Karstification Processes in Haditha Vicinity, West Iraq

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Abstract
In the valley of the Euphrates River to the south of the Haditha city (West Iraq), the dissolution of the carbonate rocks which underlie residual soil gives rise to numerous sinkholes. These sinkholes are a potential hazard to human safety and damage to the existing infrastructure. The exposed rocks in the area under consideration belong to the Euphrates Formation of the Early Miocene age, specifically the Middle Member of the formation. Tens of sinkholes have developed with different shapes, sizes, activities, and maturities, others are under development indicating that the karstification process is still ongoing. Some of the sinkholes have spectacular scenes and can be used for touristic purposes. The karstification process has a negative impact on the infrastructure in the Haditha vicinity, especially the Hadith Dam, where extraordinary treatments to the foundation of the dam were considered to be in a safe status. We have studied different published articles and reports, which dealt with the karstification in the Haditha vicinity. Moreover, we have interpreted satellite images, and topographical and geological maps to recognize the existing sinkholes and study them. Filed trips were performed for long interrupted intervals (1984 until 2022) to collect significant data and perform field photographs for the interesting scenes.

Keywords: Sinkholes; Maturity; Activity; Karstification; Euphrates Formation; Haditha

1. Introduction

The Haditha vicinity is one of the most karstified areas in the western part of Iraq (Al-Naqash and Al-Talabani, 1988; Hamza, 1997). The karstification process is still active, as witnessed by the recent (after 1984) developed sinkholes (Fig. 1), and as the safety treatments taken in the Haditha Dam (Adamo et al., 2018; Al-Ansari et al., 2018; Sissakian et al., 2021). The karstification process in the area started in the Early Pleistocene and might even from the Late Pliocene (Hamza, 2007). However, according to Stevanovic et al. (2009), the karstification in the northern part of Iraq has started since the Paleocene, however; they mentioned that the second karstification phase has started since the Oligocene–Miocene and is still active.

In the studied area (Fig. 1), the exposed rocks are mainly limestone, dolomite, and rare marl of the Euphrates Formation (Early Miocene) and the Nfayil Formation (Middle Miocene) (Sissakian and Mohamed, 2007; Sissakian and Fouad, 2015); therefore, they are highly susceptible for dissolution. As the rock dissolves by the circulated surface and groundwater paces and caverns develop underground providing there is topsoil to keep the moisture, accordingly, the surface will be susceptible to the development of sinkholes. Sinkholes are very dramatic, as land can stay intact for quite some time until underground spaces get very big. If there is not enough support for the land above the spaces, a collapse...
of the land surface will occur, resulting in sinkholes. This is the case in the studied area, where new sinkholes were developed (No. 56; we named it Bayan sinkhole and No. 57; named Najy sinkhole (Fig. 1).

Studies dealing with karstification and karst forms in Iraq are very limited. However, there are few published works and maps including the area under consideration. Among those studies are the following: Sissakian et al. (1986) studied 55 sinkholes in the area and presented relevant data about the studied sinkholes, which were re-used in the current study. Hamza (2007) studied the sinkholes of the studied area and concluded that they are developed due to the existence of long lineaments. Sissakian and Al-Mousawi (2007) studied the karstification problems in Iraq and mentioned many examples from the studied area. Sissakian et al. (2015) studied the karst forms in Iraq and concluded that the sinkholes are either circular or oval with different diameters depth. Sissakian et al. (2021) studied the effect of karstification on the Haditha Dam, which is located within the studied area. They concluded that due to
highly karstified limestone beds in the dam site, the length of the grout curtain extended beyond the dam body for about 9064 m (Sissakian et al., 2021).

The studied area is in the central-western part of Iraq (Fig. 1), within Al-Anbar Governorate. The area extends from the north of Haditha town southward to Wadi Hauran. Most of the sinkholes are concentrated in the middle and western parts of the studied area. This study aims to elucidate the karstification process in the studied area and its consequences on the main infrastructure and the existing community in the area. Moreover, it discusses the genesis of the developed sinkholes including their types, dimensions, activity, and relationship with the exposed rocks, structural and geomorphological forms.

