Groundwater vulnerability assessment using modified SINTACS model in Wadi Shueib, Jordan

Muheeb Awawdeh, Noor Al-Kharabsheh, Mutawakil Obeidat and Mohsen Awawdeh

ABSTRACT
Water scarcity is the most serious environmental challenge that Jordan faces. Water resources require better protection and management as groundwater accounts for about 50% of the water usage in Wadi Shueib, central Jordan. Intrinsic vulnerability for Wadi Shueib (a valley located south of As-Salt city) watershed was assessed using modified SINTACS model using GIS techniques. According to our model, the investigated area encompassed very high, high and moderate areas of potential pollution with area coverage <1%, 26% and 51%, respectively. The high potential pollution is mainly influenced by combined contributions of parameters such as; unsaturated zone, aquifer media, lineaments density and effective infiltration.

Sensitivity analysis indicates that lineament density is significant for the calculation of the groundwater vulnerability index. Nitrate concentrations measured in selected wells and springs were compared with the model to inspect its reliability. The validation rate of our model reaches more than 70%, which is an indication of acceptable modelling approach. Moreover, there was a good match of vulnerability classes with land use land cover categories as indicators of groundwater vulnerability. The SINTACS method proved its versatility even in this complex hydrogeological environment.

1. Introduction
The vast bulk of accessible fresh water worldwide is groundwater. Due to its low susceptibility to pollution compared to surface water (Jackson et al. 2001; Foster and Chilton 2003), groundwater is considered to be the most important source of potable water. However, researches show that groundwater contamination by different types of pollutants is worth investigation.

In arid regions like Jordan, water resources are very limited where the available amounts of current water is about 150 cubic metres per capita per year (Hadadin et al. 2010). Moreover, water quality has deteriorated due to various sources of pollution, and over-abstraction. Preventing the pollution of aquifers is considered a priority over both environmental and economical pollution remediation. Accordingly, aquifer protection is pivotal and essential for sustainability and preservation of groundwater resources (Liggett and Talwar 2009; Awawdeh and Jaradat 2010; Demiroglu and Dowd 2014; Chenini, Zghibi, and Kouzana 2015). Groundwater susceptibility is intrinsic (natural) and specific. The former is defined as the ease of which contaminants, introduced into the ground surface, could reach and diffuse into groundwater (Vrba and Zaporozec 1994). Intrinsic vulnerability is assessed and mapped based on the hydrogeological properties of the aquifer system and is independent of the nature of pollutant and contamination scenario (Civita 1994; Zwahlen 2004). On the other hand, specific susceptibility defines the susceptibility of aquifers to a group of pollutants or to only one particular contaminant (Vrba and Zaporozec 1994; Schneebelen et al. 2002).

A comprehensive groundwater vulnerability model should include parameters describing a potential risk of contamination of a specific site or location (Varol and Davraz 2010; Moratalla et al. 2011; Chenini, Zghibi, and Kouzana 2015). Due to the necessity of a resourceful method that helps protecting groundwater resources from contamination, scientists have developed aquifer vulnerability techniques to predict the most vulnerable areas (Khemiri et al. 2013) and to evaluate aquifer vulnerability e.g. DRASTIC (Aller et al. 1987), GOD (Foster 1987), AVI (Van Stemponvoort, Evert, and Wassenaar 1992), and SINTACS (Civita 1994). In addition, various approaches have been used to assess and map groundwater vulnerability such as process-based methods.
statistical, overlay and index methods (Marcolongo and Pretto 1987; Schnebelen et al. 2002; Antonakos and Lambrakis 2007; Brindha and Elango 2015; Chenini, Zghibi, and Kouzana 2015; Javadi et al. 2017).

The most common ones are the index and overlay methods. They are considered simple and were established based on combining maps of various physiographic attributes (geology, soil, aquifer media, depth to water, etc) and other factors controlling groundwater vulnerability of the region by assigning a numerical score or rating to each attribute (Brindha and Elango 2015). The basic steps of applying these methods are: (1) analysis of raw data; (2) ranking features on a map (3) integration of maps and (4) classification of the integrated map based on an index (Brindha and Elango 2015). They are mainly applied to porous aquifers and can be performed within a GIS environment (Güler, Kurt, and Korkut 2013). The main advantage of these methods is that some of the factors such as rainfall and depth to groundwater can be available over large areas, making them suitable for regional-scale assessments (Thapinta and Hudak 2003; Al-Kharabsheh 2015).

The overall objective of this study is to assess groundwater vulnerability to contamination in Wadi Shueib area using a modified SINTACS method along with geospatial techniques. The lineaments density will be incorporated into the model and finally the model is validated based on nitrated measurements of water samples.

