment, flash floods impact many nations. This paper gives a general description of flash floods that occurred in Jeddah, Saudi Arabia. A review explored the literature on flash floods in Saudi Arabia using bibliometric analysis and visualizations, highlighting the significance of tackling this issue. Several sources, including Google Scholar, Scopus and Web of Science (WoS), were employed to gather the study's data. Software for bibliometric analysis, most notably VOS Viewer, was used to view and analyze the data. The study employed "flash floods in Saudi Arabia" as its key index term and mainly concentrated on research publications that were accessible in the Scopus database between 1977 and 2023. Several analytical methods, such as co-authorship analysis, co-occurrence analysis and citation analysis, were used to analyze the literature. Network visualization of the Saudi Arabian flash flood reviews carried out shows a considerable rise in interest in this subject. With a minimum of 4143 keyword occurrences, 261 keywords met the requirements, showing the significance and weight of flash floods in the corpus of literature, as shown in Figure 1.

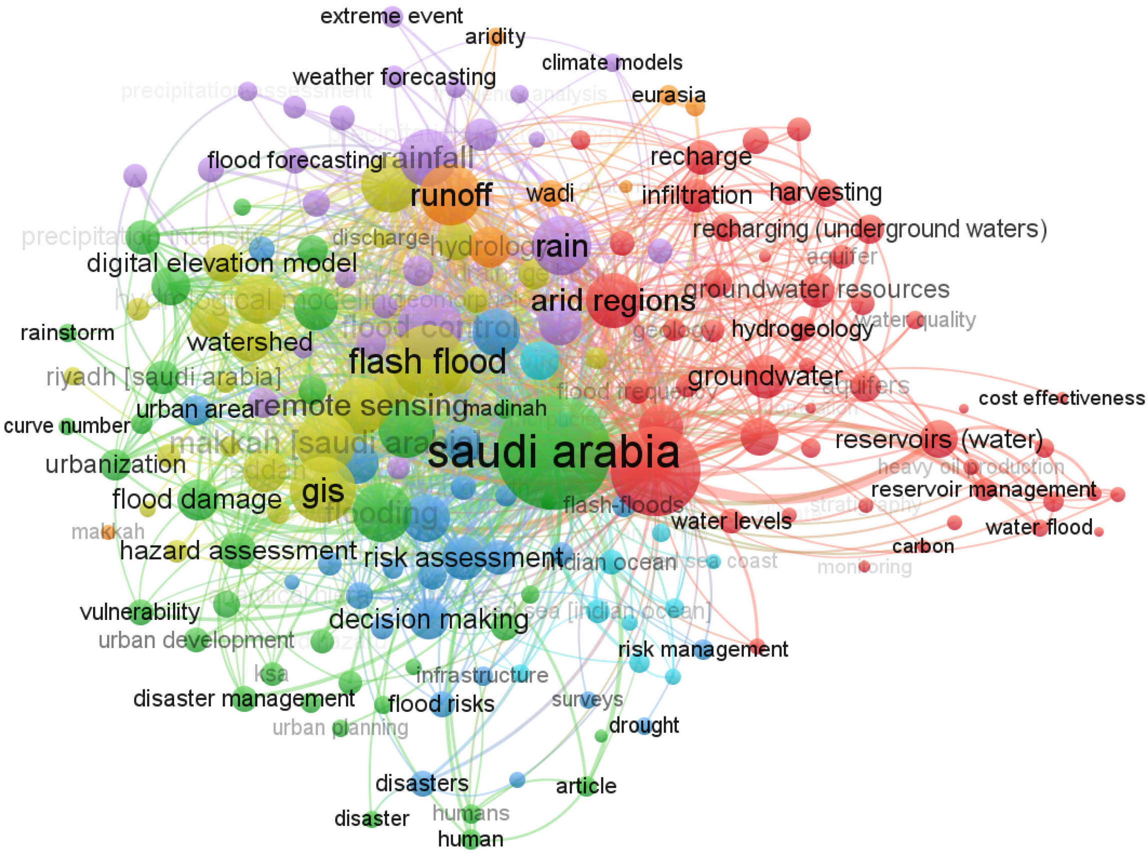

Figure 1. Database bibliometric network showing a map of keywords for the probability of occurrences (1977–2023).

3. Climatic Classification of the Kingdom

According to the Koppen–Geiger Map of climate classification, Saudi Arabia has been classified into the hot semi-arid weather zone (BWh) [19–21], as shown in Figure 2. Figure 3 depicts the mean temperature distribution in Saudi Arabia for each season using data collected between the years 1991 and 2020 by the Climatic Research Unit (CRU) of the University of East Anglia. The greatest temperature readings are recorded each year in June, July and August, while the weather gets cooler in December, January and February, according to CRU statistics [22]. The climate in Saudi Arabia remains mostly hot. Usually in summer, it becomes extremely hot, whereas it remains warm to mild during winters. From the available meteorological stations in Saudi Arabia, as shown in Figure 4, and based on data collected between the years 1985 and 2019, the National Center of Meteorology (NCM) published mean temperature maps for each month. It is evident that May, June, July, August and September had the greatest temperature values, with a maximum value that may exceed 45 °C. On the other hand, Figure 5's depiction of the lowest mean temperature records indicates that they occurred in January and December [23]. The rainfall patterns witnessed are mostly inconsistent [24]. The western region, specifically the south-western region, receives the largest rainfall. The rainfall mainly occurs during the wet season between November and April. A few intense thunderstorms of very short period during this span are claimed to have produced most of the annual rainfall [25]. In a broader perspective, rainfall in Saudi Arabia is very rare, which makes it one of the driest countries in the world [26]. The substantial variation in humidity and temperature in Saudi Arabia is mainly due to the regional subtropical high-pressure system and change in elevation. In the mountains, the annual average annual precipitation can reach up to 600 mm. This mainly happens as air reaches the mountains; it is forced to move up the windward side allowing the wind to expand and cool. This rise in elevation makes the water droplets condense, leading to the formation of clouds, followed by precipitation. On the other hand, at the leeward side, the annual average annual precipitation is noticed to be around 100 mm. The leeward side of the mountains mainly remains deficient in rainfall as most of the air that moves to the other side of the mountain is drier than normal [1]. Based on data collected between the years 1985 and 2019, NCM published the average monthly rainfall records for the whole country, as shown in Figure 6 [23].

