Effects of geomorphological characteristics on urban expansion of Jeddah city—Western Saudi Arabia: a GIS and Remote Sensing Data-Based Study (1965–2020)

Mohamed Daoudi and Abdoul Jelil Niang

Department of Geography and GIS, Faculty of Arts and Humanities, King Abdulaziz University, Jeddah, Saudi Arabia; Department of Geography, College of Social Sciences, Umm Al-Qura University, Makkah Al-Mukarramah, Saudi Arabia

ABSTRACT
This study aims to highlight the natural risks induced by spatiotemporal interaction between the geomorphological features and the urban growth of Jeddah, the largest city in Makkah Province, Saudi Arabia. The methodology is based on remote sensing and Geographic Information System (GIS) techniques. A spatial analysis of the GIS layers extracted from multisource remotely sensed data from 1965 to 2020 was performed. The results show that the urban area has doubled more than 30 times and has increased from around 36 sq. km in 1965 to more than 1,130 sq. km in 2020. Consequently, the city expands to all morphological units, resulting in multihazard susceptibility and exposure. In order to identify and prioritize the various risks associated to geomorphic processes, a map has been designed to classify the natural risk areas according to their intensity and their factors. Thus, geomorphological constraints have a significant impact on urban planning.

1. Introduction
In the wake of rapid urbanization throughout the world since the early 1970s, Saudi cities have experienced high rates of urbanization and accelerating urban expansion, mostly in the province of Makkah where the study area is located [1–4]. Cities are considered to be indicators of a country’s economic growth and development [1,4–7]. The level of urbanization in Saudi Arabia rose from 21% to 83% between 1950 and 2015 and is expected to reach 90% in 2050 [7]. This represents a higher expected rate than most urbanized regions of the world [1]. However, the utilization of urban land in the form of sprawl is a common problem for Saudi cities [7]. Urban sprawl refers to an uncontrolled, unplanned, and excessive development of urban areas on the fringes of urban agglomerations [8–12] must interact with the geomorphological features and geomorphological processes that are the basis of the natural system’s balance and a major consideration for urbanizable zone selection [13–16]. The selection of sites for the urban settlement, as well as the determination of the areas for future expansion and natural constraints in its growth, are some of the fundamental concerns of management and planning for the urban environment [16]. The initial urban site location is chosen during the founding of a city; it is designated according to one or more priority objectives [17,18]. It is extended by the surrounding spaces permanently included in these areas and potentially faces multiple risks. Geomorphic features and processes have played a very decisive role in the establishment and development of settlements [5,19,20]. Geomorphological units and processes can either constitute a constraint on urban growth, determine and control the direction of urban expansion or exacerbate the natural hazards of built-up areas [21]. However, the location and planning of major cities are generally based on socioeconomic and strategic factors [22–24].

Applied research in geomorphology is considered to be one of the most important areas of study for many development projects because it is used to assess natural potential, identify determinants and available geomorphological barriers and develop appropriate methods for solid urban expansion. Urban geomorphology examines geomorphic constraints on urban development [25], the suitability of different landforms for specific urban uses and the effects of urbanization on natural landforms and urban morphology [14,21,26]. These new urban areas are often based on existing infrastructure and do not always take into account various natural events, geomorphic hazards, geomorphology, or prior scientific studies to assess their suitability for urbanizable land [10,11]. Thus, geomorphological characteristics should be used as a baseline for the planning and management stages of cities’ sustainable development.
urban development [16,20]. Coastal cities are a natural and cultural heritage of environmental and strategic value, with space for economic projects and vital activities while also posing several risks [27–33].

Remote sensing (RS) has become one of the most valuable tools for diachronic analysis on the urban spatial expansion studies. It provides spatiotemporal data and can be combined with GIS in integrated spatiotemporal data to map and monitor the dynamics of urban growth [9,10]. RS coupled with GIS can be used to efficiently assess the impacts of geomorphic features on urban sprawl [9]. The study shows the importance of CORONA satellite images for studies of spatial and temporal changes, as these images are important sources of historical RS data with very high resolution and wide spatial coverage [33]. Population growth and road construction have been identified as the major driving forces of urban expansion [9,18,34]. In the beginning, the urban growth was characterized by its randomness. In recent years, there has been a tendency toward tight urban planning in response to the increasing population needs due to rapid demographic growth, as the city’s population increased from one million in 1970 to more than three million in 2010 [35–41]. Several geomorphological units such as littoral plain, alluvial plain, mountain hills, isolated hills, alluvial fan, sabkha, wadis and volcanic fields, have been affected by the rapid urban expansion, which has in turn affected the surface and its fragility, resulting in the formation and expansion of some dangerous areas [27,42–45]. Among the most important risks that threaten the study area are flooding, soil swelling, landslides and the cracking of buildings and roads.

This research aims to:

- Investigate the geomorphological setting of the study to understand geomorphic constraints on future urban expansion.
- Highlight the influence of geomorphological features and the extent of their control on the expansion and urban planning of Jeddah.
- Determine the type of expansion based on the geomorphological units of the surface or roads from the sea to other areas.
- Highlight the current geomorphological hazards and risks and the role of the nature of landforms regarding the future of urban planning.
- Identify and map the various geomorphic units and their components during the different stages of urban expansion
- Produce a natural hazard classification map according to geomorphological determinants and processes and consider the possibility of generalizing the results of the research to other areas that have the same variables as the sector under study, thereby protecting the environment and serving the community.