The basic argument in selecting the study area is that it is undergoing high rate of population growth and urbanization (Al-Kharabsheh and Al-Kharabsheh 2015). It hosts two wastewater treatment plants: Salt Wastewater Treatment Plant and Fuheis Wastewater Treatment Plant. Previous studies revealed that nitrate concentration in the groundwater resources are above the natural background concentration of nitrate, and even greater than the permissible limits of the WHO (2011), indicating human-induced sources of contamination (Al-Kharabsheh and Al-Kharabsheh 2014; Grimeisen et al. 2017). The output of this study may aid decision makers in taking appropriate measures to protect groundwater resources in the study area.

Different studies found that the aquifers in the Wadi Shueib area are particularly susceptible to pollution from domestic sewage leakage (Ta’any 1992; Abu-Jaber, Aloosy, and Ali 1997; Werz 2006; Margane et al. 2010). Additional sources include the application of fertilizers in the vicinity of the important freshwater springs due to the lack of enforced spring protection zones (Storz 2004; Trappe 2007). Abu-Jaber, Aloosy, and Ali (1997) pointed out that especially the A1/2 and the A7/B2 render a high vulnerability as indicated by the significantly higher concentrations of nitrate than found in the A4 aquifer. Werz and Hotzl (2007) derived maps indicate clearly the vulnerable areas and the ‘hot spots’ of potential contamination in Wadi Shueib using the European vulnerability approach (COST Action 620).

SINTACS model was derived from the DRASTIC model and has been developed for vulnerability assessment and mapping requirements (medium and large-scale maps) by Italian hydrogeologists (Civita and De Maio 1997). DRASTIC has some limitations in applications to karstic aquifers (Polemio, Casarano, and Limoni 2009) and it underestimates the pollution risk (Awawdeh, Obeidat, and Zaiter 2015; Aboulouafa et al. 2017; Maria 2018). The SINTACS method was established for hydrogeological, climatic and impacts settings, typical of the Mediterranean countries using the same parameters as DRASTIC, but the rating and weighting procedure is more flexible (Pisciotto, Cusimano, and Rocco 2015). The SINTACS parametric method offers a specific set of weights for karstic and fissured environments (Corniello, Ducci, and Monti 2004). The SINTACS method was tested for the definition of aquifer contamination vulnerability in karstic environment (Corniello, Ducci, and Monti 2004), which has similar environmental conditions to the area of our interest ‘Wadi Shueib’ of investigation. Busico et al. (2017) utilized a modified SINTACS method in order to get a more reliable view of groundwater vulnerability. The new methodology seems to show a higher correlation with observed NO3– concentrations and a more reliable identification of aquifer’s pollution hot spots. Al-Fawwaz (2010) combined geologic structures with DRASTIC and SINTACS indices. She found that without the consideration of the effects of the faults, the area would locate in middle vulnerability zones, but their presence caused an elevation in the vulnerability class. Marsico, Giuliani, and Pennetta (2004) modified SINTACS model so that more weights are given to morphological and structural data. Nitrate concentrations recorded from groundwater resources is usually used to verify the reliability of the vulnerability models (Marsico, Giuliani, and Pennetta 2004; Al-amoush et al. 2010; Kumar et al. 2013; Pisciotto, Cusimano, and Rocco 2015; Oroji 2018). Because the investigated area is considerably influenced by the tectonics of the Dead Sea area, lineament density was included into the model assuming better representation of the physical environment.

2. Description of the study area

2.1. Location and climate

The study area (Figure 1) is located at the western slopes of the eastern highlands of the Jordan rift valley, between 3530700–35532301 m Northing and 748294–
768356 m Easting (UTM coordinate system) and covers 200 km². It has a rectangular shape, with the long axis being oriented NE-SW. Elevations range between 181 m below sea level in the southwest to 1136 m above sea level in the northeast. Several Wadis are in the catchment area that drains from east to west towards Jordan Valley (Al-Kharabsheh and Al-Kharabsheh 2014). Due to the steep relief in Wadi Shueib, the climatic conditions considerably vary from the arid Jordan Valley to a Mediterranean climate in the highlands in the northeast. The average annual precipitation is highly variable over the basin influenced by topography (Riepl 2012). It is 599 mm for Hummar station (953 m asl) and 175 mm for South Shuna station (−143 m asl). In addition, the average annual temperatures vary between 17.3°C in Salt station and 25.6°C in South Shuna. Mains water for the study area is supplied by approximately equal shares of local groundwater (44% to 54% between 2011 and 2013) and water import from King Abdullah Canal (46% to 56%) (Grimmeisen et al. 2017).

2.2. Geology

The geology of the investigated area (Figure 2) is mainly dominated by the sedimentary rocks of the Upper Cretaceous (Ajloun Group). These are underlain by sandstones of the Kurnub group of the Lower Cretaceous age, outcropping on fault zones along Wadi Shueib structure (Mikbel and Zacher 1981). The Kurnub Sandstone in the study area consists mainly of cross-bedded massive bodies of porous varicoloured quartz arenite and glauconitic sandstone which is often present (Kuntz 2003). The thickness of the Kurnub Sandstone is approximately 250 m (Powell 1989). Ajloun group consists of approximately 350–400 m thick interbedded limestones, marly limestones and dolomitic limestones, whereas the Belqa group mainly includes a sequence of limestones, intercalated with thick-bedded chert but also chalk, marls, silicified limestones and phosphatic horizons (Werz 2006).

