Geospatial modelling of tropical cyclone risks to the northeast coasts of Oman: Marine hazard mitigation and management policies

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Abstract

Globally, an increasing and more dispersed population, as well as climate change, have led to growing impacts of environmental hazards, particularly across areas prone to extreme weather events such as tropical cyclones. Tropical cyclones frequently cause fatalities, damage to infrastructure, and disruption to economic activities. The north and northeast regions of Oman, particularly the Oman seacoast, are prone to the storm surges, windstorms and extreme precipitation events associated with these tropical storms. However, integrated spatial risk assessments, for the purpose of mapping cyclone risk at subnational geographic scales, have not yet been developed in this area. Here we evaluate and map cyclone risk using four independent components of risk: hazard, exposure, vulnerability and mitigation capacity. An integrated risk index was calculated using a geographical information system (GIS) and an analytical hierarchical process (AHP) technique, based on a geodatabase including 17 variables (i.e., GIS data layers) and criteria, with rank and weight scores for each criterion. The resulting risk assessment reveals the spatial variation in cyclone risk across the study area and highlights how this variation is controlled by variations in physical hazard, exposure, vulnerability and emergency preparedness. The risk maps reveal that, despite their perceived adaptive capacity for disaster mitigation, the population and assets in low-lying lands situated near the coastline in the east of Muscat, as well as the Al-Batnah south governorates, are at high risk due to cyclones. Furthermore, the coastal zones of the urban Wilayats of the Muscat governorate were also found to be at high, to very high, risk. This study has several policy implications and can provide effective guidelines for natural hazard preparedness and mitigation across the northern coasts of Oman.

Keywords: Cyclone risks, GIS, AHP, spatial modelling, index, mitigation policy

1. Introduction

Around the world, hydro-meteorological events pose a significant hazard to exposed populations and infrastructure. For example, between 2005 and 2014, 83% of all recorded natural disasters were climate-related, affecting 95% of the total vulnerable population (Erickson et al., 2019; Parida et al.,2018). Globally, between 1970 and 2019, almost 79% of all disasters were weather-, climate- and water-related and these accounted for 56% of deaths from all reported natural disasters (WMO, 2020). Alarmingly, risk is increasing due mainly to increasingly large populations living in hazardous areas. In addition, the hazards themselves are increasing as a result of climate change which contributes further to the overall increase in risk (Walsh et al., 2016; Anderson & Bausch, 2006). Moreover, the number of people who will become exposed to climate-related hazards such as rising sea-levels, cyclones and storm surges, is expected to increase in the future (Vousdoukas et al., 2018; Muis et al., 2016).

Tropical cyclones are one of the most socio-economically damaging and environmentally destructive hazards, affecting millions of people each year, particularly those living close to coasts (e.g. Schmidt et al., 2010; Cinco et al., 2016; Mallick et al., 2017, King & Gurtner, 2005). Caused by specific meteorological conditions, tropical cyclones generate thunderstorms, high-speed winds (which, in turn, can generate hazardous storm surges) and heavy rainfall (with attendant risks of pluvial and fluvial flooding). Thus, tropical cyclones often result in a large number of deaths, as well as substantial damage to property and infrastructure, particularly in coastal communities (Wu et al., 2002; Saha et al., 2015; Woodruff et al., 2013; Appeaning Addo, 2011). In deprived areas and developing countries, the effects of cyclones can be long-lasting, destroying public services such as drinking water, electricity cables, sewage, communication towers and other vital infrastructure, disrupting daily life and leading to cascading risks associated with disease outbreaks and impeding emergency aid (e.g. Bhunia & Ghosh, 2011; Ivers & Ryan, 2006; Kang et al., 2015; Patra et al., 2015).

It has been estimated that in the 21st century, if global warming and climate change continue their current trends, tropical cyclone intensities will increase (IPCC, 2019; Knutson et al., 2010; Wehner et al., 2019), with wind speeds expected to rise by 10%, and precipitation rates by almost 20% within 100 km of the cyclone eye. Increasing the resilience of communities that are exposed to tropical cyclones is, therefore, of critical importance in ongoing efforts to reduce the destruction, damage and loss of life caused by them (e.g. Beer et al., 2014; Woodruff et al., 2013; Anderson-Berry & King, 2005). A critical first step in such efforts usually involves the need to undertake accurate spatial assessments of cyclone-prone areas to help guide policy makers in their efforts to develop policy interventions, including emergency preparedness and response plans (Rao & Rao, 2008; Hoque et al., 2018; Mansour, 2019).

Many cyclones have struck the Arabian Sea and Oman Sea region during the last decade. For example, the super cyclone Gonu 2007 was a powerful storm recorded in the Arabian Sea (Deshpande et al., 2010) and in June 2010, the category 5 cyclone Phet affected southeast Yemen and Oman, as well as striking the Sistan and Baluchestan Provinces in Iran (Rahimi et al., 2015). In May 2018, the category 3 cyclone Mekunu made landfall across the southern coasts of Oman and impacted low-lying areas, particularly along the Salalah coasts (Mansour, 2019). Cyclone Chapala made landfall near the port of Mukalla in Yemen in 2015, with intense precipitation and windspeed impacting infrastructure and causing significant damage to coastal properties (Sarker, 2018). In October 2018, cyclone Luban occurred in the Bay of Bengal and the Arabian Sea, affecting the southeast coasts of Yeman and al-Mahra governorate (Jangir et al., 2020).

With a coastline extent of almost 3,165 km, stretching from Musandam in the far north to the administrative Republic of Yemen in the south-west, and overlooking three seas (the Arabian/Persian Gulf, the Sea of Oman and the Arabian Sea), Oman is particularly exposed to the effects of tropical cyclones. However, very few studies have been conducted to address the impact of tropical cyclones on Oman, and those that do exist have focused on Oman's southern coastlines, and particularly on the coastal communities there. For example, the study of Mansour (2019) analysed the effects of cyclones on the coastal Wilayat of Dhofar governorate across the southern coasts of Oman. In another study, Al Ruheili et al. (2019) used a 3D hydrodynamic model to assess quantitively property and infrastructure damage due to the flash flooding of dry riverbeds as a result of exposure to the 2002 cyclonic storm (ARB01) in the Dhofar governorate. Although the north-eastern coasts of Oman are also clearly prone to extreme, severe and devastating cyclones, which can cause large scale damage to socioeconomic infrastructure and loss of lives, there is an absence of studies assessing exposure and risk in this specific area. While the largest impacts of cyclones are expressed in coastal areas and urban communities, the socioeconomic effects can nevertheless also be severe in interior areas, especially rural areas. For example, rural infrastructure such as farms, roads, crops, dairy houses and livelihoods are all vulnerable to the impacts of cyclones (Hossain et al., 2008; Ryan et al., 2015).