The various studies conducted on the city of Jeddah in the field of urban expansion have mainly focused on the vectors of urban development [36], urban planning and management, spatial trends and directions of urban sprawl [6,35,39,41] or the environmental consequences of urbanization [27,46]. Studies concerning risks have mostly highlighted those related to sabkhas [42,44] and floods [45,47]. To the best of the authors’ knowledge, no consistent study has been conducted on the urban geomorphology or interaction between geomorphological units and urban expansion in Jeddah. This research addresses the theme of urban geomorphology for Jeddah. It investigates the multitemporal evolution of the agglomeration of Jeddah and the effects of geomorphological units on the spatial expansion of the city, the direction of the sprawl of the urban fabric, as well as natural risks and urban planning problems induced by geomorphological processes.

2. Study area

The city of Jeddah is located on the Tihamah plain – which has a maximum width of 40 km – at the foot of the Hejaz mountains, which reach heights of hundreds of metres and have granite formations dating back to the Precambrian period. This area of research is situated in the central-western part of Saudi Arabia on the Red Sea coast and is represented by the city of Jeddah and its surroundings, as it is the main urban centre of the western region (Figure 1). The importance of the city is evident for many historical, demographic, economic and urban reasons. For hundreds of years, Jeddah has been regarded as the main entrance and great gate for pilgrims to Makkah Al-Mukarramah. It is also the second largest city in the Kingdom of Saudi Arabia in terms of population after Riyadh. The city has a population of about 4.6 million – 13.2% of the total population of Saudi Arabia – according to 2020 estimates [7]. Economically, the Islamic port of Jeddah is the oldest and largest port in Saudi Arabia in terms of volume of commercial goods and passenger traffic. The port has contributed to the transformation of Jeddah into one of the most important commercial cities in Saudi Arabia. In terms of the urban aspect, the city exceeds 100 km along the Red Sea coast with an average width of about 25 km, making it the largest urban expansion after the capital, Riyadh.

3. Geological and geomorphological characteristics

The topography of the study area consists of a group of remote hills separated by flat terrain and penetrated by a temporary flow that is mostly directed toward the Red Sea. The geomorphological phenomena have
mainly resulted from states of stability and instability in the regional geology, coinciding with the rise and fall of the Red Sea level during the Pleistocene period [48]. On the basis of the texture of surface features, three structural units can be distinguished from the oldest to the most recent, respectively: the Precambrian rock unit, the lava flow unit and the recent sediment unit (Figure 2). The coastal region is surmounted by a transition zone between the Tihamah plain and Hejaz mountains. The Hejaz mountains are considered to be a source of volcanic lava (harrat), where the conical tongues, fracture lines and ancient valley streams coincide. The paths of the hydrographic network have been identified, and most of the lines are fractures, ruptures and fissures that take directions parallel or perpendicular to the stratigraphy of rocks and the Red Sea (Figure 2). They generally represent the appearance and exposure of layers and places of difference in the hardness of the rocks [49–52].

The presence of volcanic tongues with Quaternary sediments has greatly contributed to the settlement of the population and the extension of transport lines of various ranks, mainly linked to alluvial fans. This is a situation that requires determination of the degree of risk according to proximity or distance to areas likely to be at risk of flooding and disasters. Hydrologically, the region contains 24 watersheds, 16 of which face west towards the city of Jeddah, while the other eight face southwest towards the great Wadi Fatima [47] (Figure 2). The surface of the study area consists of the following main units: mountain hills, isolated hills, alluvial fans, sabkhas, harrats (lava deposits) streams, the alluvial plain and the coastal plain (see Figure 4).

4. Material and methods
RS techniques and GIS are among the most important tools used in the continuous monitoring of the spatial distribution of terrestrial phenomena in a broad framework [53–56]. High spatial resolution satellite images are essential documents for studying the historical evolution of rapidly changing phenomena, providing enormous amounts of information from consecutive periods [9,10,53]. This study highlights the importance of multisource and multitemporal satellite imagery with a spatial resolution of up to two metres from 1965 and 1972 and further images from 1986, 2009 and 2020. The methodology for this paper includes an analysis of geomorphological setting and a historical study of urban growth of more than half a century based on data from multiple sources, between 1965 and 2020. This is supplemented by cartographic documents; a Digital Elevation Model (DEM) and field work. Prior to a series of digital image processing, the data were combined into a unified map projection system. It therefore seems important to determine the initial morphology of the surface forms before urban expansion and the extent to which these govern the orientation of the urban planning through the use GIS. The flowchart of the methodology is illustrated in Figure 3.
4.1. Data used

The multitemporal and multisource data sources used in this research include satellite images, aerial photography, a DEM and a digital geologic map. The characteristics of the data are presented below:

- The satellite photographs were acquired in March 1965 and 1972 by the CORONA spy satellite mission (United States Geological Survey [USGS]) and were declassified in 1995. The data are available and can be ordered or downloaded from https://
Figure 4. Geomorphological setting and built-up area of the study area in 1965.

earthexplorer.usgs.gov. The spatial resolution of the photographs used in this study varies between 2 and 3 metres, allowing us to observe the relationship between the morphological and urban characteristics of Jeddah in the 1960s and 1970s when the urban space was concentrated in the coastal and alluvial plains.

- SPOT-CIB satellite images with a spatial resolution of 10 m. This is a set of free panchromatic images that have been geometrically and vertically corrected. The data were obtained between 1986 and 1993 by the French Space Agency and the National Center for Space Studies.
- Color Digital Aerial photography with a spatial resolution of 50 cm, acquired in 2009 by the Saudi General Commission for Surveys.
- Sentinel 2 satellite image acquired in 2020 with a spatial resolution of 10 m.
- DEM Shuttle Radar Topography Mission (SRTM) with a resolution of 30 m.
- Digital geologic map computed by the Saudi Geological Survey (SGS).