Na’ur formation (A1/A2) overlies the Kurnub sandstone, where A1 consists mainly of marls and A2 mainly composed of limestone and marly limestone. Fuheis formation (A3) is mainly consists of marl and interbedded limestone, whereas the Hummer (A4) formation consists of hard dense limestone and dolomitic limestone. Shueib formation (A5/A6) is mainly composed of marly limestone and chalky marl. Wadi Es Sir formation (A7) forms the upper part of Ajloun group, and consists of light grey, hard limestone with chert nodules. The Belqa group is subdivided into five formations (B1-B5); only two of these are found in the study area, namely Wadi Ghudran (B1) and Amman formations (B2). The former is composed of well bedded chalk and marl, with occasional beds of limestone (Ta’any 1992) and the latter consists of chert, marl, limestone, and some phosphatic bearing strata.

Figure 1. Location of the study area in Jordan.
2.3. Hydrogeology

From a hydrogeological point of view, the aquifer system in the area under consideration is divided into two main aquifer systems (Hellmut and Trippler1977): the lower Cretaceous complex (Kurnub sandstone), and the upper Cretaceous aquifer complex (Figure 3). The lower aquifer system consists of varicoloured sandstone and is exposed in the west of Mahis town; it has a thickness ranging between 220 and 300 m. The upper aquifer system includes the Ajloun and Belqa groups with an age ranging from Upper Cretaceous to Lower Tertiary. The Ajloun group represents the main aquifer system in the study area, where the aquifers are composed of limestone, dolomitic limestone, and marl. Three main formations of this group are considered aquifers. These are Na’ur formation (A1/A2), Hummar formation (A4), and Wadi Es Sir formation (A7). On the other hand, Shueib and Fuheis formations are classified as aquitards. There are twenty-two springs emerging from this aquifer system; five from A4, nine from A7 and eight from A1/A2 (Al-Kharabsheh and Al-Kharabsheh 2014). Ten representative springs were selected for the purpose of investigation in this study. Where B1 is classified as aquitard, and B2 as aquifer (Werz 2006), but B1 is missing in some places, and thus B2 directly overlies A7, forming a composite aquifer. The fractured study area is highly related to the rift valley.

3. Methods and results
3.1. SINTACS model

SINTACS is one of the most common used methods for groundwater pollution vulnerability evaluation systems. It was developed by the National Research Group for the Protection from Hydrogeological Disasters of the Italian National Research Council (Civita 1975, 1990, 1993, 1994; Civita and De Maio 1997). It is a development of the US DRASTIC model that is adapted to Mediterranean conditions (Rahman 2008) and areas with karstic features. Both models use the same parameters but applied differently. SINTACS has been preferred over many other methods because of its suitability to Mediterranean conditions, low costs,
data availability and giving reliable results when applied in different geological and hydrogeological contexts (Al-amoush et al. 2010).

The acronyms SINTACS stands for the seven parameters used in the model: Water table depth (S), Effective infiltration (I), Unsaturated zone (N), Soil media (T), Aquifer media (A), Hydraulic conductivity zone (C), and Topographic slope (S). These parameters are further classified to represent various hydrogeological settings and each class is then assigned a rating value on a scale of 1 to 10 (Kuici, El-Naqa, and Hammouri 2006). The rating assigned to each of these ranges or zones indicates their relative importance within each parameter in contributing to aquifer vulnerability. Due to the unequal significance in vulnerability assessment of these seven parameters, weights on the scale of 1 to 5 are assigned to be considered for each parameter of the model.

In order to set the SINTACS method for a karst context with intense structural influence, some improvements were suggested that is based on integrating superficial lineaments derived from remote sensing data. The SINTACS intrinsic vulnerability index is computed using equation 1 (Civita and De Maio 1997).

\[
I_{\text{SINTACS}} = \sum_{i=1}^{7} P_i \times W_i, \tag{1}
\]

Where the \(P_i\) is the rating of each parameter that the method considers and \(W_i\) is the relative weight. This intrinsic vulnerability index \(I\) was divided into six classes (Table 1) taking into consideration the addition of the lineaments parameter, meaning that greater ranges were considered for each class. All procedures were performed in ArcGIS software version 10.0.