For all the above reasons, detailed assessments of cyclone effects in Oman are needed urgently to evaluate the risk in different areas (e.g. Mansour, 2019; Hoque et al., 2018; Hoque et al., 2019). The outputs of spatial risk models would be especially helpful in providing ways to prioritise the allocation of resources to reduce the destructive consequences of cyclones, enabling decision-makers to develop effective strategic plans for disaster risk reduction, as well as operational plans for disaster management.

It is recognised that the spatial evaluation of cyclone risk can be invaluable to decision-makers and governors, enabling them to quantify the risk and put in place appropriate policy measures and mitigation plans. Thus, spatial risk analysis has been widely studied in the literature, particularly for cyclone disasters. In particular, the use of GIS and advanced geospatial techniques have been recognised as effective approaches in the spatial assessment of vulnerability and exposure to cyclones (e.g. Sahoo & Bhaskaran, 2018; Mansour, 2019, Hoque et al., 2018; Hoque et al., 2019). However, while the northeast coasts of Oman are susceptible to extreme cyclones and storm surges, studies assessing the risks of cyclone impacts using geospatial techniques at the subnational geographical scale are still rare. Apart from Mansour (2019), who employed geospatial techniques to model cyclone risk to the southern coasts of Oman, other published articles were based solely on non-spatial analysis (Fritz et al., 2010), or have addressed only atmospheric forcing and related variables (e.g., Bhutto et al., 2017; Sarker, 2017). Consequently, this paper aims to fill the knowledge gap by deploying geospatial modelling techniques to create spatial indices of cyclone hazard, exposure, vulnerability and mitigation across the coasts of the Oman Sea, and then combining these components into a single risk index.

2. Study area and data sources

The study area comprises 22,924 km^2 consisting of 22 Wilayats (states) distributed administratively amongst six governorates (Figure 1). The Muscat governorate (3,796.7 km^2) comprises six Wilayats, of which five are coastal and one, Al-Amrat, that does not border the Oman Sea coastline. Each governorate of Al-Batnah North (7,899.3 km^2) and Al-Batnah South (5,323.1 km^2) is divided into six Wilayats, both physically forming the natural region called the Al-Batnah coastal plain. In addition, two Wilayats (Samail and Bidbid) belong administratively to the Al-Dakhaliya governorate, while Dama Watayian and Sur are located within Al-Sharkya South and Al-Sharkya North, respectively. Except for four coastal Wilayats (Muscat, Mutruh, Bawshar, Aseeb) within the Muscat governorate that are considered urban zones, the rest of the administrative units involve a mixture of both urban and rural settlements.

The study area, with a population of 2.9 million inhabitants in 2019, is the most densely populated region of Oman, accounting for almost 62.5% of the total population (NCSI, 2019). The study area's geographical location, settlement concentration, large population and socio-economic conditions have rendered this area particularly exposed to cyclones. The exposure is high due to the accelerating growth of economic development as well as urbanisation. Hence, the region comprises a high percentage of the country's capital stocks and assets. Thus, measurement and spatial modelling of vulnerability and exposure of these assets to cyclone disasters is crucial to help decision-makers develop effective guidelines and risk mitigation plans.

Figure 1 Location of the study area. (Upper panel) 1(black lines show all cyclones during 1842-2021): the green line denotes an unnamed cyclone in 1898, the purple line the 2010 cyclone Phet, and the red line the 2007 cyclone Gonu). (Lower panel) Administrative zones of subnational boundaries (blue boundaries indicate the governorate level while the grey boundaries represent the Wilayat level.

2.2 Data sources

To model the effects of tropical cyclones on the coasts of the Oman Sea, a geodatabase was created, using several spatial layers and attribute datasets derived from various international and national sources (Table 1). The data layers included various atmospheric, topographical, demographic and geographical variables, which were converted into spatial criteria utilising GIS and spatial analysis techniques. For the operational modelling process, numerous steps were implemented using the ArcGIS (v.10) software to calculate indices of exposure and vulnerability to cyclones, and mitigation capacity, as discussed in section 3.

Table 1 Data sources of the spatial layers and parameters used in this study.

Data layers	Source
DEM (30m)	USGS: source: http//www.edc. usgs.gov
Cyclone track	NOAA, National Center for Environmental Information
Cyclone wind speeds	Wind speed of the storms (NOAA)
Cyclone storm heights	Ministry of Environment and Climate Affairs of Oman
Cyclone shelters	Muscat Municipality, Oman
Administrative boundary map	National Center for Statistics and Information (NCSI), Oman, 2020
Capital stocks and assets	World Development Indicators (WDI), 2020
Land use 2017	LANDSAT - 7 ETM+ Satellite Imagery (30 m Spatial Resolution)
Topographical map	Ministry of Environment and Climate Affairs of Oman, 2019
Road network	Supreme Committee of Town Planning and Ministry of Housing, Oman, 2019
Population and settlements	National Center for Statistics and Information (NCSI), Oman, 2019
Hospitals and defense centers	National Center for Statistics and Information (NCSI), Oman

2.3 Generation of spatial variables

A spatial database was created incorporating all vector and raster layers, attributes and other variables. All layers were created and projected into the Universal Transverse Mercator (UTM) zone 40 North and World Geodetic System (WGS)-1984 datum within the GIS platform. A conversion process was implemented where vector layers were converted into raster layers, and Euclidean distances and reclassification techniques were performed to generate spatial variables (Table 2).

