1. Introduction

For those involved with land development, knowledge of current or potential geohazards is a critical part of the assessment for site suitability. However, ground risk maps are seldom available in the public domain, existing only as extracts in journals in spite of essential information a map would provide in land-use planning and managing risk of natural disasters (Ganguly, Aynyas, Nandan, & Mondal, 2018; Hagen & Lu, 2011; Hestnes & Lied, 1980). Published references to geohazard maps exist in two main forms: site-specific detailing one designated area or region (e.g. Berhane & Walraevens, 2013; Dragicevic, Novkovic, Carevic, Zivkovic, & Tosic, 2011) and/or topic specific relating to a particular hazard (e.g. Çakti et al., 2016; Mason & Rosenbaum, 2002; Pritchard, Hallett, & Farewell, 2015), references to multiple types of geohazards over entire countries are rare.

Geohazards can be formed through continuous natural processes, such as weathering, though they are predominately created and accelerated by anthropogenic activity. Geohazards which have occurred, and been thoroughly investigated to determine their source, can be used to predict vulnerability in similar formations and situations elsewhere (Griffiths, 2001) and to extend this knowledge to areas not yet developed. Geohazards are related to climate, lithology and terrain, and ground hazard zones can be inferred from geological and topographic maps in combination with other tools such as geographic information systems (GIS) and remote sensing (Elmahdy & Mostafa, 2013). However, good quality geological maps may not be available or there may be incomplete coverage, and detailed ground specific data held by private companies is often confidential.

The Kingdom of Saudi Arabia has a variable geology, topography and extreme climate which give rise to a number of geohazards affecting existing infrastructure. The western region is prone to earthquakes and volcanic hazards, whereas the central and western regions of the Kingdom are exposed to floods. Landslides are a common phenomenon in the inhabited mountainous regions of the southwest. Shifting dunes and dust storms are also hazards experienced in central and eastern Saudi Arabia. Evaporitic soils are located along coastal fringes and in the south of the country in the Rub al Khali (Empty Quarter). With its expanding petroleum, technological, agricultural and tourism industry, land acquisition in less developed locations is on the rise and knowledge of geohazards is a prime concern.

Countrywide geohazards in Saudi Arabia have been documented by a few authors (e.g. Al-Bassam, Zaidi, & Hussein, 2014; Youssef & Maerz, 2013) with focus in five main areas associated with conurbation: Jizan, Jeddah, Riyadh, Dammam and Medina. This localization of reported geohazards makes it difficult to envisage ground related risks that occur elsewhere in the country without first undertaking a desk study and site visits which can be time-consuming, costly and often with access restrictions.
This study outlines the construction of introductory geohazard maps for the Kingdom of Saudi Arabia using data available in the public domain. It continues on from the work presented by Youssef and Maerz (2013) by integrating geohazards reported by others along with other available physical data. The main objectives of producing the introductory geohazard maps for Saudi Arabia were to:

- Compile and integrate all available information to date to present a combined overview of geohazards in Saudi Arabia,
- Establish updated base maps for use as a first step document in review of available information on geohazards in early stage studies for land development to allow for forward planning,
- Highlight potential future instabilities due to considered geohazards,
- Focus any future investigation on specific geohazards,
- Ultimately reduce risk and save costs for future land development.

Introductory geohazard maps for Saudi Arabia are created and presented in this study, which can be further enhanced by local investigation studies.

2. Methodology and Selected Geohazards

The theoretical framework adopted to create the geohazard maps is outlined in a flowchart shown in Figure 1 and each stage discussed in the subsections below.

2.1. Collection of Critical Data and Identification of Geohazard Types

A review of published data showing the variety and location of geohazards within Saudi Arabia was carried out using GeoRef database (American Geosciences Institute). Selected well-known geohazards observed in Saudi Arabia were chosen for the study. Each geohazard identified for assessment and inclusion on the geohazard map is explained below, which are:

- Rock Subsidence
- Tectonics and Volcanism
- Slope Instability and Flooding
- Collapsible and Expansive Soils