The technical specifications of these various data sets are presented in Table 1. The data were obtained from the USGS website https://earthexplorer.usgs.gov, with the exception of the Color Digital Aerial photography of 2009, which were downloaded from https://geoportal.sa. Based on these different data sources, it was possible to monitor the effects of landforms on urban expansion in 1965, 1972, 1986, 2009 and 2020. Note that the reasons for the choice of these uneven time periods are linked to the availability of high resolution remote sensed data for the study area.

4.2. Image processing and geospatial data extraction

Multisource and multitemporal geospatial data were geometrically corrected from control points on the orthorectified reference image, from which all others were rectified using the ERDAS IMAGINE software, aiming at the assessment, map and analyzing the interplay between the geomorphic units and urban growth from 1965 to 2020. The CORONA satellite photography, acquired in 1965 and 1972, captured as many strips were firstly mosaicked. Second, the images were geometrically corrected with carefully selected ground control points (GCPs) using the georeferenced Sentinel 2 projected in UTM and WGS Datum 1984, Zone 37 N as a reference image.

After rectification, it was found that the root mean square error (RMSE did not exceed one pixel, revealing a high geometric match between the different images. The very high spatial resolution of the images minimized errors and improved the precision of the extracted data.
Table 1. Raster datasets used for the study.

| Source no | Data Set type       | Acquisition year | Resolution (m) | Source |
|-----------|---------------------|------------------|----------------|--------|
| 1         | CORONA/Satellite photo. | 1965            | 2              | USGS   |
| 2         | CORONA/Satellite photo. | 1972            | 3              | USGS   |
| 3         | SPOT CIB 10/Satellite image | 1986          | 10             | USGS   |
| 4         | Digital aerial photo | 2009            | 0.5            | SGS    |
| 5         | SENTINEL/2/satellite image | 2020          | 10             | USGS   |
| 6         | DEM/SRTM            | 2014            | 30             | USGS   |

Note that most of the data were aerial photos it was not necessary to carry out an atmospheric correction which was only applicable on the Sentinel 2 image from 2020. In this context we have chosen a visual interpretation for identification of geomorphic features and urban fabric, all the more so as, automatic classification is not always very precise for the delimitation and identification of the different features [53]. All rectified images were exported to ArcGIS to digitize the various features. A GIS geodatabase was created with different layers included. The high-resolution of the CORONA satellite data allowed accurate delineation of urbanized areas and improved the identification and mapping of geomorphological features in the study area by visual interpretation, between 1965 and 1972. GIS layers (polygon) of the initial morphology and geomorphological map of the urban environment that characterized the study area before the rapid urban expansion were produced. The other images from different dates have been used to generate GIS layers illustrating the landforms created by urbanization, the urban morphology and the impact of urban activities on geomorphic processes at different periods. The generated layers were compiled and presented in a GIS database including the geomorphic units’ evolution during the different periods. Spatial analysis techniques with various GIS geoprocessing tools have been utilized in order to appreciate the effects of geomorphological features and their control on the urban expansion of Jeddah. The urban features that are located within each geomorphic feature were highlighted. This provided a visual and historical perspective of the interplay between the urban expansion and geomorphological features or processes. Finally, the spatial extent of the urban settlement located within each morphologic unit were measured. In addition, the geological maps and field investigations permitted the highlighting of map hazards and risk zones.

5. Results

5.1. Initial morphology of the study area before urban expansion

The initial geomorphic units of the study area were identified and mapped from the high-resolution CORONA image of 1965. Figure 4 illustrates the mapping of geomorphological characteristics of the study area in 1965, before the urban expansion of the last few decades. This map includes the major geomorphic units that provide baseline information for urban management and planning. It is the reference for urban geomorphology configuration and can serve to define suitable areas for future urban expansion planning and development. The major geomorphic unit components of the study area are mainly mountainous areas consisting of mountain hills and isolated hills, alluvial fans, harrats (volcanic fields), wadis (streams), sabkhas (salt-crusted depressions), and alluvial and littoral plains. The mountainous areas located in the eastern part of the study area are one of the main factors that influence flood development [23,45]. The altitude in these areas ranges between 150 and 800 m. Many geomorphic hazards and processes are associated with mountainous areas; which constitute a significant constraint to urban expansion and planning.

The distribution of the various geomorphic units is illustrated in Figure 4. The mountains occupy an area of 573 sq. km (24% of the study area), while the harrats and alluvial fans cover 94 sq. km (4%) and 46 sq. km (2%), respectively. The alluvial plain represents the largest part of the study area, covering 897 sq. km (37% of the study area). An area of 435 sq. km (18%) is occupied by valleys and the sedimentary plains of wadis, while the remainder of the study area is covered by littoral or coastal plains (330 sq. km, 14%) or urban areas (36.2 sq. km, only 1.5% of the study area). The urban areas are located mainly on the alluvial plain (28.2 sq. km) and the coastal plain (8 sq. km). The sabkhas account for approximately 26% of the coastal plain.

Note that other relevant terrain related information such as lithology and geological structures were derived from the digital geologic map. This initial morphological framework of the study area indicates that geomorphological features are fundamental determinants of the city’s expansion and development. The increasing demand regarding urban space will exacerbate the geomorphic hazards and processes associated with the various geomorphological units.

5.2. Stages of the urban expansion of Jeddah during 1965–2020

Spatial monitoring of the extent of built-up areas in Jeddah through the use of satellite RS data highlighted a rapid urban expansion of the city during the period of 1965–2020. The city underwent unprecedented changes in its urban growth due to the increase in population and developments in the economy and service sector, which affected the Red Sea coastal strip adjacent to the city due to urban expansion and various land uses, both governmental and private. The map presented in Figure 5 was produced based on visually.
Figure 5. Urban expansions of Jeddah over the years based on visually interpreted using remote sensed data; Corona 1965, 1972, Spot 1986, digital aerial photos 2009 and Sentinel image 2020.