### 3.2. Preparation of the parameter maps

#### 3.2.1. Water table depth (S) map
This parameter represents the depth from the ground level to the water table. The greater the depth results in

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**Figure 3.** Aquifer systems in the study area.
lower vulnerability since the thickness of the unsaturated zone reduces pollution due to physical and chemical processes. There is no available network of wells for groundwater monitoring in the area and consequently no groundwater contour map is available. Margane et al. (2010) assumed that the hydraulic system is well interconnected and that water levels in the different hydraulic units are more or less identical at a location controlled by topography and degree of fracturing. Werz (2006) estimated an average thickness of the unsaturated zones as 60 m for Naur aquifer, 50 m for Hummar and 75 m for Wadi Sir aquifers. These data were adopted to map the depth to groundwater table. According to Civita and De Maio (1997), this parameter is given a weight of 5, and the rating value for the Kurnub and alluvium aquifers is 3, whereas for other aquifers it is 1, since they are considered deep.

| Intrinsic Vulnerability Index (I) | Vulnerability Class |
|----------------------------------|---------------------|
| less than 90                     | Very Low            |
| 90–110                           | Low                 |
| 110–150                          | Medium              |
| 145–195                          | High                |
| 200–220                          | Very High           |
| more than 220                    | Extreme             |

Table 1. Ranges of intrinsic vulnerability index (I) (after Civita and De Maio 1997).

| Station Id  | Station Name                     | Average Annual Precipitation (mm) |
|-------------|----------------------------------|-----------------------------------|
| AM0001      | Salt                             | 608                               |
| AM0002      | Wadi Shueib Agricultural Sation  | 392                               |
| AM0005      | Hummar                           | 599                               |
| AM0006      | Ira                              | 349                               |
| AN0002      | Wadi Esir                        | 589                               |
| AL0028      | Rumeimin                         | 378                               |
| AL0035      | Baqa-King Hussein Nursery        | 374                               |
| AL0045      | Um Jauza                         | 552                               |
| AM0007      | South Shuna                      | 175                               |

Table 2. The meteorological stations and their average annual precipitation.

Figure 4. The spatial distribution of effective infiltration in the study area and location of the meteorological stations.
3.2.2. Effective infiltration (I) map

Effective infiltration represents the amount of water per unit area of land which penetrates the ground surface and reaches the water table. This recharge water is thus available to transport the contaminants vertically to the water table and horizontally within the aquifer. Greater recharge means that the potential for groundwater pollution is higher. In this study, the effective infiltration parameter was calculated based on rainfall data from 9 meteorological stations (Table 2 and Figure 4). Although variable annual recharge rates were reported in different studies for Wadi Shueib (Ta’any 1992; Zagana et al. 2007), Riepl (2012) determined that the average annual recharge rate is 21% of the areal precipitation. He estimated the mean annual recharge over the water years 1995/1996 to 2008/2009 to be 9.9 MCM, which represented 21% of the mean annual rainfall. The water balance method was used by Riepl (2012) to estimate the groundwater recharge according to the following equation (Singhal and Gupta 2010):

\[ R_p = O_s + O_w - \Delta R_s \pm n, \]

where \( R_p \) is the recharge from precipitation, \( O_s \) is the spring discharge, \( O_w \) is the well abstraction, \( \Delta R_s \) is the unintentional recharge from water supply pipelines, sewer canals and septic tanks, \( n \) is the error term. It is worth mentioning that the estimated recharge given by Riepl (2012) is in good agreement with those given by Jiries et al. (2010) and the Ministry of Water and Irrigation (MWI 2004). The results showed that the infiltration rates were in the range 32–150 mm/year (Figure 4), with rating values in the range 1–6 (Table 3), increasing from the southwest to the northeast parts of the study area.

3.2.3. Unsaturated zone (N) map

Because it acts as a defence boundary against pollutants (Cucchi et al. 2008), the unsaturated zone parameter is one of the most significant parameters in vulnerability assessment. It is described as the zone below the typical soil horizon and above the water table, which is unsaturated or discontinuously saturated. The information about detailed lithological characteristics and rock units of the unsaturated zone are shown in Table 4 and Figure 2 (Mikbel and Zacher 1981; Powell 1989; Muneizel and Khalil 1993; Werz 2006). The scores were based on Civita and De Maio (1997). Eight different classes of the unsaturated zone were recognized in the study area (Figure 2), with rating 9 represents 39%, found to prevail in most parts of the basin except in the eastern part. The unsaturated zone with a rating of 2.5 and 5.5 represent 27.5% and 13.2% respectively, found to prevail along the wadies in the study area (Figure 5).

3.2.4. Soil media (T) map

Soil media refers to the uppermost portion of the unsaturated zone and constitutes the first defence line of the hydrogeological regime (Civita and De Maio 1997). Therefore, it plays a primary role in assessing groundwater intrinsic vulnerability. Soil media has shown a significance impact on the amount of recharge that will infiltrate into the ground and hence on the ability of a contaminant to move vertically into the vadose zone Al-amouss et al. 2010). The soil media parameter was prepared using soil maps from the Ministry of Agriculture in Jordan (Ministry of Agriculture 1994). Eighteen soil units have been identified within the study area. Because the groundwater intrinsic vulnerability is highly controlled by the textural characteristics of the soil (Al-amouss et al. 2010), the texture of the soil map units was evaluated according to the classification of the dominant series of each unit. The rating of soil textures (Figure 6) was performed based on values suggested by Civita and De Maio (1997) as given in Table 5. The rating value ranged between 1 and 8. The rating values equal or less than 3 represent about 58% of the basin and dominating the middle and northeastern part of the basin. The soil units with high rating values represent only 15% of the study area.