2.1.1. Rock Subsidence

Large scale ground subsidence is generally attributed to areas of karst morphology whereas small scale subsidence can be attributed to changes in the soil structure (see collapsible and expansive soils). Karst is a geomorphological feature present where formations contain soluble minerals and where the action of water causes dissolution (Amin & Bankher, 1997). The presence of natural voids and cavities in subsurface karstic limestones creates major problems for civil engineering foundations. The eastern part of Saudi Arabia is covered by the Shedgum Plateau which contains tertiary carbonates and evaporites of the Er Radhuma, Rus, Dammam, Hadrukh, Dam and Hofuf geological formations. Sinkholes, solution cavities and caves have been reported by Metwaly and Alfouzan (2013) and Edgell (1990). Further sinkholes have been found to occur in the north-eastern region near the cities of Al Khafji and An Nu‘ayriyah (Youssef et al., 2016; Youssef, El-Kaliouby, & Zabramawi, 2012) where the Hadrukh Formation is overlain by sand and gravel. Potential contributors to this ground subsidence include lowering the groundwater table with pumping from the underlying Dammam Aquifer (Youssef et al., 2016).

The central part of Saudi Arabia also suffers from subsidence caused by karst morphology (Memesh, Dini, Gutiérrez, & Wallace, 2008). The Cretaceous Sulaiy formation is prevalent to the east of Riyadh and the Jurassic Arab formation is beneath Riyadh. Both are limestones which contain layers of anhydrites and are susceptible to karstification. Other limestones in central Saudi Arabia such as the Jurassic Jubaila, Hanifa and Tuwayq Mountain could also be susceptible to dissolution. Sinkholes have also been reported several hundred kilometers south of Riyadh in the towns of Layla and As Sulayyil associated with the Upper Jurassic Hith formation (Kempe & Driks, 2012). Salt diapirs (or salt domes) can also give rise to ground collapse due to the dissolution of halite and are prevalent in the south western part of the Kingdom around Jizan (Amin & Bankher, 1997).

Caves have been documented by the Saudi Cave Unit (2007) associated with the Umm er Radhuma and Aruma sedimentary formations in the central
and north-eastern part of the country. Caves are also found within volcanic rocks known as Harrats which occur in the western part of the Kingdom (Pint, 2009). The expansive volcanic terranes are prone to the formation of lava tubes that can similarly collapse due to subsurface erosion (groundwater soil piping) or when loaded by structures.

2.1.2. Tectonics and Volcanism

Volcanic and seismic activity are the main sources of tectonic events in Saudi Arabia. Areas associated with heightened levels of seismicity are situated along transform faults in the Red Sea and the Gulf of Aden to the west and south of the country, and the subduction zone associated with the Zagros Fault in the north. The Dead Sea transform fault along the Gulf of Aqaba is the most seismologically active region of Saudi Arabia (Al-Bassam et al., 2014). Minor tremors associated with magma movement are frequently detected within the volcanic region along the western side of Saudi Arabia (Lindsay & Rashad Moufti, 2014).

Recent volcanic activity is observed on the western side of Saudi Arabia in the form of volcanic fields known as Harrats. The largest monogenetic volcanic field occurs at Harrat Rahat which produced a fissure eruption in 1256 CE created lava flows to within 20 km of the city of Al-Madinah (Lindsay & Rashad Moufti, 2014). Periodic seismic swarms recorded in this region also suggest the potential for future eruptions.

2.1.3. Slope Instability and Flooding

Slope instability in Saudi Arabia is mainly as a result of road construction in mountainous terrain and occurrences have been recorded only at limited locations, mainly in the west of the country associated with the Hejaz mountains. The mountain range runs North-South along the eastern coast of the Red Sea. The majority of these studies have concentrated on the Jizan region to the extreme south west of the country where the elevation can reach 2600 m. Here, landslide susceptibility has been documented in the Faifa area (Alharbi et al., 2014), Ar-Rayth and Al-Hasher areas (Youssef, Al-Kathery, & Pradhan, 2015) which are all to the northeast of Jizan. Vulnerable roads within the Hail region of Saudi Arabia have been recorded by Herehe (2016) as being untreated although escarpments identified in the central part of the kingdom by Al-Refeai and Al-Ghamdy (1994) comprising Jubaila, Arab and Hanifa formations could be susceptible to instability in any future developments.