Table 2. Stages of urban growth in Jeddah during the period under consideration (1965–2020).

| Year | Area (sq. km) | Increased area (sq. km) | % to 2020 area | Annual rate (sq. km) |
|------|---------------|-------------------------|----------------|---------------------|
| 1965 | 36.2          | –                       | 3.2            | 0                   |
| 1972 | 77.1          | 41.5                    | 6.8            | 5.9                 |
| 1986 | 605.6         | 528.5                   | 53.5           | 37.7                |
| 2009 | 841.8         | 236.2                   | 74.4           | 10.2                |
| 2020 | 1130.9        | 289.1                   | 100.0          | 26.2                |

Interpreted high spatial resolution images from different sources and years to allow for comparison and evaluation of urban growth patterns in Jeddah since 1965. The GIS baseline layer of the urban fabric was generated by the CORONA satellite photography in 1965, when the city of Jeddah was small and compact after the demolition of the wall that surrounded it in 1947. The urban expansion over the years 1965, 1972, 1986, 2009 and 2020 is shown in Table 2 and Figure 5.

The total urban area covered 36.2 sq. km in 1965, which means that the Jeddah of that time occupied only 3.2% of the city’s current total area. The urban land growth was accelerated and more than doubled in the following seven years; hence, Jeddah came to cover 77.1 sq. km (6.8% of the current area), growing at a rate of 5.9 sq. km per year. The highest rate of urban growth was recorded during the years 1972–1986. This urban explosion corresponds to the oil boom period [33,36,39]; the total built-up area was multiplied by 7.8 and came to cover 605.6 sq. km, with an urban growth rate average of 37.7 sq. km per year. This also means that every year for 14 years, the city of Jeddah gained a piece of urban area greater than the initial urban area it had in 1965, with 53.5% of the actual urban patterns built in this period. Jeddah witnessed an economic opening, public and private investments and oil revenues in the public sector. The private sector also benefitted from government facilities and bank loans, which assisted in increasing the size of the commercial and industrial sectors of the city. In the next period 1986–2009, which is the longest period at 23 years – a deceleration of urban growth was recorded; however, the built-up area increased and reached 841.8 sq. km and the city grew by 236.2 sq. km, with an average rate of 10.2 sq. km per year. This slowdown in urban expansion may have been due to the large increase in the previous period and the advantage that government agencies...
had to acquire land without using it. Land acquisition was instead a means of proving ownership and benefitting from the real estate circulation of land during this period [33]. At present, the city has grown considerably and reached an area of 1,130.9 sq. km, with an annual increase of 26.2 sq. km between 2009 and 2020. Most of this increase has occurred in the northern and eastern directions for residential use or tourist complexes and entertainment projects in northern Jeddah. It is worth noting that urban growth is taking place at the expense of the sea, which has been backfilled over an area of 32 sq. km during the monitoring period for various land use types, namely residential, commercial, investment, governmental and public activities [33].

5.3. Impact of urban growth patterns on initial geomorphology

The ArcGIS Spatial Analyst extension was used to perform geospatial analysis on GIS layers generated from multitemporal images to monitor and evaluate the geomorphic features converted to built-up areas. The Intersect tool was used to identify the geomorphic features located within urban components for each period and calculate the areas of landforms that fell in the urban growth during the 55 years observed.

The results of urban growth at the expense of initial geomorphology are presented in Figures 6 and 7 and Table 3. The total area affected by the urban expansion over the years 1965, 1972, 1986, 2009 and 2020 exceeds 1,000 sq. km. The urban patterns occupied 36.2 sq. km in 1965, equivalent to 1.5% of the study area, at the expense of the Tihamah alluvial plain (28.2 sq. km) and the coastal plain (8 sq. km). During the second period (1965–1972), which coincided with the beginning of the first oil boom, the area of the original morphology affected by urban extent doubled to 77 sq. km (3.2% of the study area) after only seven years. The city began to expand to other morphological units in addition to alluvial and littoral plains (58 and 15.6 sq. km, respectively), particularly the wadis (2.45 sq. km), the sea and alluvial fans (0.7 and 0.24 sq. km, respectively). The most area and the largest percentage of geomorphic features impacted by the urban growth were recorded between 1972 and 1986, with more than a quarter of the study area affected. The city extended in all directions and into all morphological landforms as follows: alluvial plain (346.7 sq. km), littoral plain (192.3 sq. km), wadis (39.8 sq. km), sea and Sharm – a small arm of the sea – (14.8 sq. km), mountain hills (4.5 sq. km), isolated hills (3.5 sq. km), alluvial fans (3.15 sq. km) and harrats (0.85 sq. km). During the longest period 1986–2009, urban expansion was relatively limited compared to the previous period. The built-up area continued to expand on different sides, while urban fabrics were built in the heights and valleys and parts of isolated hills and mountainous hills were removed. The increased built-up area at the expense of the morphological units in the period of 2009–2020 represents a cumulative of all the years observed. The area of the urban patterns occupied about 46% of the original geomorphological area and was distributed as follows: alluvial plain (23.4%), coastal plain (10.3%), wadis (5.7%), sea and Sharm (1.4%), mountain hills (3.1%), isolated hills (1.9%), alluvial fans (0.9%) and harrats (0.2%). This analysis found that the urban areas first occupied low areas (such as the coastal and alluvial plains) but gradually reached the heights. Furthermore, it has been found that the construction of roads has reduced the geomorphological constraints.