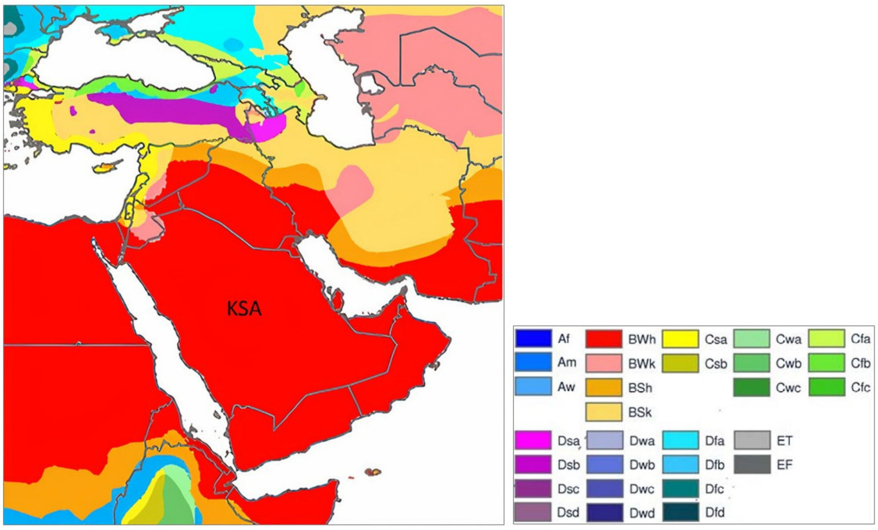

Figure 2. Koppen–Geiger climate map for Saudi Arabia [20].

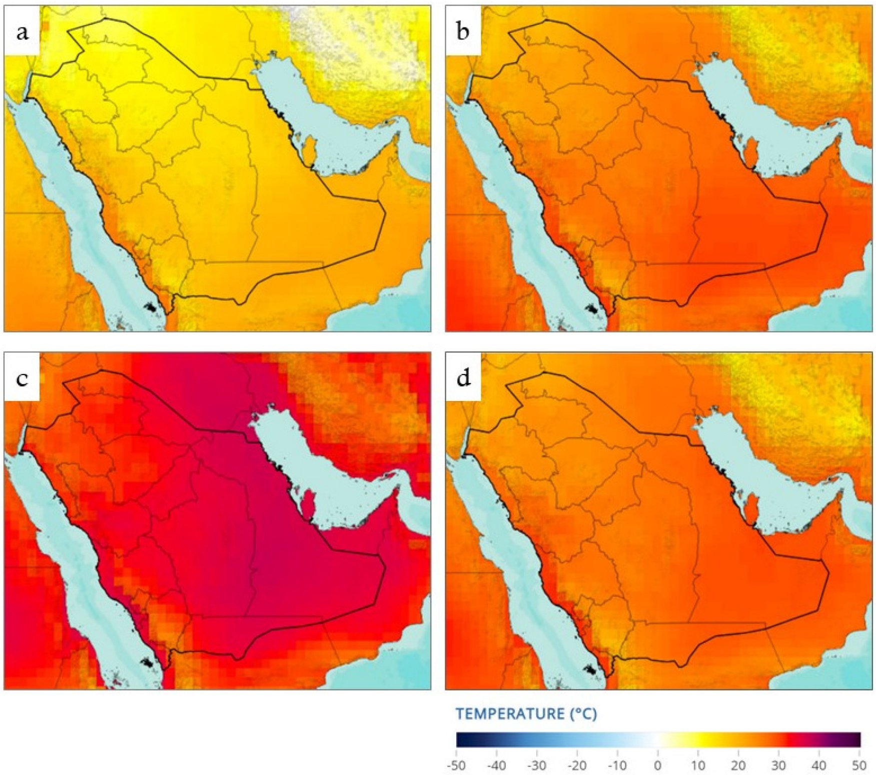

Figure 3. Observed climatology of mean temperature, 1991-2020, Saudi Arabia: (**a**) December, January and February; (**b**) March, April and May; (**c**) June, July and August; and (**d**) September, October and November [22].

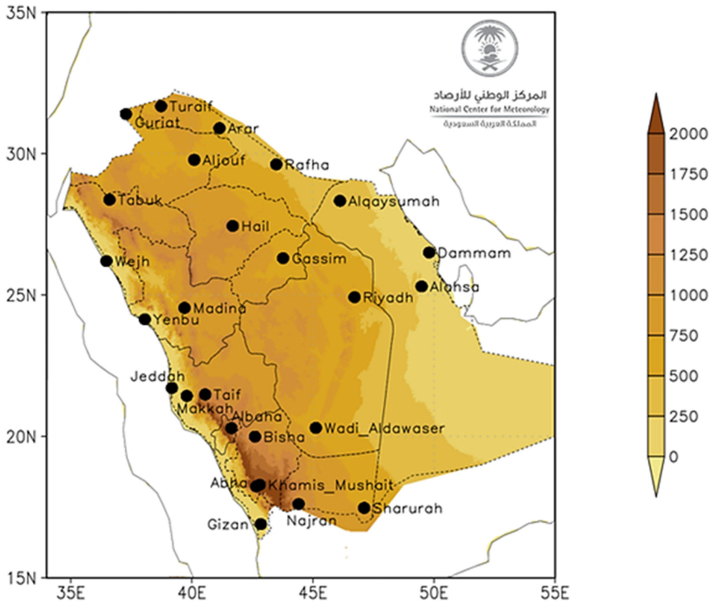

Figure 4. Meteorological stations in Saudi Arabia and the land elevation in (m) [23].