Cyclone risk is the expected loss (i.e., destructive or damaging consequences) resulting from interactions between components of the system including: (i) hazard (i.e. a cyclone event of given magnitude and its probability of occurrence); (ii) exposure (i.e. the population exposed to cyclones), (iii) vulnerability (i.e. the propensity of exposed places to suffer from adverse effects when they are impacted by cyclone occurrence), and (iv) mitigation potential. To model the spatial distribution and variation in cyclone risk, a multicriteria evaluation (using the criteria listed in Table 2) was utilised as a basis for criteria scoring, ranking and weighting indices for the four drivers of overall risk. The characteristics of each criterion, and the mapping procedures, are described in the following subsections.

Table 2 Overview of the selected criteria and techniques employed in this research to calculate indices of cyclone hazard, physical and socioeconomic exposure, vulnerability and mitigation capacity.

Criteria	Method of calculation	Rationale	Relation to risk
Hazard variables:			
Cyclone intensity	Kernel density estimation applied to historical (1898-2010) tropical cyclone tracks	The devastating effects of cyclone increase towards the cyclone eye (Chang et al., 2009). locations that are located close to the eye expose to strong wind, heavy rainfall and inundation.	Positive (+)
Physical and socioeconomic exposure variables:			
Elevation	Elevation = Natural break classification of SRTM DEM values. The absolute vertical accuracy = ±16 m.	Surface elevation changes have direct impacts on cyclone risks (Hoque et al., 2018). Higher elevations are less exposed to storm surges while low lying areas are quite vulnerable to cyclone threats.	Negative (-)
Slopes	$Slope = \frac{y_{1} - y_{2}}{x_{1} - x_{2}}$	Crucial criterion to assess exposure of coastal areas to cyclone risk. Low slops show high risks while steep slopes are less exposed to inundation (Hoque et al., 2018, Mansour, 2019).	Negative (-)
Proximity to coastline	Euclidean distance from coast which is calculated based on: $d_{ij} = \sqrt{\sum_{k=1}^{n} (x_{ik} - x_{jk})^2}$	The intensity of storm surge is a function of distance from coasts (Hoque et al., 2019; Alam et al., 2020). Areas that are located close to the coasts, shoreline and islands are more exposed to high cyclone risks than inland.	Negative (-)
Soil	Classification of soil types in the study area	The impacts of cyclone floods, precipitation, and inundation on soil vary according soil properties and categories (Evans et al., 2011; Kishtawal et al., 2012; Mansour, 2019). Some of soil types such as loam and clay are exposed to saturate of water sea.	Soil type
Capital stocks and assets	Natural break classification of capital stocks and assets concentration across the study area	The losses from cyclone are a function of the value of material assets (capital stock) affected by the storm surge and other cyclone's components (Schmidt et al., 2009; Ye et al., 2019).	Positive (+)
Vulnerability variables:			
Population density	Pop. Den$= \frac{\text{N. of people in zone a}}{\text{Area size of zone a (km2)}}$	Population density is associated with evacuation decision and cyclone preparedness plan. The higher population densities, the greater risk of cyclone impacts (Hoque et al., 2018, Hoque et al., 2019; Mansour, 2019).	Positive (+)
Elderly populations (80+)	Number of elderly people aged 80 and above in each subnational geographical zone.	Cyclone poses greater risks to older people who are often suffer from long-term illness and have limited abilities to cope with cyclone impacts (Astill & Miller, 2018).	Positive (+)
Disabled population (%)	Percentage of disabled population in each geographical zone	Disabled people have limited access to shelters, legal assistance and essential services during cyclone event (Baker et al., 2019).	Positive (+)
Female Widows (%)	Percentage of female widows in each geographical zone	Female-headed households are highly exposed to high cyclone risks. The abilities of widowed women to cope with cyclone impacts are less compared to men-headed households. (Delfino et al., 2019)	Positive (+)

Mitigation variables:			
Vegetation cover	**Classification** of vegetation cover	Wide and densely vegetation cover particularly along coastline can relatively protect or at least reduce the impacts of cyclone on shores (Hoque et al., 2019; Mansour, 2019).	Negative (-)
Proximity to shelters	**Euclidean distance** from shelters locations	Evacuation plans and preparation depends on accessibility to shelters. The number of cyclone shelters is significantly correlated with cyclone infrastructural management. Low distance to shelters indicates low risks and vice versa (Quader et al., 2017)	Negative (-)
Proximity to hospitals	**Euclidean distance** from hospitals locations	Hospitals play vital roles during disaster event and cyclone risk mitigation depends on health facilities' coverage as well as accessibility (Mansour, 2019).	Negative (-)
Proximity to defense centres	**Euclidean distance** from defense centers	The risk mitigation is a function of short distances to defense centers in each geographical zone (Mansour, 2019)	Negative (-)

2.3.1 Cyclone hazard

Kernel density estimation was used to create a spatial layer as a proxy of cyclone intensity by combining all the track locations and intensities of all cyclones that crossed the study area since records began in 1842 (Figure 2).

Figure 2 Spatial distribution of the past cyclones' intensities defining the cyclone hazard across the study area: Hazard index computed applying kernel density estimation to cyclone tracks.

2.3.2 Exposure and vulnerability

The concept of exposure indicates the degree to which people and assets are exposed to a particular cyclone disaster (Freeman & Ashley, 2017). Vulnerability refers to proportion of the population or asset set that is expected to be lost if a given event occurs and is related to the physical, environmental and socioeconomic circumstances of populations and assets (e.g., building strength) (Fuchs et al., 2012; Kaźmierczak & Cavan, 2011). In the present research, 9 variables were identified to create an index that combines both exposure and vulnerability to cyclones across the study area. Five criteria (Table 2) were created to represent exposure to cyclone impact: proximity to the coastline, elevation, slopes, soil categories (Figure 3), and capital stocks and assets (discussed below and in Figure 4).