Flash flooding is a common occurrence in Saudi Arabia associated with intense rainfall, dry sun-baked soil and lack of preventative measures to eliminate or reduce flood potential in low lying areas. Rainfall accumulates in the mountains in the western and central upland areas filling wadis and discharging water combined with debris onto the plains below. In urban areas, flooding may be acute because unplanned residential housing often covers topographically low regions and obstructs natural drainage systems (Al-Bassam et al., 2014). However, accumulated debris within drainage conduits in urban areas and in minor ephemeral wadis originating from the previous runoff events locally increases the flood potential. Valleys flowing to the west are steep and water run-off may reach the Red Sea coastal area as sheet flow (Shehata & Amin, 1997) or accumulate in morphological depressions along the piedmont plain (Bajabaa, Masoud, & Al-Amri, 2014). Shehata and Amin (1997) reported that in the Al-Lith salt flat area flood water remains stagnant for days due to its flat topography and low permeability. According to Al-Bassam et al. (2014), volumes of wadi flow from the Arabian shield to the east are much lower with the highest runoff volumes located within the wadis Al-Dwasir and Najran. Flood-prone areas have been gathered from studies carried out by Bajabaa et al. (2014) and Youssef and Maerz (2013).

2.1.4. Collapsible and Expansive Soils

Soils which exhibit an expansive and/or collapsible nature are widespread in arid environments and are typically of Quaternary age. These include soils with elevated concentrations of evaporites (sabkha) and soils which upon contact with water expand (expansive soil) or collapse (loess).

Sabkha. Sabkha (or sabkhat, pl) is a medium to fine-grained saline deposit derived from the Arabic term for ‘salt-flat’ and often contain a number of evaporite minerals in ‘retrograde’ stability, (i.e. the most soluble evaporites are found at the top of the profile and less soluble at the base). They typically occur in tropical latitudes where evaporation by solar radiation exceeds water ingress and where groundwater levels are typically close to the surface. Sabkha can cause the ground to collapse and heave depending upon certain conditions and salt elevated groundwater can damage cementitious and ferric materials.

Coastal sabkha deposits are located in the western Red Sea area north of Jeddah (Bahafzullah, Fayed, Kazi, & Al-Saify, 1993; Banat, Howari, & Kadi, 2005; El Abd & Awad, 1991; Hossain & Ali, 1988), south of Jeddah (Serhan & Sabtan, 1999), Al Lith (Basyoni, 1996) and Jizan in the southern Red Sea (Basyoni and Aref, 2015; Erol, 1989). Eastern coastal sabkha area includes the areas around Al-Jubayl (Al-Awayj, Heakal, Al-Asheikh, & Reda, 1992; Al-Shuhail, 2011; Chafetz & Rush, 1994; James & Little, 1994), between Al-Jubayl and Damman (Al-Shuhail & Al-Shaibani, 2009; Alnuaim & El Naggar, 2014), west and south of Dhahran (Al-Shuhail, 2011; Al-Shuhail & Al-Shaibani, 2013).
Inland sabkha formed within inter-dunal depressions are located predominantly in the south east of the country within the Rub’ al-khali close to the borders with Sultanate of Oman, the United Arab Emirates, State of Qatar and isolated pockets north of Makkah in the west of Kingdom of Saudi Arabia (Al-Dakheel, Hussein, Mahmoudi, & Massoud, 2009; Matter, Neubert, Preusser, Rosenberg, & Al-Wagdani, 2015).

**Expansive Soils.** Problems with expansive soils in the Kingdom have been reported by Abduljauwad (1991) to cause ground heave, cracking and breakup of pavements, and by Aiban (2006) to cause damage to reinforced concrete pile caps, masonry walls and grade beams. In the east, geological units including the Rus, Dammam, Hadrukh, Dam and Hofuf formations have been found to contain water expansive clay minerals (Abduljauwad, 1991; Aiban, 2006) and in the central western part of Saudi Arabia around Medina, soils were found to contain smectite (Okasha & Abduljauwad, 1992). In the north west of the country around Tabouk, the high swelling characteristics of weathered Tertiary shales was attributed to extreme desiccation under hot arid climates (Erol & Dhowian, 1990).

**Loess.** Loess are deposits of wind-blown silt-sized particles. They are typically unconsolidated, porous with low bulk density, and can become unstable leading to ground fissuring, subsidence and potential liquefaction.