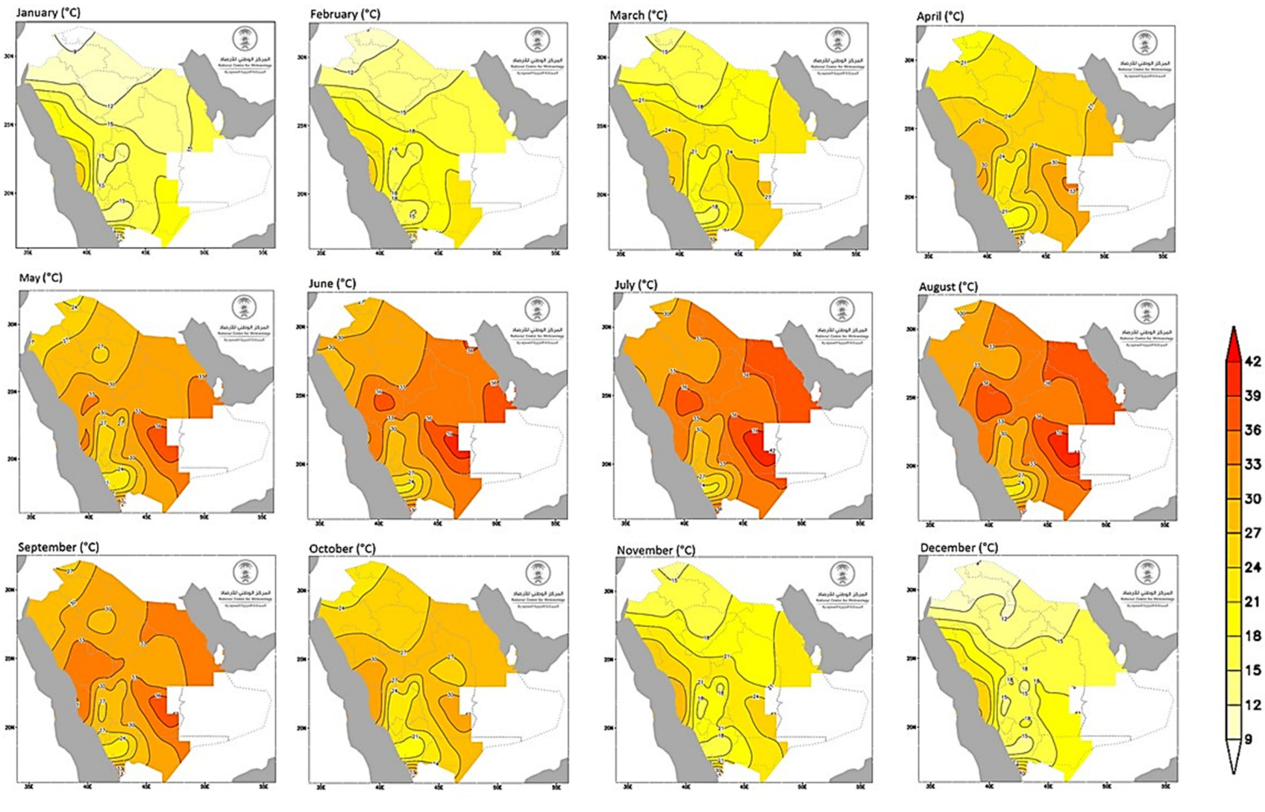

Figure 5. Monthly mean temperature maps based on 1985–2019 record [23].

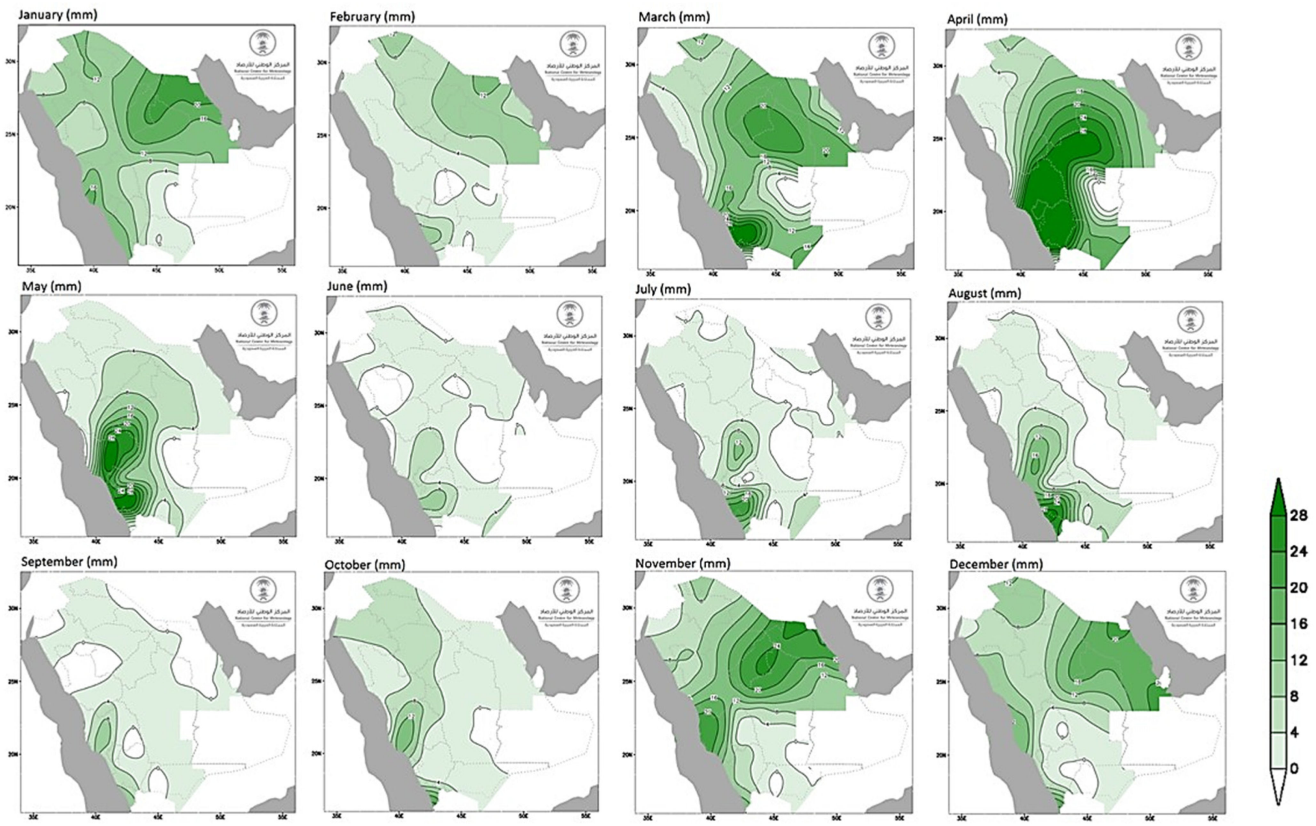

Figure 6. Monthly mean rainfall maps based on 1985–2019 records [23].

4. Climate Change's Effects on Flooding in Saudi Arabia

Climate change, which refers to long-term changes in the Earth's climate, is currently a significant worldwide concern. Specifically, it refers to the increase in global average temperatures brought on by human activities such as the burning of fossil fuels, deforestation and industrial processes [27–31]. These activities release greenhouse gases (GHGs) into the atmosphere, which trap heat and lead to the greenhouse effect [32]. As a result, the planet is experiencing various impacts and more frequent and severe weather conditions such as a rise in temperature, storms and flash floods [33,34]. According to the Climate Change Knowledge Portal (CCKP) report of 2020 [5], the mean temperature in Saudi Arabia increased by around 1.5 °C between the years 1901 and 2021, as shown in Figure 7. It has been further stated that the maximum temperature increases at a rate of 0.71 °C each decade based on recorded data of the period between 1978 and 2009. On the other hand, the mean and minimum temperature values increase at a rate of 0.60 and 0.48 °C per decade, as shown in Figure 8 [35]. In this context, it can be clearly noticed that there are significant effects of climate change on the Saudi Arabia weather, which can impact flash flood events and increase their probability [36].