| Table 3. SINTACS rating and weighting values for Effective Infiltration (I) (Civita and De Maio 1997). |
|-----------------------------------------------|
| **Rating** |
|------------------|---|
| 250–325          | 9  |
| 175–250          | 8  |
| 150–175          | 7  |
| 125–150;400–450  | 6  |
| 100–125;450–500  | 5  |
| 75–100;>500      | 4  |
| 60–75            | 3  |
| 50–60            | 2  |
| <50              | 1  |
| **Weight = 4**   |    |

| Table 4. SINTACS rating and weighting values for the geologic formations in the study area. |
|-----------------------------------------------|
| **Formation** | **Symbol** | **Thickness (m)** | **Rating** | **Area%** |
|----------------|------------|-------------------|------------|-----------|
| Amman Silicified limestone                    | B2         | 50                | 9          | 8.72      |
| Wadi Um Ghudran                                 | B1         | 20                | 3          | 4.80      |
| Wadi As Sir                                    | A7         | 130–150           | 9          | 30.11     |
| Wadi Shueib                                    | A5/A6      | 30                | 2.5        | 16.56     |
| Hummar                                        | A4         | 45                | 7.5        | 9.17      |
| Fuheis                                        | A3         | 70                | 2.5        | 10.93     |
| Naur Formation                                 | A1/A2      | 110               | 5.5        | 13.19     |
| Kumub                                        | K          | 250               | 6.5        | 6.51      |
| **Weight = 5**                                  |            |                   |            |           |

Therefore, the unsaturated zone and soil media are two primary parameters in groundwater vulnerability assessment.
area and found mostly in the northwestern and southeastern part of the basin.

3.2.5. **Aquifer media (A) map**

This parameter takes into account the processes occurring below the water table (Cucchi et al. 2008). The main aquifers in the study area are (Figure 3): 1) Lower Ajloun, 2) Amman-Wadi Es Sir, 3) Alluvium, and 4) Kurnub Sandstone. Information about the individual aquifer characteristics was obtained from available hydrogeological and geological information (Ta’any 1992; Werz 2006; Riepl 2012). The rating values of the aquifers were 4, 8, 9, and 7, respectively. The aquifers with rating values 7, 8, and 9 represent about 52% of the basin. The Lower Ajloun aquifer (rating value 4, 2010) is found in the northern and southern parts of the basin.

3.2.6. **Hydraulic conductivity (C) map**

Hydraulic conductivity is a measure of the ability of the aquifer to transmit water. Higher conductivity values typically correspond to high vulnerability to contaminants. It controls the rate at which groundwater will flow under a given hydraulic gradient. The rate at which groundwater flows also controls the rate at which the contaminant moves away from its entry point. The values of hydraulic conductivity (Table 6) ranged from 1 to 4 m/day (Margane et al. 2010) were used to develop the hydraulic conductivity surface. The values fall into two zones only with rating values 5 and 6 according to Civita and De Maio (1997).

3.2.7. **Slope (S) map**

Topography parameter refers to the slope of the ground surface and has an influence on vulnerability assessment regarding to either water and pollutant will preferably run
The source of information related to this parameter was ALOS PALSAR Global Radar Imagery (12.5 m DEM) obtained from Alaska Satellite Facility (2017). The elevations (Figure 7) in the study area range between −181 m and 1136 m asl, and the slope is in the range 0–190% (Figure 7). The rating of slope values was assigned as per the SINTACS model as given in Table 7. About 54% of the study area is dominated by steep slopes i.e. low rating values (1 and 2).

### 3.2.8. Lineaments density map

Lineaments are significant guide of groundwater exploration, since it controls its movement and storage (Rao, Chakradhar, and Srinivas 2001; Sener, Davraz, and Özcelik 2005; Preeja et al. 2011), and affect groundwater

![Soil ratings map of Wadi Shueib.](image)

**Figure 6.** Soil ratings map of Wadi Shueib.

**Table 5.** SINTACS rating and weighting values for Soil Media (T) (Civita and De Maio 1997).

| Soil Media (T)      | Rating |
|---------------------|--------|
| Clay                | 1–1.5  |
| Silt clay           | 1.5–2  |
| Clay loam           | 2–3    |
| Silt clay loam      | 3–4    |
| Silt loam           | 3.5–4  |
| Loam                | 4–5    |
| Sandy clay loam     | 4.5–5  |
| Sandy loam          | 5.5–6  |
| Sandy clay          | 6.3–7  |
| Peat                | 7.5–8  |
| Sandy               | 8–8.5  |
| Clean sand          | 9–9.5  |
| Clean gravel        | 9.5–10 |
| Thin or absent      | 10     |

Weight of parameter = 4

**Table 6.** The hydraulic conductivity (C) and its SINTACS rating values for Wadi Shueib aquifers.

| Name of Hydrological Unit | Hydraulic Conductivity (m/day) | Rating value |
|---------------------------|--------------------------------|--------------|
| Alluvium                  | 4                              | 6            |
| Kurnub                    | 3                              | 6            |
| Amman/Wadi Sir            | 2                              | 6            |
| Hummar                    | 2                              | 5            |
| Naur Formation            | 1                              | 5            |

Weight of parameter = 3
flow and contamination. Hence, high lineaments density values mean more vulnerable is the groundwater to pollution (Mabee, Hardcastle, and Wise 1994; Lee 2003; Sener and Davraz 2013).