Urbanization in mountainous areas and valleys increases the risks related to geomorphology. It should be noted that the granitic rocky hills, basaltic lava blankets and valleys that played roles in preventing the Eastern urban expansion of Jeddah in the early periods of the monitored years seem to have become less influential, particularly in regard to the establishment of roads to facilitate the movement of transport and provide services facilities, as can be seen in Figure 8. Among the manifestations of urban sprawl, we can note unplanned urban settlement on alluvial fans. Through the urban sprawl, the mountainous area neighbouring and beds of streams were occupied by settlements (Figure 8).

In order to identify and prioritize the various risks associated to geomorphic processes, a map has been designed to classify the natural risk areas according to their intensity (high, medium, low) and their factors, both geomorphological and structural (flooding, alluvial fans, slopes, cracks, sabkhas). This risk map represents an important component of risk management and can be used as a guide for urban expansion and planning (Figure 9).

This map is the result of integrated geospatial data including geological information such as lineaments and sabkhas, hydrological processes such as wadi beds, geomorphological processes inherent to geomorphic units, topographical information such as elevations, slopes and field work observations, subsidence and flood areas.

6. Discussion

This study emphasizes the importance of the geomorphologic features for urban growth and planning. Geomorphology is often the basis of the choice of the first site and constitutes a constraint to urban development direction. However, the urbanization is a factor of modification of initial geomorphological setting. Thus, the interaction between the rapid urban expansion and geomorphological processes can result in increasing exposure to natural hazards. This study, like most of the results obtained in similar research show the importance of taking into account geomorphological characteristics for urban development.
plans [5, 15–21, 31, 45, 56, 57]. The majority of these similar studies indicate also that flood Risk and tectonic hazards constitute the most important threat linked the geomorphic hazards in urbanized areas.

6.1. Geomorphological constraint on urban development

The morphological framework mapped in 1965 represents the baseline information for monitoring and planning future urban trends of the study area. Geomorphological features are fundamental determinants of the city’s expansion and development. Geomorphological planning policies are very important in reducing the impact of natural disasters on urban areas [58]. The increasing demand for urban space will exacerbate the geomorphic hazards and processes associated with the various geomorphological units in Jeddah city. The main geomorphological features identified in this study are units of varying origin, including structural, fluvial, erosional and depositional. The mountainous areas are an important constraint that affects urban growth. The elevated area of Jeddah city has been subject to hazardous geomorphological processes (such as mass wasting) and fluvial geomorphological processes during the catastrophic floods of Jeddah in 2009 and 2011. In this sector the flow turns into torrents which can be defined as a stream of water flowing with great rapidity and violence. This part of the city was the most damaged area during these events [7, 43, 45, 47, 59, 60].

Figure 6. Urban expansion on expense of the original geomorphology during period 1965–2020.

Figure 7. Percentage of increase in urban expansion at the expense of the morphological units during the years of observation.
### Table 3. Areas in sq. km and percentages of the urban extent on the geomorphic units during the years of observation.

|                  | 1965  | 1972  | 1986  | 2009  | 2020  | 1965  | 1972  | 1986  | 2009  | 2020  |
|------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|                  | Area  | %     | Area  | %     | Area  | %     | Area  | %     | Area  | %     |
| Sea              | 0     | 0.02  | 0.7   | 0.02  | 14.8  | 0.6   | 18    | 0.7   | 33.3  | 1.4   |
| Littoral plain   | 8     | 0.34  | 15.6  | 0.6   | 192.3 | 7.9   | 220.6 | 9.2   | 246.6 | 10.3  |
| Sabkha           | 28.2  | 1.16  | 58    | 2.4   | 346.7 | 14.3  | 449.7 | 18.6  | 569.6 | 23.4  |
| Wadi             | 0     | 0.01  | 0.24  | 0.0   | 3.15  | 0.13  | 10    | 0.4   | 20.2  | 0.9   |
| Alluvial fan     | 0     | 0.01  | 0.01  | 0.0   | 3.5   | 0.14  | 24.5  | 1.01  | 47.6  | 1.9   |
| Harrat           | 0     | 0.01  | 0.01  | 0.0   | 4.5   | 0.18  | 28.4  | 1.2   | 72.7  | 3.1   |
| Isolated Hills   | 0     | 0.01  | 0.01  | 0.0   | 4.5   | 0.18  | 28.4  | 1.2   | 72.7  | 3.1   |
| Mountain hills   | 0     | 0.01  | 0.01  | 0.0   | 4.5   | 0.18  | 28.4  | 1.2   | 72.7  | 3.1   |
| Total            | 36.2  | 1.5   | 77    | 3.2   | 605.6 | 25.1  | 841.7 | 34.9  | 1130.9| 46.9  |

![Figure 8. Potential risks on urban expansion in mountainous areas and valleys between 1965 and 2020.](image)

6.2. The interaction between geomorphic processes /hazards and urban sprawl

The interplay between geomorphic units and urban growth from 1965 to 2020 can be analyzed from different perspectives. The interrelations between natural landforms and urbanization are complex [21]. The geomorphological processes may increase disaster risk. These interrelationships were noted during the different stages of development of Jeddah between 1965 and 2020. The geomorphological features of the coastal area have been profoundly modified during the observation period [20,62]. Consequently, risks related to geomorphological processes threaten all recreative infrastructures and roads built along the coastal area [33,57].

The constraint formed by the mountains is marked in certain places by the appearance of mountainous areas surrounded by unplanned urban settlement in the eastern zone of the study area, this is apparent in
places where the mountains could not be removed. The urban sprawl extended to the mountains during recent decades after the alluvial plains and isolated hills. Thus, urban sprawl has become the main challenge of urban growth management at the local level.