Figure 3 Spatial parameters of physical exposure: (a) proximity to shorelines, (b) elevation, (c) slopes, (d) soil types)

To evaluate spatially the expected economic losses resulting from severe cyclone impacts, the geographic distribution of capital stocks and asset values is essential, particularly to represent the increased concentration of wealth, settlements and material assets in exposed areas. To ascertain spatial distribution of the capital stocks across the study area, four map layers (educational stocks, employment in the service sector, houses of high-income groups, and stocks of health sector) were generated (Figure 4). Most educational assets are located close to the coast, particularly in the Muscat governorate and Al-Batnah coastal plain (Figure 4a). Similarly, a spatial layer of the assets of employment in all service sectors was created (Figure 4b). The distribution of assets of high-income group houses is demonstrated in Figure 4c, concentrated along the Muscat, Al-Batnah North and South governorates. Although health facilities are an indispensable element of hazard mitigation capacity, direct economic losses can, of course, be caused to the health sector by cyclones. The linear strips of Muscat and Al-Batnah are described as densely populated and highly developed. Hence, health services are also concentrated mainly along and near coastlines (Figure 4d).

Figure 4 Spatial layers representing capital stocks and assets: (a) educational assets, (b) assets of employment in all service sectors, (c) assets of high-income group houses, and (d) health-related stocks.

Figure 5 Spatial layers representing sociodemographic vulnerability: (a) population density, (b) elderly population 80+, (c) disabled population, (d) female widows.

To assess the sociodemographic vulnerability to the impacts of cyclones, four criteria were developed including: population density, the proportion of elderly (aged 80 or over) people, the proportion of disabled people, and female widows. A map layer of population density was generated based on the latest 2019 population estimates (NCSI, 2019) (Figure 5a). Cyclone disasters have far-reaching impacts on all populations within exposed communities. However, elderly people are more vulnerable to cyclone impacts than adults and children, as they often suffer from long-term illness and are financially insecure. During cyclone events, they can become trapped in their houses surrounded by floods and have limited access to services and emergency aid (Heid et al., 2016). A spatial layer of the population aged 80 and above was generated as a proxy indicator of the vulnerable elderly population across the study area (Figure 5b). Poor and marginalised groups such as children, female widows, and disabled people are among the most vulnerable populations to cyclone hazard effects, so two layers representing the percentage of disabled people and female widows were also created (Figure 5 c & d).

2.3.3 Mitigation capacity

Cyclone risk reduction is defined as reducing the likelihood of destruction, damage, and losses resulting from a cyclone event (Few, 2013). For the implementation of preparedness and reduction strategies, a wide range of services and facilities should be evaluated, particularly health and civil defence facilities. Spatial layers of structural mitigation features were generated, particularly cyclone shelters, hospitals and defence centres. Vegetation cover was also covered, particularly mangrove forests and other dense trees, that form belts and protect coastal communities from strong waves, significantly reducing wind strength and mitigating devastating storms (Figure 6a). Measuring the distribution of facilities, their coverage, and accessibility is an essential step to strengthen disaster responses and management. Shelters and medical centres should be adequate and accessible, with schools or other community establishments used as cyclone shelters in some cases (Figure 6b). Suitable maintenance of health facilities is an effective strategy in hazard reduction, specifically hospital and clinics which are vital facilities and provide the population with medication and treatments. The short distance to hospitals and defence centres indicate highly accessible facilities, while long distances to these services suggest a higher probability of losses (Figure 6 c & d).

Figure 6 Spatial distribution of mitigation capacity layers: (a) vegetation cover, (b) proximity to nearest shelter, (c) distance to nearest hospital, and (d) proximity to nearest civil defence centre.

3 Methods: Towards a Multi-Factor Cyclone Risk Index

3.1 Analytical Hierarchal Process (AHP)

3.1.1 Criteria Ranking and standardisation

To meet the requirements of weighted overlay within a GIS environment, all the selected criteria described in Section 2 were converted into the raster format. All these raster layers were then categorised into five classes, with 1 denoting a very low value and 5 a very high value (Table 3).

Table (3) Criteria ranking based on the contribution to cyclone risks

Components	**Criteria**	**Ranking scale**				
		1 Very low	**2 Low**	**3 Moderate**	**4 High**	**5 Very high**
	Kernel density of cyclone tracks	< 1.44	1.45 – 4.10	4.11 – 6.80	6.81 – 9.40	>9.40
Exposure	Proximity to coastline (km)	< 9	10- 20	21 - 33	34-50	>50
	Elevation (m)	< 250	250 - 550	551-1000	1001-1400	>1400
	Slope (degree)	< 5.4	5.5 - 14	15 - 23	24 -35	>35
	Soil types	Rocky outcrops	Gypsum	Sandy skeletal	Gravelly sandy	Alluvial loamy
	Capital stocks and assets	Very low	Low concentration	Moderate concentration	High concentration	Very high
Vulnerability	Population density (person/km^2)	< 2	2 – 3	3 – 4	5 – 9	> 9
	Elderly populations (size)	< 196	197 - 402	766- 799	767 -959	>959
	Disabled populations (%)	< 0.71	0.72 – 1.7	1.8 – 3.6	3.7- 5.9	> 5.9
	Female widows (%)	< 3.1	3.2 – 4.2	4.3 – 5.2	5.3 – 6.0	> 6.0
Mitigation	Proximity to hospitals (m)	< 10000	11000-18000	19000 - 26000	27000 - 43000	>43000
	Proximity to defense centers (m)	< 8600	87000- 22000	23000 - 35000	36000– 42000	>42000
	Vegetation cover	Very high cover	High cover	Moderate cover	Low cover	No cover
	Proximity to cyclone shelters (m)	< 4300	4400 – 79000	8000 - 14000	15000 -24000	>24000

Calculating a spatial index of cyclone risk requires normalising all the employed criteria onto the same scale and, thus, the selected variables were transformed using a linear scale transformation:

$$\boldsymbol{V} = (x_i - \min_c)/(\max_c - \min_c) \qquad (1)$$

where $\boldsymbol{V}$ refers to the standardised variable, $\min_c$ and $\max_c$ represent the minimum and maximum values of the criterion c, respectively, and x_i indicates the value of a single cell in each spatial raster layer.

3.1.2 AHP weighting criteria

Weighting criteria is often used to calculate an overall value based on each performance criterion. After establishing a uniform set of selected criteria, deriving these criterion weights is an essential stage in calculating the spatial risk index.