2. Materials and Methodology

The main data used in the current work are from a published work by Sissakian et al. (1986), we have used the data of 55 studied sinkholes, including the dimensions of the sinkholes, the exposed rocks at the concerned area, fissure directions, and the locations (Fig. 1). However, we have added two new sinkholes, which were not developed yet during the study of Sissakian et al. (1986) that was in 1984; accordingly, the number of the studied sinkholes is 57. The sinkhole data were reinterpreted and divided into two main groups (A and B). The sinkholes of Group A are developed in the rocks of the Euphrates Formation, whereas those of Group B are developed within the rocks of the Nfayil Formation, in the western part of the studied area (Sinkholes Nos. 26–34) (Fig. 1).

A contour map of the concentration of the sinkholes was drawn (Fig. 2). For drawing the contour map of the sinkholes’ concentration (Fig. 2), the studied area was divided into a grid with a spacing of 03’ 30” X 03’ 30” degrees of latitude and longitude. Within each rectangle, the number of the existing sinkholes was added to the center of the rectangle. The contour map was drawn at an interval of one sinkhole using Arc GIS software (Fig. 2).

![Fig. 2. Contour map of the concentration of the sinkholes in the studied area](image)

A Rose diagram (Fig. 3a) was constructed for 39 measured fissures in the floors of 33 sinkholes to show the main fissures’ directions of the sinkholes, which are shown in Fig. (1). The data used are shown in Table 1. Rose diagrams for the measured dip direction and strike of the persisting joints were constructed using GeoRose software (Fig. 3b and c), and the user data are shown in Table 2.
active sinkholes, where the stream overflows in flood time when the swallow hole cannot accept all the rainwater (Monroe, 1970). Mainly developed in their floors (Fig. 5b), and the floors are filled with soil and collapsed rocks from the rims of Groups A and B (Fig. 4a), whereas inactive sinkholes are those where no fissure is developed in their floors (Fig. 5b), and the floors are filled with soil and collapsed rocks from the rims (Fig. 5b). Mainly, “half-blind valley” exists in such inactive sinkholes, where the stream overflows in flood time when the swallow hole cannot accept all the rainwater (Monroe, 1970). The data about the sinkholes were statistically processed and arranged in tables. The data about the shapes of the sinkholes are presented in Table 3, the diameter – depth relation data are presented in Table 4 and the data on the status of the sinkholes are presented in Table 5.

Table 1. Fissure directions in the studied sinkholes

<table>
<thead>
<tr>
<th>Fissure direction (º)</th>
<th>No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 45 NE</td>
<td>5</td>
</tr>
<tr>
<td>46 – 90 NE – E</td>
<td>9</td>
</tr>
<tr>
<td>91 – 136 E – SE</td>
<td>2</td>
</tr>
<tr>
<td>137 – 180 SE – S</td>
<td>11</td>
</tr>
<tr>
<td>181 – 226 S – SW</td>
<td>5</td>
</tr>
<tr>
<td>227 – 270 SW – W</td>
<td>4</td>
</tr>
<tr>
<td>271 – 314 NW – SW</td>
<td>0</td>
</tr>
<tr>
<td>315 – 360 NW – NE</td>
<td>5</td>
</tr>
</tbody>
</table>

Fig. 3. Rose diagrams, a) 39 Fissures’ directions as measured in 33 sinkholes, b and c) Dip direction and strike of 79 measured joints, respectively

A diameter–depth relation diagram was constructed (Fig. 4), to indicate whether there is a relation between these two parameters or otherwise. We have drawn two diagrams: 1) diameter – depth relation of Groups A and B (Fig. 4a); and 2) diameter – depth relation of active and inactive sinkholes (Fig. 4b). Both diagrams were drawn using the Excel program. For indicating active and inactive sinkholes, we have adopted the idea of Sissakian et al. (1986). Active sinkholes are those, which show one or more fissures in their floors (Figs. 1 and 5a), whereas inactive sinkholes are those where no fissure is developed in their floors (Fig. 5b), and the floors are filled with soil and collapsed rocks from the rims (Fig. 5b). Mainly, “half-blind valley” exists in such inactive sinkholes, where the stream overflows in flood time when the swallow hole cannot accept all the rainwater (Monroe, 1970). The data about the sinkholes were statistically processed and arranged in tables. The data about the shapes of the sinkholes are presented in Table 3, the diameter – depth relation data are presented in Table 4 and the data on the status of the sinkholes are presented in Table 5.