6.3. Geomorphic hazards implications of urban expansion

Various geomorphic hazards are associated with areas of urban expansion can be observed in the field (Figure 10). The expansion of new urban masses on the beds of the wadis has led to exposure to frequent catastrophic floods, such as those that occurred in 2009, 2011 and 2017. The topographical and geological characteristics of the mountainous regions mean that these torrents (large streams of water that moves very fast) carry with them huge quantities of sediment with gravel, sand, silt and clay textures, which increases the risk of flooding. Furthermore, the existing drainage channels are not sufficient to absorb the quantities of floodwater. To protect the city from the risk of flooding and to find urgent solutions to these dangers, dams have been built across streams in some valleys [45].

In addition, the alluvial fans overlooking the plain of Wadi Fatimah, located in the southeast and upon which urban blocks are installed and crossed by some main roads (Figure 8), are very vulnerable to flood and can be more dangerous than other places. This is because they carry huge quantities of sediments of different sizes and erosion products from the top of the catchment area. Urban growth also involves geomorphological effects that lead to units of anthropogenic origin, including drainage and stream channel modifications, destruction of initial geomorphological features and modification of natural geomorphic processes all of which have contributed to the worsening of flooding problems.

There are also risks related to geology, including numerous long faults visible on the geological map and risks of subsidence related to tectonics which are observed in certain sections of the city and should be considered for future urban planning. Among these tectonics’ risks observed in the field, we can note swelling of the ground and the cracking of buildings and roads (Figure 10), including the Al-Haramain project, asphalt cracks on the Abdulaziz bin Al-Baz street and cracking of the embankment areas, broken embankments in the Al-Sanabel and Al-Ajaweed plans, cracking on several
streets in the Al-Tayseer plan and landing activity in the Riyadh plan and on Usfan road. Also, to be noted are the sabkha areas north and south of Jeddah that are close to the sea, as well as cracks due to the salinity of the soils and the nature of the surface formations [33,44].

6.4. Growth direction and future perspective

It is essential to understand and integrate the geomorphological environment choosing suitable lands for future urban expansion and to reduce the associated geomorphic risks. The multitemporal analysis of the RS data of Jeddah city indicates that the expansion occurred toward the northern and southern directions along the coast and coastal plain during the first decades due to existence of geomorphological constraints in the east, such as streams and mountainous areas. The axes of the urban expansion in mountainous areas are linked to the lithology and the degree of slope. This has played an important role in the urban delimitation patterns. Population growth is the main driving force behind the urban expansion of the city, both in terms of providing housing and space for infrastructures, and for public and social services and economic activities. Jeddah has experienced faster and larger population growth than other Saudi Arabian cities, reflecting the economic development of the Kingdom of Saudi Arabia [33,42]. There are currently unplanned urban settlements and land subdivisions outside current urban footprints and urban sprawl has become the main challenge of urban growth management at the local level (7). The rapid urban expansion occurred randomly without taking geologic and geomorphic situations into consideration which has contributed to increasing geomorphic risks especially in the context of climate change.

7. Conclusion

This study emphasizes the importance of geomorphological characteristics for urban growth and planning. The geomorphological setting is often the basis of the choice of the first site and constitutes a constraint to the urban development. This study has also demonstrated that RS and GIS techniques are effective tools to monitor and map geomorphological processes and hazards related to urban expansion. They provide spatiotemporal data and can be combined with GIS in integrated geospatial data to better understand the progressive changes in natural hazard risk induced by the dynamic of urban growth. The results indicated significant urban expansion since 1965. The total built-up area has grown rapidly from around 36 sq. km in 1965 to more than 1,130 sq. km in 2020. During this
period, more than 1,000 sq. km of geomorphological units were converted into built-up areas. The expansion occurred firstly toward the northern and southern directions due to existence of geomorphological constraints in the east, such as streams and mountainous areas. The urban growth towards mountain regions in recent years, involves geomorphic hazards and urban sprawl which have contributed to the worsening of flooding problems. Consequently, all future urban planning projects related to the expansion of the city from the eastern slope should contain an appropriate solution to the problems of flooding and determinants related to the geomorphological characteristics. In addition, various risk zones appear in several places in the city. To reduce disaster risks, urban planning and spatial organization work have become necessary. Thus, natural hazard classification map, according to their intensity and their driving forces, represents an important component of risk management and can be used as a guide for future urban expansion and planning.

Acknowledgements

The research team would like to thank the Deanship of Scientific Research at King Abdulaziz University for its financial support for this investigation (Project Number G:196-125-1441).

Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

Mohamed Daoudi http://orcid.org/0000-0003-1734-7564
Abdoul Jelil Niang http://orcid.org/0000-0003-4609-6055