AHP is a pairwise comparison algorithm developed by Saaty (1977, 1980). The method is a statistical approach for computing weights on the basis of a hierarchical structure and the relative importance of identified criteria. The pair comparison matrix is calculated by considering two criteria at a time. In the present study, the pair comparison matrix was calculated on a scale of 1 to 9 where 1 refers to equal importance and 9 represents an extreme importance between the compared criteria.

Professional judgement was used to assign weights, based on input from three experts, each of whom lives in the study area and has a deep knowledge of cyclone impacts. Table 4 depicts the outputs of the AHP including the weights of all the criteria and their associated consistency ratios. The consistency ratios are all smaller than 0.1, which indicates that consistent judgements were made by each of the three experts.

Table (4) The relative importance of the selected variables and consistency ratios calculated from the matrices of the pairwise comparison.

Components	Criteria	Weight	Consistency Ratio
Hazard	Proximity to cyclone eye (km)	100	n/a
Exposure	Proximity to coastline (km)	35	0.08
	Elevation (m)	15	
	Slope (degree)	10	
	Soil types	9	
	Capital stocks and assets	31	
Vulnerability	Population density (person/km^2)	42	0.03
	Elderly populations (size)	20	
	Disabled populations (%)	24	
	Female widows (%)	14	
Mitigation	Proximity to hospitals (km)	20	0.05
	Proximity to defense centers (km)	14	
	Vegetation cover	28	
	Proximity to cyclone shelters (km)	38	

The pairwise comparison the matrix is defined as follows:

$$m = \left[c_{ij}\right]_{nxn} \qquad (2)$$

$$\begin{bmatrix} c_{11} & c_{12\ldots\ldots} & c_{1n} \\ c_{21} & c_{22\ldots\ldots} & c_{2n} \\ c_{1n} & c_{2n\ldots\ldots} & c_{nn} \end{bmatrix}$$

Overall, the matrix has the property of reciprocity and is expressed mathematically as follows:

$$\mathrm{c}_{ij} = \frac{1}{c_{ij}} \quad (3)$$

After producing the pairwise comparison matrices, the vector of weights, $\boldsymbol{w} = \{\boldsymbol{w_1}, \boldsymbol{w_2}, \dots\dots, \boldsymbol{w_n}\}$ is computed based on two steps: first, normalising the matrix $\boldsymbol{m} = [\boldsymbol{c_{ij}}]_{\boldsymbol{nxn}}$ as follows:

$$c_{ij} = \frac{c_{ij}}{\sum_{j=1}^{n} c_{ij}} \quad (4)$$

for all $j = 1, 2\dots, n$.

Then, the weight for each criterion is computed as:

$$w_i = \frac{\sum_{j=1}^{n} c_{ij}}{n} \quad (5)$$

for all $i = 1, 2\dots, n$.

To justify the consistency of the pairwise comparison scores provided by expert judgement, the consistency relationship (CR) is calculated as follows:

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \quad (6)$$

The comparisons and judgement scores are consistent if the value of CR is smaller than or equal to 1, while they are considered inconsistent if CR is larger than 1. The CR depends also on the consistency index (CI) and the random index (RI) and is calculated as follows:

$$\frac{\lambda_{max} - n}{n-1} \quad (7)$$

where $\boldsymbol{\lambda_{max}}$ is the largest Eigenvalue of the matrix, $\boldsymbol{n}$ specifies the order of the matrix, and RI denotes to the average of the resulting CI, depending on the order of the matrix (Saaty 1977).

3.2. Calculation of cyclone risk indices

3.2.1 Cyclone Hazard Index (CHI)

To calculate an overall index of cyclone hazard, the cyclone intensity layer discussed in Section 2.3.1 was utilized as a proxy of the hazard components (e.g., particularly intense precipitation, winds, storm surges and waves).

3.2.2 Cyclone Vulnerability and Exposure Index (CVEI)

A vulnerability and exposure index was calculated as the sum of physical, socioeconomic and demographic criteria as follows:

$$CVEI = \frac{\sum_{i=1}^{N} w_i x_{1ve} * x_{2ve} \ldots\ldots x_{n\,ve}}{N} \tag{8}$$

where $\boldsymbol{w_i}$ is the weight assigned to each criterion derived from the APH method. $\boldsymbol{X_{1ev}}$ represents vulnerability and exposure criterion 1 while $\boldsymbol{N}$ indicates the total number of criteria.

3.2.3 Cyclone Mitigation Capacity Index (CMCI)

Mitigation efforts are considered essential measures to reduce the destruction of property and loss of life. The mitigation capacity index was calculated as follows:

$$MC = \frac{\sum_{i=1}^{N} w_i x_{1m} * x_{2m} \ldots\ldots x_{n\,m}}{N} \tag{9}$$

where $\boldsymbol{w_i}$ is the weight assigned to each criterion derived from the APH method. $\boldsymbol{X_{1m}}$ signifies mitigation capacity criterion 1 while $\boldsymbol{N}$ indicates the total number of criteria.

Cyclone Risk Index (CRI)

The cyclone risk index (CRI) was calculated based on combination of the hazard, exposure and vulnerability, and mitigation capacity indices as follows:

$$\mathrm{CRI} = \frac{CHI * CVEI}{\mathrm{MCI}} \tag{10}$$

4. Results

In this section, we present the findings of the geospatial modelling process, providing maps of the calculated hazard, exposure and vulnerability, as well as mitigation indices.

4.1 Hazard index

Spatial patterns of hazard index are associated with storm height, proximity to the cyclone eye, precipitation intensity and wind speed. These variables were used to model the cyclone hazard and are strongly associated with shaping the degree of cyclone intensity. Figure 2 illustrates the spatial distribution patterns of cyclone hazard determined across the study area. The characteristics of cyclone hazard over the northern coastal Wilayats are well captured, with large areas of the coastal Wilayats of the Muscat governorate, particularly Al Seeb, exhibiting a potentially very high level of hazard. High levels of hazard are indicated also along the coasts of Sur Wilayat in the far east. Similarly, the hazard map shows portions of very high and high hazard along the Wilayats of the Al-Batnah South coastal plain, such as Barka, Al-Musanaah, and Aswayq, whereas the hazard levels are very low in areas of higher elevation and steeper slope, especially in the interior regions of Sohar, Shnas, Liwa, and Muscat. Overall, the eastern segments of the study area are exposed to a severe hazard, while the northwest is less impacted by a significant cyclone hazard.