Because the study area is considerably affected by the tectonics of the Dead Sea area, lineaments density was assigned a weight value of 5. Lineaments considered in the study area (Figure 8) represent geological structures such as fractures and faults. A lineament density map was generated using the kernel density method in ArcGIS and then rated into 10 values (Figure 8) to account better for its spatial variability. The lineament density was in the range 0–5.20. The most vulnerable groundwater according to lineament density is found in the northern and central parts of the study area particularly along wadis.

3.3. The intrinsic vulnerability map

The intrinsic vulnerability map of the study area was derived by using Equation (1). The obtained index values were then reclassified into five levels of vulnerability (Figure 9(a)). The classes represent the relative potential to pollution within the investigated area.

In terms of area coverage, < 1%, 26%, and 51% of the study area are classified as having very high, high, and medium potential to pollution, respectively (Table 8). The very high and high vulnerability classes dominate the northwestern and middle parts of the basin stretching along the main wadis towards the south. The high pollution potential is mainly influenced by the combined contribution of the parameters: unsaturated zone (rating 9), aquifer media (B2/A7, rating 9), effective infiltration (rating 8), and lineaments density (rating >7). On the other hand, soil media is acting as mitigating factor of the pollution, as most of the study area is covered by soil rating values less than 5.

3.4. Sensitivity analysis

Sensitivity analysis study the contribution of individual variables and the input parameters on the resulting output of an analytical model and permits recognition of layers which are more critical for the analysis (Napolitano and Fabbri 1996; Ducci 2010). From a practical point of view, because vulnerability maps are tools used by planners for socio-economic decisions, sensitivity analysis is
useful for validation and consistency evaluation of the analytical result and for a correct interpretation of the vulnerability maps (Napolitano and Fabbri 1996).

Two sensitivity tests are usually carried out: the map removal sensitivity analysis and the single parameter sensitivity analysis. The map removal sensitivity analysis is used to evaluate whether it was really necessary to use all the parameters. The map removal sensitivity analysis identifies the sensitivity of the model by removing one parameter each time of running the model (Napolitano and Fabbri 1996). In particular, map removal sensitivity analysis was developed for weighted sum intersection overlays and can be easily applied to the expression to compute the SINTACS indexes (Napolitano and Fabbri 1996). A variation index \( V \) for each model parameter is computed using the following equation (Gogu, Hallet, and Dassargues 2003):

\[
V = \frac{P - P'}{P} \times 100
\]  

Where:
- \( V \): the variation index
- \( P \): the potential value in each cell computed using Equation (1)
- \( P' \): the potential value of each cell excluding the one parameter

The variation index could be positive or negative, depending on the influence of the single parameter in decreasing or increasing the groundwater vulnerability index. The value of this index gives an idea of the magnitude of such a variation. The results of map removal sensitivity analysis showed that most variations are due to the unsaturated zone, whereas soils and slope were the least. Although its value is very close to the parameters of aquifer media hydraulic conductivity, lineaments density occupies the fourth rank in the variation index. This rank is a good indication of considering the significance of lineament density as a major factor in the calculations of the groundwater vulnerability index. Based on these findings a single parameter sensitivity

Figure 8. The spatial distribution of lineaments and the rating values of lineament density.
A sensitivity test was carried out to assess the influence of each parameter of the SINTACS model on the potential value. In this analysis real or ‘effective’ weight of each parameter was calculated by using the equation (Napolitano and Fabbri 1996):

$$W = \frac{X_w X_{sc}}{P} \times 100$$

(3)

**Table 8.** Area coverage (%) by each vulnerability class in Wadi Shueib.

| Vulnerability Class | Modified SINTACS (theoretical weights) | Modified SINTACS (effective weights) | Original SINTACS |
|---------------------|----------------------------------------|--------------------------------------|------------------|
| Very Low            | 3.91                                   | 2.39                                 | 4.76             |
| Low                 | 18.29                                  | 11.92                                | 35.76            |
| Medium              | 51.6                                   | 44.53                                | 44.22            |
| High                | 26.14                                  | 39.59                                | 15.23            |
| Very High           | 0.06                                   | 1.94                                 | 0                |