The location of loess deposits in the Kingdom of Saudi Arabia has been identified from references to be associated with fluvial/alluvial deposits such as in Al-Yutamah, south of Medina (Bankher & Al-Harthi, 1999), in the Riyadh area associated with wadi deposits of fluvial nature reported by (Al-Refeai & Al-Ghamdy, 1994) and 100 km south of Riyadh (Al-Awaji, 2001).

Shehata and Amin (1997) reported loess-like deposits in several locations along the Red Sea coast around and south of Jeddah, especially in Al-Lith and in the eastern part of the country southwest of Dhahran. The presence of loess has also been shown to occur in the northern part of the Kingdom around Tabouk by Amin and Bankher (1997).

### 2.2. Base Map Selection

Table 1 presents the primary data sources used to create the base map.

Key base map characteristics were:

- Cities and administrative boundaries,
- Simplified geological stratigraphic units,
- Topographic data incorporating major geomorphological units such as mountain chains, escarpments,

| Sl No. | Data name and date | Format | Source | Content information | Resolution/sensors | Link |
|-------|-------------------|--------|--------|---------------------|-------------------|------|
| 1     | The geologic map of the Arabian Peninsula by US Geological Survey (Pullen et al., 1998) | PDF    | Open   | Geology, oil and gas fields and geologic provinces | 1:4500000 | http://pubs.usgs.gov/of/1997/ofr-97/080/OF97-080B/OF97-080Bb.pdf |
| 2     | Satellite imagery from Google Earth (accessed 2019) | Multiple OpenGL | Yes | Background image and base map | 10 m to 30 cm | https://www.google.com/help/terms_maps/ |
| 3     | Digital Elevation Model (2000) (downloaded 2019) | SRTMHGT files at 1-arcsecond resolution (3601x3601 pixels) in a latitude/longitude projection (EPSG:4326) | Yes | Topography and structural details | 30 m horizontal/synthetic aperture radar | https://www2.jpl.nasa.gov/srtm/ |
| 4     | Administrative Boundaries of Kingdom of Saudi Arabia (Hijmans, 2015) | Multiple Vector (Line) | Open   | Cities and administrative boundaries, boundaries of wadis, land parcels, rivers and inland wetlands | N/A | https://mapcruzin.com/free-saudi-arabia-country-cityplaces-gis-shapes.htm |
| 5     | Road, Railroad Network and Inland wetlands | Multiple Vector (Line) | Open   | Road and rail networks and rivers and inland wetlands | N/A | https://mapcruzin.com/free-saudi-arabia-country-cityplaces-gis-shapes.htm |
| 6     | Hazard Earthquake Program | Multiple CSV | Open   | Historic seismic events | N/A | https://earthquake.usgs.gov/earthquakes/browse/aLinear vertical absolute height error of less than 16 m, linear vertical relative height error of less than 10 m, circular absolute geolocation error of less than 15 m, circular relative geolocation error of less than 20 m, and circular relative geolocation error of less than 15 m, and circular relative geolocation error of less than 20 m, and circular relative geolocation error of less than 15 m. C-band system (5.6 cm; C-RADAR) and an X-band system (3.1 cm; X-RADAR). |
plateaus, coastal plains and hill-shade developed through a digital elevation model (DEM).

2.3. Geohazard Database Development

For the preparation of geohazard maps, use of GIS database was selected over shape files (.shp) due to the volume of available data to ensure better performance and storage capabilities. The GIS database for geohazards was developed with ESRI ArcGIS software based on geographic entities (spatial, non-spatial data) using the selected base map. Geohazard database development included identification of data themes (geohazard layers, land use, land covers, transport networks, etc.) along with specification of the contents and representations of each thematic layer, which encompass how the geographic features are to be represented for each theme (for example, as points, lines, polygons, or raster), definition of their attributes, organization of feature classes and raster data into datasets.

The geohazard database includes several GIS datasets. GIS datasets for each data theme can be used independent of others. For this study, it was aimed to use datasets together with other information layers so that the fundamental spatial behavior and spatial relationships were maintained and were consistent between related GIS data layers. The reference coordinate system used for the database is WGS84.