4.2 Exposure and vulnerability indices

Two indices which represent exposure to cyclones were developed based on physical (proximity to coasts, elevation, slopes and soils) and socioeconomic (educational, health, housing services assets) variables. Figure 7 depicts areas that are exposed to the natural risks of a cyclone, with the terrain, roughness of the landscape and elevation fundamental to determining the level of vulnerability to cyclone risks, where low-lying land situated near the coastline demonstrates very high levels of vulnerability. The study area was divided into two main sections, coastal zones and elevated land. Similar to the distribution of hazard patterns, the low-lying areas of Al-Batnah Wilayats and Muscat governorate are highly, and very highly, vulnerable to cyclones. According to the simulated index of physical vulnerability, these areas are at lower elevation and more likely to experience a high level of cyclone destruction and damage. In contrast, the interior and southern parts are characterised by steeper slopes, high elevations, and outcrop rocky land and, thus, are exposed to low, and very low, cyclone risks, particularly with respect to inundation and storm surges.

Figure 7 Map of the simulated physical vulnerability index.

The risk of damage to capital stocks and assets is mostly a combination of the concentration of educational, health and service facilities close to vulnerable areas. The index of economic exposure to cyclone risks is presented in Figure 9. Overall, the calculated index revealed that 7.3% of the total area encompasses capital stocks in the four sectors that are at high, and very high, risks, while almost 11.7% are exposed to low, and very low, risks, with most of the study area (81%) comprising assets that are considered at medium risk. It is clear that the higher concentration of capital stocks and assets is exposed to high, and very high, risk across Muscat, AlSeeb and Bowsher Wilayats within the Muscat governorate. Likewise, the coastal portions of Al-Batnah Wilayats, particularly Aswayq, al-Musanaah and Sohar, are exposed to a high level of risk and losses. The spatial variation in capital stocks exposure to cyclone hazards are linked to concentrated urban settlements involving the largest number of public and private facilities.

Figure 8 shows the index of sociodemographic vulnerability across the Wilayats of the study area. The number of people vulnerable to cyclone impacts is larger in some coastal Wilayats, such as Aseeb within Muscat governate and Aswayq and Shinas in Al-Batnah governorate. Generally, the eastern part of the study area is characterised by low sociodemographic vulnerability, except for Muscat, Matruh and Bowsher Wilayats, which shows a medium level of vulnerability. Notably, and unlike the eastern parts, some interior zones in Al-Batnah south governorate are characterised by relatively high vulnerability scores, particularly Al-Awabi and Al-Rustaq, due to the high proportion of elderly and disabled individuals there.

Figure 8 Map of the simulated sociodemographic vulnerability index.

4.3 Mitigation capacity index

Figure 9 provides a map of the derived mitigation index which is classified into five classes. Higher mitigation capacity indicates well-designed emergency services, while lower-capacity suggests low accessibility and under-coverage of facilities. The calculated mitigation capacity index illustrates that 47.9% of the study area falls into the high, and very high, mitigation capacity categories, these areas being located mainly in the urban Wilayats within the Muscat governorates and coastal zones of Al-Batnah Wilayats. Unsurprisingly, the urban districts of Sur in the eastern part of the study area, as well as the urban zones of Al-Rustaq, Samail, and Bidbid, are characterised by high levels of mitigation capacity. Most residential areas in the south of the study area are dominated by a medium level (32.2% of the study area) of mitigation capacity. In general, most localities and rural locations in the northwest and southern parts of the Sohar, Liwa, Shinas Wilayats in the Al-Batnah North governorate have low, and very low, mitigation capacities. Low and very low mitigation capacities (19.9% of the study area) also exist in the eastern and southern parts of Qurrayat, Al-Amrat, Al-Khabourah and Sur Wilayats. While coastal areas are well serviced by health, civil defence, shelter facilities and built-up capacities against the cyclone hazard, the interior areas, particularly the rural zones, suffer from a low coverage of such services which negatively affect their preparedness, response and recovery policies.

Figure 9 Map of the simulated mitigation capacity index

4.4 Map of cyclone risk index

The cyclone risk index was computed by employing equation (10), and a map illustrating the spatial distribution patterns of cyclone risks so-derived was produced (Figure 10). As expected, the coastal areas of Muscat governorate, particularly the northern Wilayats, represent an area of very high risk and are likely to be severely affected by cyclones. Similarly, the far east, as well as the east and southeast parts of Sur Wilayat, are also at a very high level of risk. The resulting risk map also indicates that a large area of the study region is located in the very high (17.6%) to high (18.9 %) risk zones. Cyclone risk is medium across most of the north parts of the administrative boundaries and this level of risk affects almost 21.5% of the study area. Most of the study region is located under the two risk categories (very low and low), which together form the largest percentage (41.9%) of the risk distribution. Unsurprisingly, most areas that are considered to be low, or very low, risk zones are located further from coastlines (except for Muscat and Qarrayat Wilayats) and characterised by high elevation and low values of infrastructure index.

Figure 10 Map of the simulated multiple risk index

Figure 11 reveals that the urban Wilayats of Muscat governorate as well as Sur Wilayat in the east are ranked as the most at risk to cyclone hazard, with a large proportion of these Wilayat areas classified as high, to very high, risk intensity (Bawshar 29.2 %, AlSeeb 95.9%, Matruh 85.4 %). Correspondingly, across the Al-Batnah coastal plain, Barka (93.3%) and Al Suwayq (56.2%) are the most risk-prone zones, while within non-coastal Wilayats, Al-Rustaq (22.7%) and Nakhal (46.5%) were the most susceptible to the cyclone hazard. Nonetheless, and although these latter two Wilayats are inland areas and located farther away from the coasts of Oman Sea, they demonstrated high scores in the socioeconomic vulnerability and physical exposure indices, as well as low scores of mitigation capacity.

Figure 11 Distribution of overall cyclone risk across the administrative zones of the study area in squared kilometres.