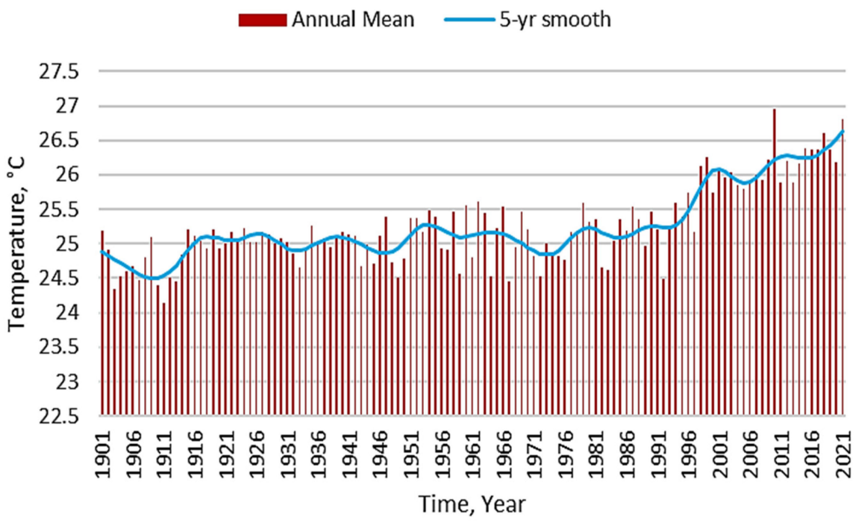

Figure 7. Observed average annual mean temperature for Saudi Arabia for 1901–2021 [5].

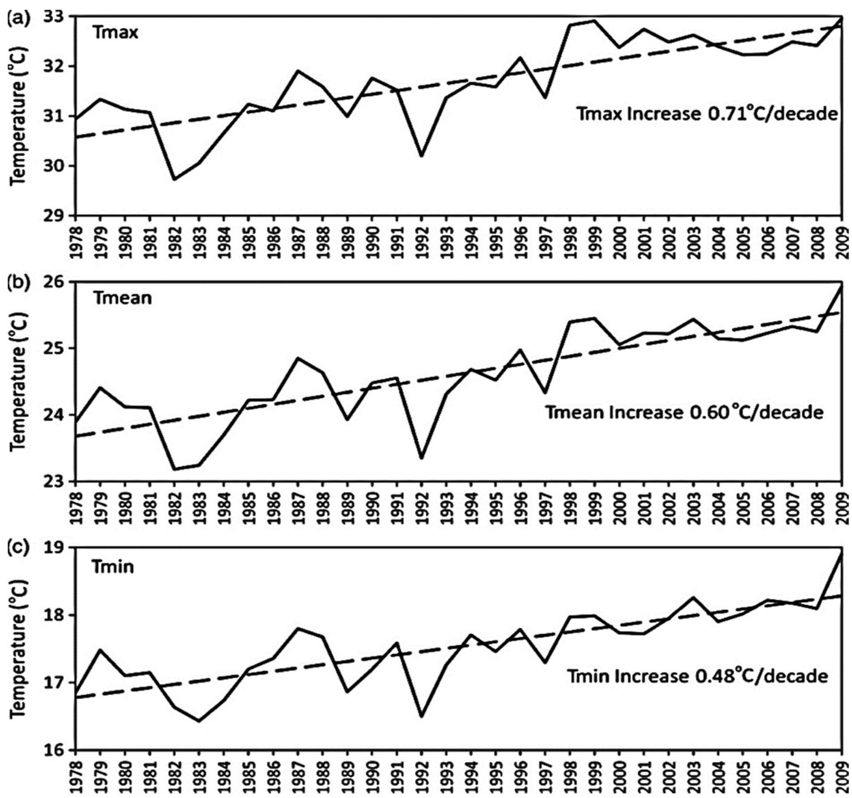

Figure 8. Temperature variation with time over Saudi Arabia based on observed data between 1978 and 2009: (**a**) maximum trend, (**b**) mean trend and (**c**) minimum trend [35].

Rainfall intensity and pattern are directly affected by climate change and global temperature rise [37]. As a result of the mean temperature rise, the atmosphere can hold more moisture, causing an increase in the intensity of rainfall events over a short period. Furthermore, rainfall patterns become irregular, at which time some areas may experience prolonged droughts followed by intense rainfall, which can result in flash floods [38,39]. Investigations on climate change effects on the rainfall temporal trends in the Jeddah area between the years 1965 and 2015 showed that there was an increment in the rainfall intensity with an average value of about 12 mm [25]. Another study adopted two emission scenarios, namely A2 and B2, which were developed by the Intergovernmental Panel on Climate Change (IPCC) to evaluate the climate change impacts on Saudi Arabia based on

37 stations as shown in Figure 9. For precipitation changes under scenario A2, the selected locations are projected to experience an average precipitation increase of 39%. This increase varies across the locations, ranging from a decrease of 0.8% in Arar to a substantial increase of 111.1% in Dhahran. Out of the 37 locations considered, 32 of them are expected to see a precipitation increase of more than 20%, while 11 locations are anticipated to experience a significant increase of more than 50%. In contrast, under the B2 scenario, the average precipitation change is projected to be 6.7%. The maximum increase is expected to occur in Guriat, with a change of 57.5%, while the minimum change is projected to be a decrease of −79.6% in Al Baha. Among the locations, 12 are expected to witness a precipitation change exceeding 20% [40].