**Table 9.** The effective weights of parameters from single parameter sensitivity test.

| Parameter | Theoretical Weight (%) | Min | Max | Mean |
|-----------|-------------------------|-----|-----|------|
| S         | 16.13                   | 3.0 | 21.58 | 11.32 |
| I         | 12.90                   | 2.25 | 26.81 | 12.69 |
| N         | 16.13                   | 7.25 | 42.45 | 22.89 |
| T         | 12.90                   | 2.10 | 29.17 | 8.72  |
| A         | 9.68                    | 6.45 | 29.35 | 13.80 |
| C         | 9.68                    | 8.06 | 21.58 | 13.00 |
| S         | 6.45                    | 1.04 | 22.86 | 4.81  |
| L         | 16.13                   | 2.86 | 40.82 | 12.77 |

Water table depth (S), Effective infiltration (I), Unsaturated zone (N), Soil media (T), Aquifer media (A), Hydraulic conductivity (C), and Topographic slope (S), Lineaments Density (L)

**Table 10.** Comparison of nitrate concentration in wells and springs and SINTACS vulnerability classes in Wadi Shueib.

| Well/Spring Id | Name          | Type | Nitrate (ppm) | Vulnerability class |
|----------------|---------------|------|---------------|---------------------|
| AM0534         | Mahis spring  |      | 33.7          | medium              |
| AM0526         | Azraq Fuhaïs  | spring | 28.5         | medium              |
| AM0528         | Sharea' spring|      | 29.1          | low                 |
| AM0522         | El Hummar     | spring | 32.2          | low                 |
| AM0530         | Baqourieyyeh  | spring | 32.4          | low                 |
| AM0533         | Al-Alali      | spring | 20.6          | low                 |
| AL2423         | Yazidiyya No5 | well  | 27.2          | medium              |
| AM1004         | Um Atiyyeh    | well  | 35.1          | medium              |
| AM1027         | Wadi Jrea'a No3 | well | 36.8          | medium              |
| AM0512         | Hazzir        | spring | 40.2          | low                 |
| AM0520         | Um Zarrorah   | spring | 32.6          | medium              |
| AM0542         | Um Jurban     | spring | 66.0          | low                 |
| AM0506         | Jadour Fouqa  | spring | 62.0          | low                 |
| AM0504         | Jadour Tahta  | spring | 62.6          | low                 |

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Where w and s are the weight and rating for the parameter X assigned in each cell respectively, and P is the potential value as computed in Equation (1). For each cell, the sum parameter effective weights are 100% for all parameters. Although the effective weight of lineament density is lower than its theoretical weight (Table 9), its importance is comparable to other parameters of the model such as effective infiltration and hydraulic conductivity. The effective weights of parameters were used to derive the final vulnerability map. The results (Table 8) show the very high vulnerability class has increased by 2%, whereas the area covered by the high vulnerability class increased by about 13%. These increases were at the expense of the other vulnerability classes. It is worth mentioning that the classes medium and high are mainly underlain by the B2/A7 aquifer, indicating that this aquifer is the most vulnerable aquifer. This can be attributed to many factors, such as the fractured and karstified nature unsaturated/saturated zone, considerable hydraulic conductivity of the aquifer (2 m/day), and lineaments density.

### 3.5. Model validation

A complete aquifer vulnerability assessment requires validating the model with field data. The most common approach is to compare the vulnerability map with the actual occurrence of some common pollutant in groundwater (Ghazavi and Ebrahimi 2015). The evaluated vulnerability of Wadi Shueib was compared with nitrate concentrations in the water resources of the basin. This is because nitrate is the most frequently human-introduced pollutant into groundwater, and it has become a common problem worldwide (Obeidat et al. 2012).

Nitrate contamination of groundwater is a global issue due to its harmful effects on human health as well as on aquatic ecosystems (Anornu, Abass, and Adomako 2017; Zhu et al. 2019). Exceedance of the WHO nitrate guideline value (50 mg/L) in drinking water may lead to health problems, such as methemoglobinemia, stomach cancer, spontaneous abortion, thyroid disorder, and others (Fan and Steinberg 1996; Ward et al. 2005; WHO 2011; Yang et al. 2014). Moreover, elevated nitrate concentrations can lead to eutrophication and hypoxia in surface water (Archanà et al. 2018). Besides the adverse health and ecological impacts, nitrate pollution of water has negative economic impacts, owing to the high costs of remediation techniques applied to decrease nitrate concentration (Jiang et al. 2011). Groundwater with nitrate concentration exceeding the guideline value (5–10 mg/L) is considered contaminated due to human activities (Panno et al. 2006). Sources of this highly mobile ion include agricultural fertilizers, uncontrolled disposal of sewage, animal breeding operations, leachate leakage, and atmospheric deposition (Wakida and Lerner 2005; Xue et al. 2012; Ma et al. 2016).

Fourteen samples were collected from upper aquifer system representing 11 springs and 3 groundwater wells and analysed for nitrate concentration. The sampling campaign was carried out in the rainy season (January and February 2018). The methods described by Lenore, Greenberg, and Eaton (1998) were followed during fieldwork and laboratory chemical analysis.