References

[1] United Nations, Department of Economic and Social Affairs, Population Division, World Urbanization Prospects: The 2018 Revision (ST/ESA/SER.A/420). New York: United Nations; 2019.
[2] Moustapha AF, Costa FJ, Noble AG. Urban development in Saudi Arabia: building and subdivision codes. Cities. 1985;2(2):140–148.
[3] Al-Hathloul S, Mughal MA. Urban growth management: the Saudi experience. Habitat Int. 2004;28(4):609–623. doi:10.1016/j.habitatint.2004.02.003.
[4] Alahmadi M, Atkinson PM. Three-Fold urban expansion in Saudi Arabia from 1992 to 2013 observed using calibrated DSM-OLS night-time lights imagery. Remote Sens. 2019;11:2266. doi:10.3390/rs11192266.
[5] Mohapatra SN, Pani P, Sharma M. Rapid urban expansion and its implications on geomorphology: a remote sensing and GIS based study. Hindawi Publishing Corporation Geography J. 2014, Article ID 361459: 10. doi:10.1155/2014/361459.
[6] Hegazy I, Helmi M, Qurnfulah E, et al. Assessment of urban growth of Jeddah: towards a liveable urban management. Int J Low-Carbon Technol. 2021;16(3):1008–1017. doi:10.1093/ijlct/ctab030.
[7] UN-Habitat, Saudi Cities Report 2019, Ministry of Municipal and Rural Affairs, 2019 King Fahd National Library Cataloging-in-Publication Data, Riyadh: 2019. 234 pages. https://unhabitat.org/saudi-cities-report-2019, last accessed 03 October 2021.
[8] Pozoukidou G, Ntriankos I. Measuring and assessing urban sprawl: A proposed indicator system for the city of Thessaloniki, Greece. Remote Sens Appl: Soc Environ. 2017;8:30–40. doi:10.1016/j.rsasse.2017.07.005.
[9] Xu T, Gao J. Controlled urban sprawl in Auckland, New Zealand and its impacts on the natural environment and housing affordability. Comput Urban Sci. 2021;1(16). doi:10.1007/s43762-021-00017-8.
[10] Ahmad F, Goparaju L. Analysis of Urban sprawl Dynamics using geospatial Technology in Ranchi City, Jharkhand, India. J Environ Geography. 2016;9(1–2):7–13. doi:10.1515/jengeo-2016-00023.
[11] Rai K. Urban Sprawl analysis using GIS Application of Bhagur City. Int J Res Appl Sci Eng Technol. 2021;9:861–868.
[12] Chetry V, Surawar M. Urban sprawl assessment in eight Mid-sized Indian Cities using RS and GIS. J Indian Soc Remote Sens. 2021. doi:10.1007/s12524-021-01420-8.
[13] Le Berre I, Robert S. L’urbanisation face à l’océan. Agathe Euzen; Françoise Gall; Denis Lacroix; Philippe Cury. L’océan à découvrir. CNRS éditions. 2017:208–209. 978-2-271-11652-9. halshs-01626607.
[14] Thornbush M. Geography, urban geomorphology and sustainability. Area. 2015;47(4):350–353. doi:10.1111/area.12218.
[15] Csima P. Urban development and Anthropogenic geomorphology. In: Szabó J, Dávid L, Lóczy D, editors. Anthropogenic geomorphology. Dordrecht: Springer; 2010. doi:10.1007/978-90-481-3058-0_12.
[16] García PMB, Augustin CHRR, Casagrande PB. Geomorphological index as support to urban planning. Mecator, Fortaleza, v 19. dec.(2019). doi:10.4215/rm2020.e19003.
[17] Kilicoglu C, Cetin M, Aricak B, et al. Integrating multicriteria decision-making analysis for a GIS-based settlement area in the district of Atakum, Samsun, Turkey. Theor Appl Climatol. 2021;143:379–388. doi:10.1007/s10661-021-08562-1.
[18] Kilicoglu C, Cetin M, Aricak B, et al. Site selection by using the multi-criteria technique—a case study of Bafra, Turkey. Environ Monit Assess. 2020;192:608. doi:10.1007/s10661-020-08562-1.
[19] Persico L, Lanman H, Loopesko L, et al. Geomorphic processes influence human settlement on two islands in the Islands of four Mountains, Alaska. Quat Res. 2019;91(3):953–971. doi:10.1017/qua.2018.112.
[20] Pareta K. Geomorphic control on urban expansion a case study of Sagar Town (M. P.). Int J Adv Sci Tech Res. 2012;1(2).
[21] Reynard E, Pica A, Coratza P. Urban geomorphological heritage. An overview. Questiones Geographicae. 2017;36(3):7–20. Bogucki Wydawnictwo Naukowe, Poznan.
[22] Bathrellos GD, Gaki-Papanastassiou K, Skolidoumou HD, et al. Potential suitability for urban planning and industry development using natural hazard maps and geographical–geomorphological parameters. Environ Earth Sci. 2012;66:537–548. doi:10.1007/s12665-011-1263-x.
[23] Youssef AM, Pradhan B, Sefry SA, et al. Use of geological and geomorphological parameters in potential suitability assessment for urban planning development at Wadi
Al-Aslā basin, Jeddah, Kingdom of Saudi Arabia. Arab J Geosci. 2015;8:5657–5660. doi:10.1007/s12517-014-1663-9.

Hassan A, Almatar MG, Torab M, et al. Environmental urban plan for Failaka Island, Kuwait: a study in urban geomorphology. Sustainability. 2020;12:7125.

Cooke RU. Geomorphological hazards in Los Angeles: A study of slope and sediment problems in a metropolitan county. London: Allen & Unwin; 1984.

Mandarino A, Faccini F, Terrone M, et al. Anthropogenic landforms and geo-hydrological hazards of the bisagno stream catchment (Liguria, Italy). J Maps. 2021;17(3):122–135. doi:10.1080/17446567.2020.1866704.

Basaham AS, Rifat AE, El-Sayed MA, et al. Sharm obhur: Environmental consequences of 20 years of uncontrolled coastal urbanization. JKAU MarSci. 2006;17:129–152. A.D./1427 A.H.

Martínez ML, Intralawan A, Vázquez G, et al. The coasts of our world: ecological, economic and social importance. Ecol Econ. 2007;63(2–3):254–272. doi:10.1016/j.ecolecon.2006.10.022.

EL-Raey M. Impact of Climate Change: Vulnerability and Adaptation Coastal Areas in Tolba, M.K. and N. Saab (Eds): Arab Environment: Climate Change. Impact of Climate Change on the Arab Countries; report of the Arab Forum for Environment and Development (2009).

Al-Sheikh A. Management of environmental degradation of Jeddah coastal zone, Saudi Arabia, using remote sensing and geographic information systems. J Am Sci. 2011;7(5):665–673. http://www.jofamericanscience.org/journals/am-sci/am0705/95_5414am0705_665_673.pdf.

Gupta A, Ahmad R. Geomorphology and the urban tropics: building an interface between research and usage. Geomorphology. 1999;31:133–149. doi:10.1016/S0169-555X(99)00076-8.