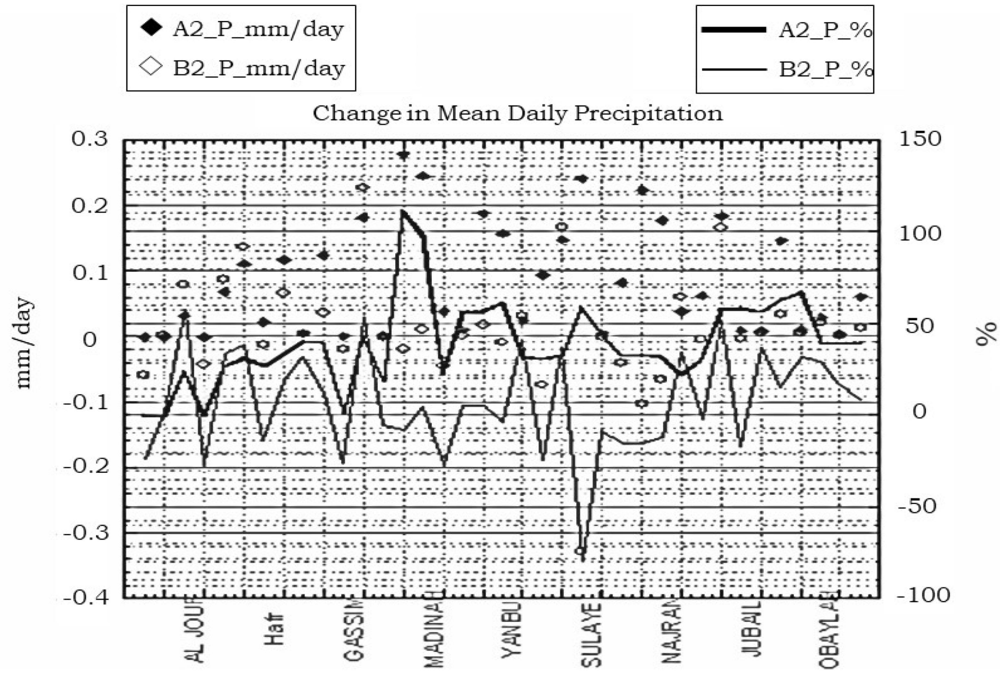

Figure 9. The change in daily mean precipitation in mm/day for the 37 locations in Saudi Arabia for A_2 and B_2 scenarios [40].

5. Topography Associated with Slope Instability and Flash Flooding in the Kingdom

The topography, geology and variation in the climatic conditions make the Kingdom of Saudi Arabia vulnerable to number of geohazards, which in turn severely affect its infrastructure [41,42]. Volcanic hazards and earthquakes are common in the western region; however, the western and central regions have been experiencing floods more frequently. The mountain ranges of the south west region are more prone to land sliding, whereas the eastern part experiences shifting dunes and dust storms [43].

Slope instability and flash floods have been evident. The roads constructed in the mountainous region mainly linked with the Hejaz mountains in the western part of the country have witnessed severe slope instability incidents [44]. Elevations in the Jizan region, which is located at the extreme south west of the country, can reach up to 2600 m. The Faifa, Ar-Rayth and Al-Hasher areas located at the northeast of Jizan have been documented to be susceptible to land sliding [45,46]. Flash flooding has been a common phenomenon, which mainly happens due to the lack of preventive measures, the intermittent intense rainfall and the dry soil desiccated near the ground surface [47]. Accumulation of rainfall in the mountainous regions of the west and the central upland areas fill the wadis, which generates surface runoff together with debris that flows onto the plains below. Concerning urban areas, the scenario becomes acute due to unplanned housing in the low-lying flood-prone regions, which in turn affects the natural drainage [48]. The valleys flowing into the west are sharp and steep; thus the generated runoff reaches the Red Sea coastal area mainly in the form of sheet flow [49]. Conversely, flows from the wadis have been reported to be low, with the highest runoff volumes witnessed at wadis Al-Dwasir and Najran. The flat topography of the land and the low permeability allows the flood water to remain stagnant for days, which at time affects rescue operations. A comprehensive description about the areas of critical slope instability and the zones with flood potential in the western region of the Kingdom has been illustrated in Figure 10 [43].

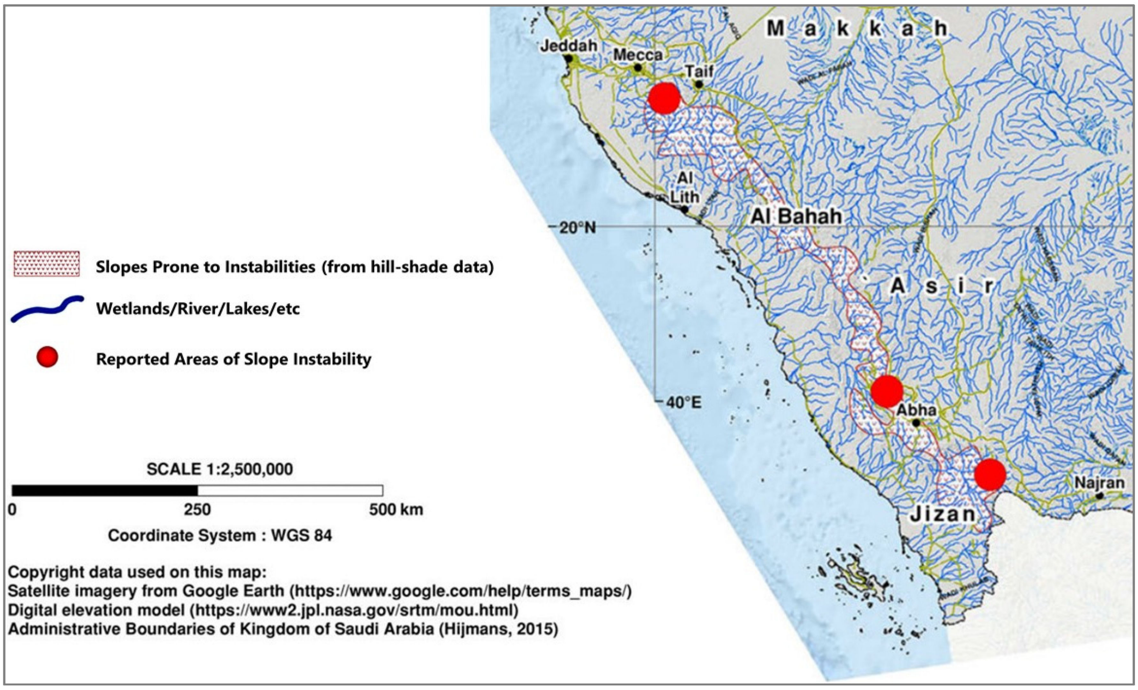

Figure 10. The areas of critical slope instability and the zones with flood potential in the western region of the Kingdom (www.mapCruzin.com) (adapted from [43]).

6. Major Flash Flood Events in Jeddah City

The flash floods in 2009 and 2011 severely affected the infrastructure, including houses, vehicles, mass transit and telecommunication networks. Absence of any early warning system was one of the factors contributing to the significant losses brought on by flooding. In many areas, locals noticed the water level rising in several locations within the flooded zones [50]. Another perspective is that if the authorities and decision makers had addressed the higher reaches of the wadis, the effects of the flash flood events in 2009 and 2011 may have been less severe. By doing this, the regions to the east of the Al-Haramain highway would have been protected.