Comparing the SINTACS vulnerability maps with nitrate concentrations is a common practice by researchers (Marsico, Giuliano, and Pennetta 2004; Al-amoush et al. 2010; Kumar et al. 2013; Pisciotta, Cusimano, and Rocco 2015; Oroji 2018). Kumar et al. (2013) and Pisciotta, Cusimano, and Rocco (2015) validated the SINTACS model with nitrate concentrations and found significant relationship. Al-amoush et al. (2010) and Marsico, Giuliano, and Pennetta (2004) compared the results of SINTACS index map with groundwater nitrate concentrations recorded in wells. Kuisi, El-Naqa, and Hammouri (2006) observed the rising values of the nitrate concentration in groundwater wells in the Jordan Valley area, which motivated them to map the vulnerability of groundwater aquifer using SINTACS model.

The maximum acceptable nitrate concentration (NO₃⁻) for drinking water is 50 mg/L according to the WHO (2011), whereas it is 70 mg/L according to the Jordanian drinking water standards JS 286:2001 (JISM 2001). Nitrate concentrations in the study area were in the range between 20.60 and 66.00 mg/L of NO₃⁻ (Table 10). All samples have nitrate concentration exceeding the guideline value of anthropogenic origin, and only three samples having concentration exceeding the maximum permissible value set by the WHO (2011).

| Vulnerability Class | Built-Up Area (%) | Agriculture (%) | Rangeland (%) | Forest (%) | Water Body (%) | Rocks (%) | Bare Soil (%) |
|---------------------|-------------------|-----------------|--------------|------------|---------------|-----------|---------------|
| Very Low            | 4.64              | 25.51           | 31.56        | 0.52       | 0.06          | 0.53      | 37.19         |
| Low                 | 16.20             | 41.03           | 25.03        | 0.15       | 0.32          | 0.19      | 17.07         |
| Medium              | 17.81             | 40.93           | 24.21        | 0.19       | 0.06          | 0.80      | 16.00         |
| High                | 21.15             | 46.10           | 25.02        | 0.01       | 0.00          | 0.06      | 7.66          |
| Very High           | 23.85             | 55.38           | 18.46        | 0.00       | 0.00          | 0.00      | 2.31          |
Nitrate concentrations were classified into 4 classes (low (<20 mg/L), medium (30–50 mg/L), high (50–70 mg/L) and very high (>70 mg/L) for the purpose of comparison with vulnerability classes of SINTACS (Table 10). The low class involves samples with a low risk for human or the environment, and the medium class involves samples with nitrate concentrations high enough to indicate the influence of human activities (Spalding and Exner 1993). Nitrate concentrations in the high and the very high classes exceed the recommendations for drinking water set by WHO (2011) and JISM (2001), respectively.

Using the original SINTACS model (Figure 9(b)), only 5 samples were found within the correct categories of vulnerability (Table 10). On the other hand, when compared with the modified model (Figure 8(a)), 10 samples (out of 14) matched the vulnerability classes i.e. 71% of the total samples. Although the samples AM0504, AM506 and AM0542 were found in the medium class, the first two samples are within the margins of the high vulnerability class. This can be explained by the complex geology of the study area and the geographical distribution of the point sources of pollution.

Table 11 shows a good match of vulnerability classes when compared with land use land cover categories as indicators of groundwater vulnerability. Jawarneh and Biradar (2017) used Landsat imageries to map the land use land cover in the study area (Figure 10). The results of comparison show that vulnerability classes have a direct relationship with agriculture and built-up areas, while it has an inverse relationship with forest and rangelands. It is well established that agriculture and built-up areas contribute to groundwater contamination, while forests and natural vegetation protect them from being contaminated.

4. Conclusions
The study has clearly demonstrated that regional-scale assessment of aquifer vulnerability using GIS
and SINTACS could be used to depict areas that are more likely to be contaminated. The results verify that the modified SINTACS index by adding an extra element (lineaments) is suitable for karstic and structurally affected areas, since the model shows a closer correlation with its geological characteristics. The vulnerability map shows the markedly influence of the lithological and morphological settings on the contamination vulnerability assessment. The SINTACS method proved its versatility even in this complex hydrogeological environment. The rate of model validation against nitrate concentration reached more than 70%, which is a good indication of acceptable modelling approach.

The site-specific analysis is costly. Thus, these assessments can be used as tools but not as an alternative method for detailed site-specific analysis in zones of concern. In addition, the vulnerability assessment maps are significant for the strategic water plans in Jordan and in decision-making for the purpose of establishing polluting industries in a given locality such as petrochemicals or refineries. Finally, the use of SINTACS method is proved to be a useful tool in defining the aquifer vulnerability even in a strongly impacted area by geological processes.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Muheeb Awawdeh http://orcid.org/0000-0001-5467-2679

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