4.5 Validation

Here, a qualitative damage dataset and information about the effects of the Gonu cyclone were utilized to validate the reliability of the produced risk index (Gonu Situation Report No. 1; Report on Gonu, 2011**)**. A comparison was developed between the levels of damage associated with cyclone Gonu and the predicted risk levels in each administrative zone. The comparison indicates that the coastal Wilayats located in the northeast (e.g. AlSeeb, Barka, Mutrah and Muscat) and the far east (e.g. Sur) parts of the study area were influenced severely by tropical cyclone Gonu (Table 5). Although all coastal zones across the study area are highly exposed to cyclone impacts, the Wilayats located in the north were less influenced compared to the eastern parts. Accordingly, the damage and destructive levels from the cyclone in most of the northern zones were characterised as at high to intermediate risk. On the other hand, the interior Wilayats (e.g. Al-Rustaq and Al-Awabi) were impacted significantly by intense cyclonic rainfall and wind velocity, particularly in the mountainous areas and locations with rugged topography. Consequently, and compared to the coastal zones, these Wilayats reported intermediate to low levels damage. To enable fair comparison between the observed destruction and predicted risk categories, the observed levels of cyclone impacts and damage were rated based on scores of 100 and a thematic map was created to show the spatial distribution pattern for the two risk levels (Figure 12). The maps show that, in general, the observed pattern of cyclone damage associated with cyclone Gonu resembles the predicted higher risk level across most of the study area. For example, it is clear that the degrees of risk are quite similar in some of the Wilayats that are located in the east (Sur and Qurayyat), Middle (Al-Musanaah and As Suwayq) and north (Sohar). Therefore, and albeit in the absence of quantitative damage data at the subnational scale, the calculated risk index is considered to be reliable in respect to its ability to model spatially the impacts of tropical cyclones across the Oman Sea coasts.

Table (5) The observed damage versus the calculated high-risk levels across the administrative zones of the study areas.

Wilayats	Observed Damages	Observed Risk Level	Observed Risk Score*	Predicted Risk Level (sq km) **
Samail	Flooding from dry riverbeds	Very Low	35	794.27
Al-Rustaq	Heavy flood into canyons and dry riverbeds	Intermediate	70	501.69
As Suwayq	Inundation in the coastal lay-land areas; Cuts in electricity supplies	High	85	536.66
Nakhal	Flooding from dry valleys and riverbeds.	Low	40	423.74
As Seeb	Inundation in the coastal lay-land areas; flights halted; Cuts in electricity, water, communication supplies.	Very high	90	444.42
Wadi AlMaawil	Intense precipitation and flooding from dry valleys and riverbeds.	Low	45	0.00
Bawshar	Inundation in the coastal lay-land areas; Cuts in electricity supplies.	High	85	95.23
Al-Musanaah	Inundation in the coastal lay-land areas; Cuts in electricity and water supplies.	High	80	523.97
Al-Awabi	Rainfall and flooding from dry valleys and riverbeds. Cuts in electricity.	Intermediate	60	79.36
Mutrah	Inundation in the coastal lay-land areas; Cuts in electricity and water supplies.	Very high	90	19.06
Liwa	Inundation in the coastal lay-land areas; Cuts in electricity and water supplies.	Intermediate	70	111.66
Al-Amrat	Strong waves and heavy rainfall flooded streets; Cuts in electricity and water supplies.	High	80	0.00
Barka	Inundation in the coastal lay-land; natural gas, halting production; sustained damaged switchgear due to flooding. Cuts in electricity and water supplies.	Very high	90	0.00
Shinas	Heavy rainfall and flooding. Cuts in electricity and water supplies.	Intermediate	65	369.99
Bidbid	Rainfall and flooding from dry valleys and riverbeds. Cuts in electricity.	Low	40	299.09
Saham	Coastal roads flooded; Cuts in electricity and water supplies.	High	85	13.00
Qurayyat	Coastal roads flooded and destruction, inundation in the coastal lay-land Cuts in electricity and water supplies.	High	80	408.46
Sur	The liquefied natural gas terminal was hit by the storm. Inundation in the coastal lay-land and heavy rainfall flooded streets; Cuts in electricity and water supplies.	Very high	95	1584.13
Khaburah	Strong winds, heavy rainfall and flooding. Cuts in electricity and water supplies.	Intermediate	55	334.59
Sohar	Evacuation of the port workers; A total shutdown of Sohar's oil refinery. Inundation in the coastal lay-land.	Very high	90	372.34
Dama Wtayain	Strong winds and rainfall and flooding from dry valleys and riverbeds. Cuts in electricity.	Very low	40	37.90
Muscat	Desalination plants interruption; strong winds uprooted electrical poles; heavy rainfall flooded streets; Cuts in electricity and water supplies.	Very high	95	0.00

(*) The observed risk score is based on the observed level damages from the Gonu cyclone in each Wilayat.

(**) The predicted higher risk level in each Wilayat calculated in squared km^2.

Figure 12 Comparison between spatial distribution of (a) observed cyclone damage associated with the 2007 cyclone Gonu and (b) predicted cyclone risk across the zones of the study area.

5. Discussion

Previous events, especially the 2007 Cyclone Gonu, provide clear evidence that the coasts of the Oman Sea are cyclone-prone areas. However, despite significant research, regionally and globally (e.g. Alam et al., 2020; Hoque et al., 2018; Hoque et al., 2019; Arthur et al., 2008), on the spatial assessment of cyclone risks, to the best of our knowledge, no research has yet been published to identify areas of cyclone risk across the coasts of the Oman Sea. Accordingly, conducting spatial modelling and assessment of cyclone risks at subnational zones is of great importance, not only to achieve suitable preparedness plans, but also to support the development of protection and mitigation strategies.

In this research, geospatial techniques, as well as the AHP method, were incorporated to model and generate maps of hazard, socioeconomic exposure, vulnerability, mitigation capability and ultimately cyclone risk. Our findings are consistent with previous results in other areas (Hoque et al., 2019; Patra et al., 2013; Quader et al., 2017), confirming that low-lying areas and coastal urban settlements are associated with greater risk of damage and casualties due to the cyclone hazard. This research also highlights how specific interior areas are characterised by high, and very high, risk scores, particularly in Al-Rustaq and Al-Awabi Wilayats. The significant threat of cyclone devastation across these zones can be attributed to the predicted intensity of windstorms, heavy rainfall, and the risk of floods and the propagation of water flow through dry valleys in these locations (Table 5). In addition, these places also demonstrated high scores in terms of their demographic vulnerability, as well as low ranks for their mitigation capacities.