Flash floods are caused by a variety of variables, including natural ones like high monsoon rain, powerful convective rainstorms and inadequate drainage, as well as human, geomorphological and geological factors [51]. Recently, an increase in the frequency of flash floods has been witnessed in Saudi Arabia [52]. Extreme rainfall events lasting up to several hours (three hours each) have been witnessed in the Jeddah area in recent years, ending up in catastrophic flash flood events. In November 2009, 70 mm of rainfall was noticed in just 3 h during a storm event which resulted in massive floods, fatalities and damage to both infrastructure and property. These floods in 2009 resulted in the deaths of over 113 people, over 10,000 residential and commercial properties being damaged. Another major event in 2011 with rainfall measuring 111 mm in 3 h led to massive destruction including a dam breakdown. Some glimpses of these flooding events can be seen in Figure 11 [25].

Figure 11. Major flash flood events in Jeddah—(**a**,**b**) (adapted from [52]) and (**c**,**d**) (adapted from [25]).

7. Geomorphology, Geology and Urbanization in nearby Jeddah City

Geomorphologically, Jeddah City is located toward the east of the Red Sea coastal plain surrounded by wadis deposits, hills and pediments [53]. The area comprises landforms which are both flattened foothills (mainly alluvium deposits) and mid- to low-size low-lying rounded hills (the elevation of which may vary from tens of meters to a few hundred meters). The wadis close to Jeddah City include wadi Muraikh, wadi Qus, wadi Asheer, wadi Methweb and wadi Ghulail. The general sloping trend of these wadis is centered towards the Jeddah Metropolitan area. Moreover, this area crosses many streams, which helps transport the surface runoff towards the urban center during a flooding event. Further, the roads and other infrastructure built on the flattened foothill contribute as an impervious cover, which drastically worsens the flooding conditions during the event of intense rainfall [54]. Geologically, the pediments and hills consist of andesite and dacite (forms of volcanic rocks) and diorite and granite (forms of intrusive rocks). On the other hand, Holocene sediments cover the areas between the wadis [55]. Urban changes play a vital role since they directly relate to the impact of flooding. It has been reported that the old Jeddah City has now expanded towards the east, mainly due to population increase. To ensure the infrastructure needs of the expanded areas, new developments have been made in areas which are low-lying and prone to flash flooding [54]. The cross section of the sloping terrain comprises the major shelves in the study area, namely an elevated shelf, sloping terrain and a coastal zone. The coastal zone ranges between 10 to 20 km, but it can extend up to 50 km in some areas with an average altitude of 15 m. On the other hand, the sloping terrain joins the coastal zone and the elevated shelf. This shelf contains steep slopes, at some places having a width of up to 5 km and an average altitude of almost 40 m. Furthermore, the elevated shelf has a width of nearly 25 km with a varying altitude of about 150–200 m (at some places some peaks exceed 500 m) with an average slope gradient of around 6.5 m/km. A schematic view of these shelves can be seen in Figure 12 [56].

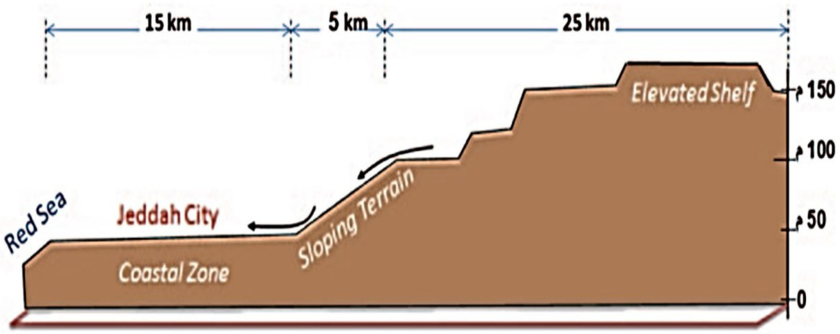

Figure 12. Shelves around Jeddah City [56].

8. Rainfall Characteristics of Jeddah City

When the precipitation exceeds 25 mm/h, heavy rainfall is said to have taken place [57]. The northerly winds rising from the eastern Mediterranean Sea leading towards the Arabian Gulf have been accounted responsible for the heavy rainfall in Jeddah [58,59]. The pluviometric mode of rainfall in Jeddah has faced severe variations [60]. For instance, there have been recorded dry years when there was no rainfall at all, i.e., 1986, and there have also been witnessed wet years, with annual precipitation of 284 mm in the year 1996, as shown in Figure 13 [61]. Precipitation analysis shows that despite heavy precipitation, rainfall events in 1970s did not record major floods, the reason being that no urban developments were in the zones of high flood risk at that time. On the other hand, precipitation in 1996 was exceptional, which caused damage since the rainfall event lasted for many days [62]. Rainfall here mostly occurs in winters between October and April, depending on the climate of the temperate zones, whereas it only slightly relates to the monsoon, which occurs between July and September. This is evident from the average monthly rainfall amounts for each month of the year for different cities including Jeddah, as shown in Figure 14 [63].

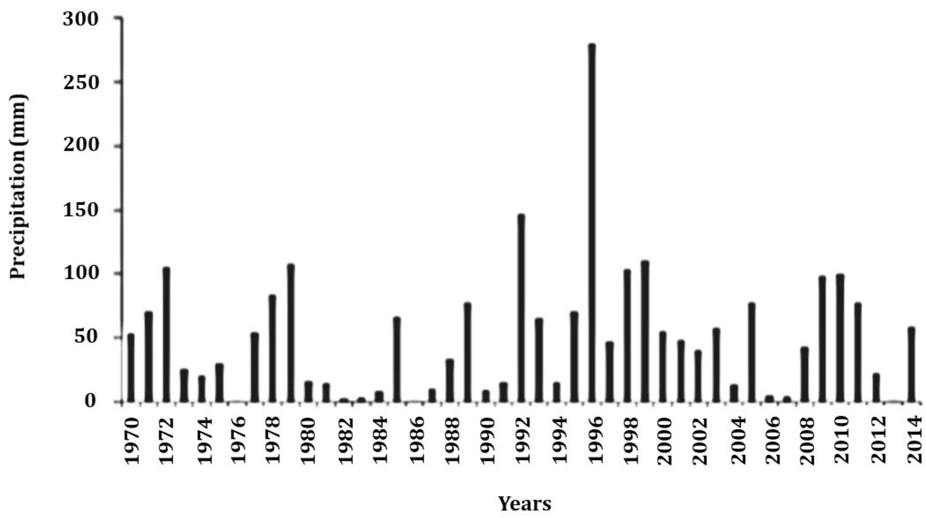

Figure 13. Annual precipitation for Jeddah City [61].