2.4. Development of the GIS model

Development of GIS model for capturing data theme layers and displaying geohazards and was carried out in two stages in this study:

2.4.1. Stage 1: Extraction of data from scanned images

Recent advances in computer technology and GIS software have allowed for more complex data models to be captured digitally on personal computers (Kramer, 2000).

Scanned images were geometrically rectified to selected coordinate systems by adding control points to be imported into the GIS model. This process of aligning images is called georeferencing. In the absence of any field survey for the study, control points were extracted from available scanned data or from most recent Google Earth image.
Encoding a georeferenced image into digital mapping platform was performed by digitizing the required layers from the georeferenced image into vector digital format as points, lines and polygons.

All the digitized data was further subjected to post-processing to minimize topology and spatial errors, which included checking:

- Incompleteness of the spatial data (<5%)
- Locational placement errors of spatial data (<3%)
- Distortion of the spatial data (<10%)
- Incorrect linkages between spatial and attribute data (<15%)
- If attribute data is wrong or incomplete (<15%)

The check for the accuracy of digitization was undertaken to avoid discrepancy between input and output digitized layers. Estimates of accuracy are given for each bullet point in parenthesis. Because the maps were to be presented in 1:2,500,000 scale, the US National Map Accuracy Standard for horizontal accuracy was followed to determine the horizontal accuracy as 0.02*250000*2.54/100 = 1270 ground meters accuracy. This is the conversion from imperial scale to metric (see https://www.tceq.texas.gov/gis/natmap.html).

2.4.2. Stage 2: Incorporation of publicly available digital spatial data

Available vector data (road network, boundaries, coastal boundaries, water bodies, earthquake locations, etc.) in public domain was added to the base map along with digital elevation model (DEM) from Shuttle Radar Topography Mission (SRTM) data obtained from the US Geological Survey (USGS) website. The SRTM product specifications are presented in Table 1. Vertical accuracy of SRTM data used for this study is <16 m in linear vertical absolute height error (Rodriguez et al., 2005).

Composite (main map) and individual geohazard maps have been produced for Saudi Arabia as an output of the study following the adopted methodology and implemented stages explained above. All features in the Main Map are stored in separate GIS layers and any other layer combination and layout for applied
maps is possible. Examples are given in Figure 2 which shows formation prone to subsidence and Figure 3 which shows regions with critical slope gradients vulnerable to instability, reported areas of slope instability and zones with flood potential. A further example shown in Figure 4 presents reported and predicted soil geohazards which when built upon can result in subsidence, ground heave and corrode ferrous and cementitious materials. These Quaternary deposits include sabkha, expansive soils, fluvial deposits and aeolian deposits (dunes and loess). For this map, it should be noted that the precise geological formation responsible for expansive soils is not clear from the published information and loess is not related to a geological formation, rather to an erosional process. Only sites where expansive soils and loess have been observed were placed on the map and further integration with site studies are required to understand their wider distribution. Presented geohazards maps can be considered as a baseline for future studies and early stages of land-use planning to gain an overall visual assessment of the spatial distribution of geohazards with respect to the geology and physical aspects of the country.

3. Conclusions

A series of introductory geohazard maps for the Kingdom of Saudi Arabia have been created for selected geohazards with publicly available data and information to provide an updated base document for use as an initial reference for early planning stages of future studies. The geohazards selected were rock subsidence, tectonics and volcanism, slope instability and flooding and collapsible and expansive soils. A base map was created from open source and copyright data onto which data points and digitized images of reported geohazards were added from a GIS database. Extending the reported occurrence of geohazards to rock and soil formations prone to subsidence, predicted geohazards were added in the form of colored polygons. The composite geohazard map was then subdivided into a series of simplified geohazard maps depending upon the type of geohazard required.

The straightforward methodology adopted for this study can be implemented to create similar maps elsewhere to reduce risks associated with geohazards when planning site developments or for predicting natural disasters. The maps presented in this manuscript are not
considered complete and can be further enhanced by adding remote sensing data (LiDAR and synthetic aperture RADAR images), which have the potential for monitoring evolving events such as dune migration, slope stability, ground subsidence and with site-specific surveys.

Software

ESRI ArcGIS 10.5.1 was used for all analysis and map production.

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Disclosure statement

The study was performed with publicly available data so no potential conflict of interest is expected by the authors.

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