Karim N, Wael E, Mahmod H, et al. Raised Coral Reefs and Sedimentary environments of Haddat Ash Sham Ironstones, Western Arabian Shield, Saudi Arabia. Asian Trans Basic Appl Sci. 2015;8:5617–5630. doi:10.3133/pp560A.

Brown GF, Schmidt L, Dwight H, et al. Geology of the Arabian Peninsula. Shield Area of Western Saudi Arabia. U.S. Geological Survey Professional Paper 560-A, US Government Printing Office, Washington, (1989)n pp 158–161. doi:10.3133/pp560A.

Mansour AM, Madkour HA. Raised Coral Reefs and Sediments in the Coastal Area of the Red Sea in Rasul and I.C.F. Stewart (eds.), The Red Sea, Springer Earth System Sciences; 2015. doi:10.1007/978-3-662-45201-1_23.

Al Saud M. Assessment of flood hazard of Jeddah area 2009, Saudi Arabia. J Water Resour Prot. 2010;2:839–847. https://www.scirp.org/pdf/JWARP20100900007_90229224.pdf.

Brown GF; Schmidt L, Dwight H, et al. Geology of the Arabian Peninsula. Shield Area of Western Saudi Arabia. U.S. Geological Survey Professional Paper 560-A, US Government Printing Office, Washington, (1989)n pp 158–161. doi:10.3133/pp560A.

Moufifi MR, Hashad MH. Volcanic Hazards assessment of Saudi Arabian Harrats: geochemical and isotopic studies of selected areas of active Makkah-Madinah-Nafud (MMN) volcanic rocks. Final project Report (LGP-5-27) submitted to King Abdulaziz City for Science and Technology, Riyadh, Saudi Arabia.

Mirza M. Structural and morphological aspects of the lava field (Harrat) in western Saudi Arabia with special reference to the central basaltic area (case study: Harrat Kushib). Educ Soc Human J Umm Al-Qura Univ. 2008;20:297–382. (in Arabic).

Taj RJ. Stratigraphic setting, facies types and depositional environments of Haddat Ash Sham Ironstones, Western Arabian Shield, Saudi Arabia. Asian Trans Basic Appl Sci. 2011:1–2.

Dauodi M. Use of Remote Sensing in the Detection and Discrimination the Lineaments in North-east of Jeddah, Saudi Arabia. Journal of Service Center for Research Consulting, Faculty of Arts, Division of Geographical Studies and Research, Menoufia University, Egypt; 2015. 27p, (in Arabic).

Alenezi NSAA. Analysis of Urban Growth and Trends in Jeddah Using Remote Sensing Techniques and Geographic Information Systems. PhD Thesis, (2019) Umm Al Qura University, 269p.

Peter V. Jeddah’s environmental problems. Geogr Rev. 2003;93:3. ProQuest.

Dauodi M. Risque d’inondation et vulnérabilité de la ville de Jeddah, Arabie saoudite. Geo Eco Trop. 2014;38(2):259–270. http://www.geocetopreb.fr/uploads/publications/pub_382_03.pdf.

Tsatsaris A, Kalogeropoulos K, Stathopoulos N, et al. A case study of the City of Olsztyn, Remote Sens. 2020;12(11):1784. doi:10.3390/rs12111784.

Tsatsaris A, Kalogeropoulos K, Stathopoulos N, et al. Geoinformation Technologies in support of Environmental hazards monitoring under Climate Change: An extensive review. ISPRS Int J Geoinf. 2021;10(2):94. doi:10.3390/ijgi10020094.

Berila A, Isfui F. Two decades (2000–2020) Measuring urban sprawl using GIS, RS and landscape metrics: a Case Study of municipality of Prishtina (Kosovo). J Ecol Eng.
[56] Niang AJ, Hermas E, Alharbi O, et al. Monitoring landscape changes and spatial urban expansion using multi-source remote sensing imagery in Al-Aziziyyah Valley, Makkah, KSA. The Egypt J Remote Sens Space Sci. 2020;23(1):89–96.

[57] Daoudi M, Niang AJ. Detection of shoreline changes along the coast of Jeddah and its impact on the geomorphological system using GIS techniques and remote sensing data (1951–2018). Arab J Geosci. 2021;14:1265. doi:10.1007/s12517-021-07605-2.

[58] Adeli Z, Khorshiddoust A. Application of geomorphology in urban planning: Case study in landfill site selection. Procedia - Social Behav Sci. 2011;19:662–667. doi:10.1016/j.sbspro.2011.05.183.

[59] Almodayan A. Analytical hierarchy (AHP) process method for Environmental Hazard mapping for Jeddah City. Saudi Arabia J Geosci Environ Prot. 2018;6:143–159. doi:10.4236/gep.2018.66011.

[60] Youssef AM, Sefry SA, Pradhan B, et al. Analysis on causes of flash flood in Jeddah city (Kingdom of Saudi Arabia) of 2009 and 2011 using multi-sensor remote sensing data and GIS. Geomatics, Nat Hazards Risk. 2016;7(3):1018–1042. doi:10.1080/19475705.2015.1012750.

[61] Daoudi M. A systematic approach to assess the impact on the environment: Flood Risk model. Egypt J Environ Change. 2015;7(2):43–52. (in Arabic). https://ejecsite.files.wordpress.com/2016/12/3-10.pdf.

[62] Daoudi M. From A Geomorphological Field to An Urban Expansion Space: The Case of Sharm Abhur in North Jeddah - Saudi Arabia. Geographical and Cartographic Research Series, Geographical and Cartographic Research Center, Faculty of Arts, Menoufia University, Egypt; 2015. (in Arabic).