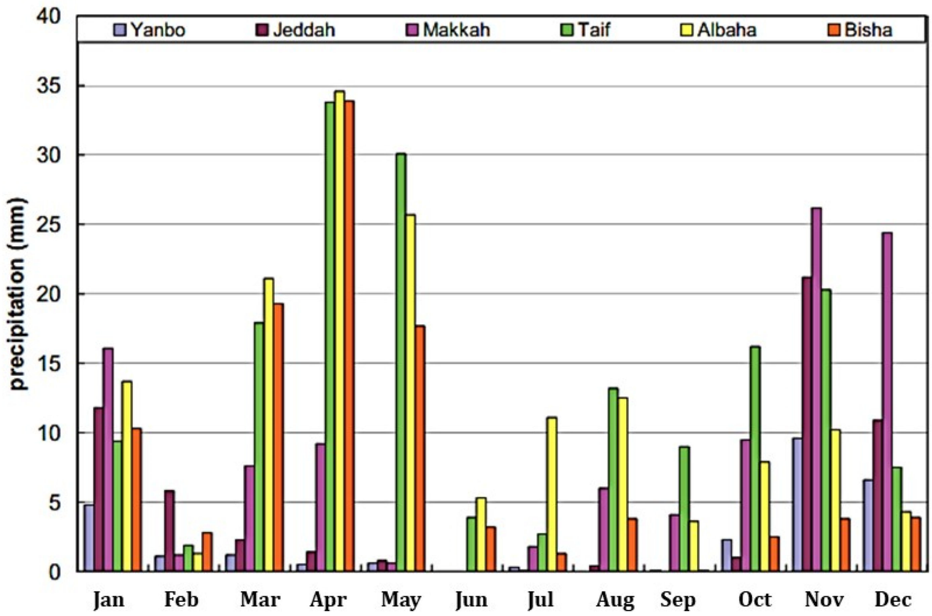

Figure 14. The average monthly rainfall totals for several cities, including Jeddah, for each month of the year [63].

9. Urban Expansion of Jeddah City

The population of the Kingdom reached 31.54 million in the year 2015, whereas in the year 1950 it was only 9.9% of the said population. Further, by 2030, it is expected to reach 39.1 million [62]. Saudi Arabia, being the world's fastest when it comes to urbanization, has experienced massive growth in its major urban centers since 1973 [64,65]. Such a sprawl in urbanization will make it challenging for the municipalities to expand their jurisdiction to ensure the population's needs. Moreover, such urban expansion would also be a challenge to the public sector authorities to ensure the infrastructure needs of the growing population. The government's public initiatives, i.e., the land grant policy and interest-free loans, have been accounted responsible by many observers for the massive expansion of suburban zones into major cities like Jeddah and Riyadh [66].

Jeddah is located on a coastal plain called "Tihama". It has remained a commercial center mainly because of the harbor in the city which was to serve as a route for pilgrims to the holy places in the Kingdom. The demolition of the wall of the ancient city in 1947 is said to be the point of turning into the modern phase of the city's growth. Pumping of fresh water from the wells in Wadi Fatimah helped the city grow at a faster pace in terms of population. Later, after the Second World War, the Kingdom witnessed a rise in its oil revenues. At the same time, central authorities were established to look after the affairs of the country. This led to construction activities in the country, mainly in the western and middle regions [66]. Furthermore, the cause of dramatic expansion in Jeddah is said to be transit stations where people used to come to perform religious tasks and stayed there afterwards. The average population growth rate worldwide is usually between 1.5 to 2%, whereas in Jeddah and nearby localities it has reported to reach up to 20% [56]. Currently, Jeddah's 2023 population is now estimated at 4.86 million, with a growth rate of 1.72% [67]. The geographic distribution of urban settlement in Jeddah City between 1975 to 2011 can be seen in Figure 15 [56].

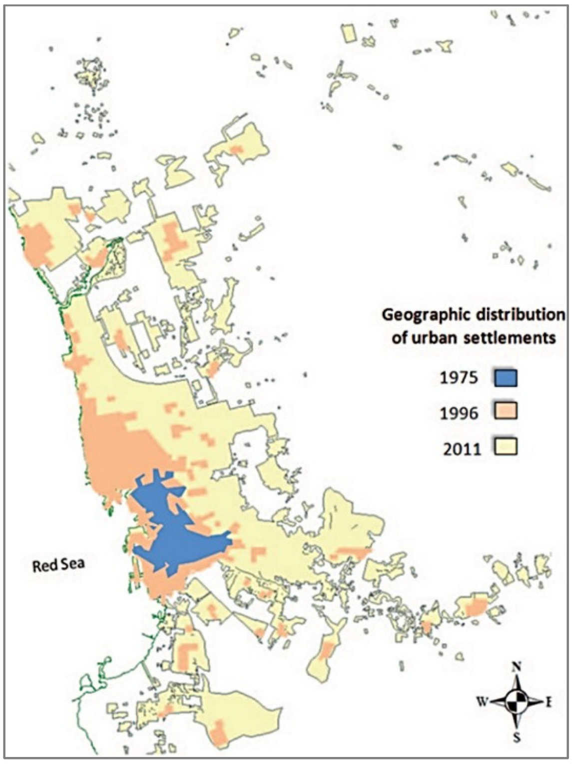

Figure 15. The geographic distribution of urban settlement in Jeddah City between 1975 to 2011 [56].

10. Current Drainage Systems and their Features—Jeddah City

To cope with flash floods, three drainage channels were previously constructed in Jeddah City, namely southern, eastern and northern channels which drain runoff water coming from fifteen catchment areas [68] towards the Red Sea, as shown in Figure 16. Being linked with the major drainage basins comprising several drainage networks, the city has witnessed massive flash events in recent years irrespective of having dams i.e., Al-Samer, Umm Al Khair and an emergency dam [61].