Given the significant threat of global climate change (Knutson et al., 2010; Ying et al., 2012; Wehner et al., 2019), there is concern about the present and future likelihood of cyclone related disasters. Furthermore, apart from the fact that the study area is cyclone-prone, it contains a great share of Oman's assets, economic activities and population densities. As capital stocks and assets should be included in any cyclone risk assessment, the distribution patterns of assets in four key sectors (housing, health, education, and employment) across the study area were incorporated into the derived exposure index. The level of exposure to cyclone risks was clearly associated with the concentration of assets and the proximity of those assets to the coastline. Notably, across Muscat and Al-Batnah, residential zones located within one kilometre of the coastline are the most economically productive areas in Oman, with a large population and high capital stock concentrations. Therefore, disruption to economic activities caused by cyclone damage could be widespread along these highly susceptible coastal zones.

In response to the devastating 2007 cyclone Gonu, efforts to reduce the vulnerability of local services and physical infrastructure to severe cyclones have gained momentum. A key focus of the government's response has been an effort to strengthen resilience in the implementation of infrastructure design. Nevertheless, rapid population growth of coastal areas in the north of Oman raises many questions and has prompted decision-makers to identify new areas for urbanisation that are not at such great risk.

In the above context, the process of spatial assessment and modelling of cyclone risks is integral to avoiding adverse disaster impacts. Since cyclones cannot be prevented, risk reduction is a crucial strategy for any disaster preparedness and management plan. Therefore, the spatial modelling and simulation of cyclone risks along the coasts of the Oman Sea is a necessary and essential step in developing a strategy to reduce disaster risk. The findings of this research are based on local-scale analyses and include several assessment indicators to provide decision-makers and planners with maps of hazard and risk intensity. Furthermore, spatially explicit management guidelines, and preparedness plans, for cyclone risk monitoring across the northern coasts of Oman can now be developed based on these assessments. Governmental policy makers in Oman should also consider the expected risks posed to the coastal areas of Muscat and Al-Batnah governorates. As these places are subject to significant ongoing infrastructure development, specifically transportation and housing planning, new roads should be designed to withstand the onslaught of cyclones. To establish planned protections from economic losses and intensive damage, protective actions, monitoring systems and emergency plans should be developed specifically along the northeast coasts from Sur city up to Sohar Port in the north. These disaster preparedness activities should include (i) identifying all public facilities, and private agencies and buildings, that are at high risk and (ii) developing substantial empowering actions that can be taken to reduce damage from future cyclones.

The extent of cyclone impacts on infrastructure across the study area varies spatially due to differences in the physical and socioeconomic vulnerability to hazard in each administrative zone. Therefore, coastal road networks, public facilities and amenities should be cyclone-resistant. For example, the plinth level and stilt of ground floors should be considered for all buildings and houses that are constructed along the shorelines of the study area. Furthermore, the unsafe natural conditions of the low-lying lands across Muscat and Al-Batnah governorates should be considered. Consequently, several measures can be taken by decision makers. For example, preserving dune formations, sand bars, constructing littoral woodlands, planting dense vegetation and engineered barriers should be considered. Appropriate protection measures should also be adopted, particularly constructing artificial breakwaters, seawalls, dykes and levees and embankments as effective barriers for absorbing wave energy and diminishing inundation risks.

Considering the future uncertainty about, as well as the stochastic nature of, tropical cyclones and related weather extremes, finer spatial resolution spatial datasets should be explored for the purpose of evaluating cyclone risk spatially. Common with other studies evaluating cyclone risk, this research was limited by the absence of detailed spatial layers on demographic and household vulnerability at the microscale, as well as the lack of available datasets on household exposure to cyclone hazard. Likewise, it was challenging to find spatial historical datasets on the impacts of previous cyclones that affected the study area. As a consequence, this study adopted a geospatial, MCA approach to combine data layers. However, with the requisite data it would be possible to consider the estimation and mapping of risk directly. Thus, in future, efforts should be directed towards obtaining more refined data on exposure, vulnerability and historical impacts. Despite these limitations, by utilizing GIS techniques, this study has contributed new insights and understanding of the cyclone impacts and, in particular, the spatial patterns of expected risk along the coasts of the Oman Sea.

The adopted geospatial modelling approach provides a means to support effective management of pre-disaster multi-hazard mitigation planning in Oman. In addition, by utilizing a geospatial approach, Omani decision-makers and planners can focus on developing disaster-resistant communities, particularly along coastal areas and places that are highly exposed and vulnerable to the cyclone hazard. To reduce future disaster risk, for example, through community plans for cyclone hazard mitigation, spatial guidelines and plans at the local community level are required. In addition, increasing local community responses to the impacts of cyclones is essential to strengthening preparedness to disaster occurrence.

6. Conclusion

In this research, an integrated risk index for tropical cyclones was calculated across the Oman coastline based on a geodatabase of 17 different data layers (criteria) grouped into four independent components of risk: hazard, exposure, vulnerability and mitigation capacity. Integrated risk was calculated spatially based on these data layers using a geographical information system and an analytical hierarchical process (AHP) technique, with rank and weight scores given for each criterion.

The predicted map of cyclone risk across the Oman coast revealed spatially where risk is greatest, but also highlighted the association between predicted risk and variation in the components of risk (i.e., physical hazard, exposure, vulnerability and emergency preparedness), thus, allowing risk reduction efforts to be targeted where needed. Specifically, the predicted map revealed high risk to the population and assets in low-lying lands situated near the east of Muscat, as well as the Al-Batnah south governorates, despite these areas having high expectations in terms of preparedness and mitigation. The map also predicted high, to very high, risk for the coastal zones of the urban Wilayats of the Muscat governorate.

This research, thus, adds to the literature on the utility of GIS and AHP for cyclone risk mapping, but also has several policy implications for Oman. In particular, the predicted maps can act as effective guidelines for natural hazard preparedness and mitigation across the northern coasts of Oman.

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