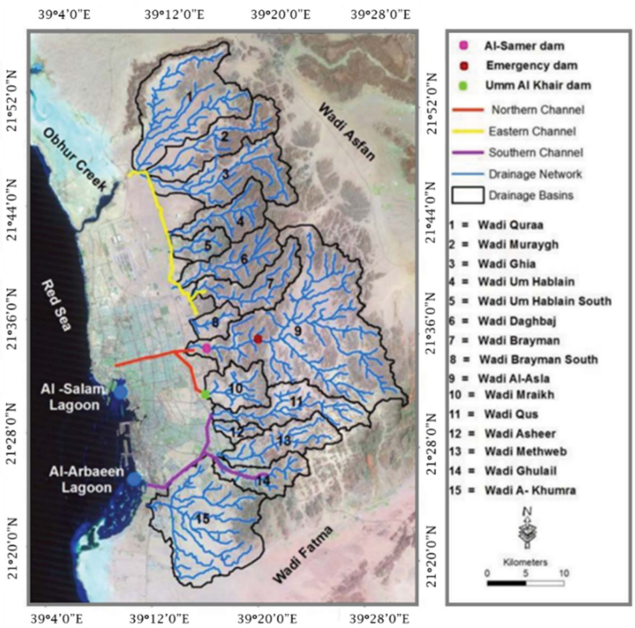

Figure 16. Drainage channels', networks', basins', dams' and wadis' locations for Jeddah City [61].

The runoff from wadis such wadis Qus, Asheer, Methweb, Ghulail and Al-Khumra is covered by the southern channel. Two branches, the northern branch and the southern branch, are further divided into this canal. While the southern branch collects the runoff from wadi Ghulail, the northern branch receives it directly from wadi Qus. The other three catchments, notably wadi Methweb, have reportedly suffered most of the recorded flood damage since they are not connected to the southern channel. Contrarily, the northern channel receives runoff from wadis such as wadi Al-Asla and wadi Mraikh. Each wadi runs through a dam first, then exits into the northern channel, where it joins the canal. Along the wadi Al-Asla catchment, the runoff is carried by two dams, namely Al-Samer and the emergency dam, whereas along wadi Mraikh, the runoff moves along Umm el-Khair dam. Based on inflow and outflow hydrographs, it has been assessed that the capability of the northern channel to cope with the runoff is adequate. Lastly, the eastern channel covers the largest number of catchments including wadis Quraa, Muraygh, Ghia, Um Hablain, Um Hablain south, Daghbaj, Brayman and Brayman south. However, based on the hydrograph assessments, it been stated that the capacity of this channel was less than a 10-year flood event [25].

11. Flood Controls in Jeddah

Flood prevention and management are major issues in Jeddah, which is located in low-lying terrain and is prone to flooding. Several significant floods have occurred in Jeddah in recent years, inflicting widespread damage and disruption [69]. A number of initiatives have been taken by the Saudi government to improve flood control and management in Jeddah [70–72]. In the Jeddah region, precautionary measures have been put in place to lessen the effects and risks of natural hazards. However, not all of these controls are efficient because of varying factors including size, site selection and even engineering techniques. Following the floods and torrential rains that occurred in 2009 and 2011, such an examination was conducted in Jeddah and the surrounding area, and it was discovered that many of the restrictions put in place had little impact. For instance, some of the structures which are old were built with almost no or little safeguard against natural disasters. This is a widespread occurrence along the western Saudi coast. Therefore, fissures and cracks are evident even in the most rigid structures. Thus, engineering standards cannot be blamed, but rather the lack of protection controls [56,73].

Flood control is said to be the most protective measure since it includes (i) building canals that will transport water from valleys to the sea [74], (ii) helping to reduce the flow energy, (iii) establishing tunnels to avoid overflow on roads, (iv) maintaining and cleaning the existing storm channel, etc. After the tragedies of 2009 and 2011, it became imperative to put in place effective measures, particularly for Jeddah City [75,76].

Among the existing flood controls in Jeddah, small-scale flood controls have been witnessed that are usually implemented by individuals or the private sector [77]. These structures are usually inexpensive and of smaller dimensions. The presence of such small-scale flood control is reported to be beneficial in reducing the damage imposed by floods. Examples of small-scale flood control measures involve small-dimension drainage alongside the roads, constructing small-dimension tunnels, creating small-scale dams using rocks to reduce the energy of water flow, etc. [78]. Large-scale flood controls, on the other hand, are measures that are used to protect large areas from flooding. These measures can be very expensive and complex, but they can be very effective in reducing the risk of flooding and its impact. Such measures are usually implemented by the government sector. It has been reported that the precautionary measures in Jeddah were not solely put in place to mitigate floods but also served other purposes, such as preserving arable land and other environmental considerations [79]. The number of large-scale environmental controls in the Jeddah region is insufficient, and many of these controls are only slightly effective for properly responding to the physical processes [73].

Based on the aspects of the damaged areas and investigation of different dimensions affected by floods, some required flood control measures have been proposed for Jeddah

City [56], namely implementation of retaining walls alongside the roads and water ways, valley obstacles that can hinder the flow energy, creating infiltration domains by excavating impervious zones to make them pervious, widening old channels by altering the existing geometric dimensions, crossing canyons and conveying channels alongside wadis, developing hyetographs for flood forecasting, etc. [80].

12. Conclusions

Saudi Arabia is thought to have recently experienced unique climatic conditions. This is obvious due to the recurrent natural disasters and heavy rains that have occurred across many regions in the area. Jeddah's flash floods in 2009 and 2011 are the most major natural disaster occurrences in history. The numerous natural catastrophe occurrences (intense rainfall) that struck various areas of the region made this apparent. Thus, enhancing land-use techniques is necessary in light of the close proximity of flood events. Additionally, transmission networks used to capture flood-related data need to be improved in order to ensure effective flood warning. There is need for development in a number of flood hydrology aspects, including flood volume, rainfall and runoff estimation to disseminate advanced real-time data. It has also been noted that some of the region's major reservoirs are not prepared to handle peak discharges during the flood seasons. Therefore, fighting urban flooding is vital. The coastal management plan requires revisions due to the dense concentration of settlements there. Consequently, the area needs to undertake institutional strengthening efforts and engage in capacity-building activities. Due to the possibility of flash floods, more daily rainfall station networks should be created in addition to flood warning systems at the outlet of every wadi. Additionally, it is important to stop building along the main wadi's channels. More precautions must be taken to reduce hazards: for instance, taking education initiatives; reviewing and implementing the current planning laws and legally forbidding structures in watercourses; carrying out further hydrological modeling studies, particularly those pertaining to urban hydraulics, given the underdeveloped sewer system in Jeddah; etc.

It is important to acknowledge certain limitations in our analysis, however; to address these limitations, future research could incorporate field studies and engage with local stakeholders to gain an in-depth understanding of the region's unique challenges. Additionally, the integration of climate change and land-use models, as suggested, holds promise for enhancing the ability to predict and mitigate flash flood hazards in Jeddah. This review sets the stage for further investigations aimed at bolstering flood resilience in the face of evolving climate dynamics.

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