Table 2. Dip direction and amount of the measured joints in the outcrops and sinkholes

<table>
<thead>
<tr>
<th>No.</th>
<th>Dip (º)</th>
<th>Amount</th>
<th>No.</th>
<th>Dip (º)</th>
<th>Amount</th>
<th>No.</th>
<th>Dip (º)</th>
<th>Amount</th>
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</thead>
<tbody>
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<td>350</td>
<td>78</td>
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<tr>
<td>2</td>
<td>354</td>
<td>90</td>
<td>22</td>
<td>322</td>
<td>88</td>
<td>42</td>
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<td>23</td>
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<td>87</td>
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<td>56</td>
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<td>66</td>
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<td>6</td>
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<td>89</td>
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<td>349</td>
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<td>295</td>
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<td>356</td>
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<td>118</td>
<td>87</td>
<td>49</td>
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<td>10</td>
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<td>88</td>
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<td>120</td>
<td>88</td>
<td>50</td>
<td>119</td>
<td>77</td>
</tr>
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<td>11</td>
<td>110</td>
<td>86</td>
<td>31</td>
<td>322</td>
<td>90</td>
<td>51</td>
<td>345</td>
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<td>12</td>
<td>112</td>
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<td>176</td>
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<td>33</td>
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<td>88</td>
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<td>15</td>
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<td>289</td>
<td>89</td>
<td>35</td>
<td>100</td>
<td>57</td>
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<td>88</td>
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<td>355</td>
<td>87</td>
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<td>118</td>
<td>89</td>
<td>56</td>
<td>354</td>
<td>79</td>
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<tr>
<td>17</td>
<td>352</td>
<td>90</td>
<td>37</td>
<td>120</td>
<td>87</td>
<td>57</td>
<td>350</td>
<td>89</td>
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<tr>
<td>18</td>
<td>298</td>
<td>88</td>
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<td>354</td>
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<td>289</td>
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</tr>
<tr>
<td>19</td>
<td>289</td>
<td>90</td>
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<td>20</td>
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<td>57</td>
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<td>354</td>
<td>78</td>
<td>60</td>
<td>268</td>
<td>45</td>
</tr>
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</table>
Fieldwork was carried out in November and December 2021 to check some of the collected data by Sissakian et al. (1986) about the studied sinkholes. Moreover, photographs of some of the sinkholes with interesting features, some of them are presented in the current article.

**Table 3. Shapes of the studied 57 sinkholes**

<table>
<thead>
<tr>
<th>Shape of the studied sinkholes</th>
<th>Circular - Basin like</th>
<th>Circular - Irregular</th>
<th>Circular - Conical</th>
<th>Circular - Cylindrical</th>
<th>Kidney shape</th>
<th>Oval - Basin like</th>
<th>Elongated</th>
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<td>4, 9, 17, 19,</td>
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<td>1, 13,</td>
<td>3, 5, 6,</td>
<td>18, 20</td>
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<td>15, 21,</td>
<td>7</td>
<td>24, 28</td>
<td>12, 41</td>
<td>40,</td>
</tr>
<tr>
<td></td>
<td>26, 27, 29, 31,</td>
<td>56</td>
<td>30, 38,</td>
<td>8, 14</td>
<td>51</td>
<td>42</td>
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</tr>
<tr>
<td></td>
<td>32, 33, 35, 36,</td>
<td>47, 55,</td>
<td>16</td>
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<td></td>
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</tr>
<tr>
<td></td>
<td>37, 39, 44, 46</td>
<td>57</td>
<td>52</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>48, 53, 54</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>21</td>
<td>4</td>
<td>9</td>
<td>8</td>
<td>5</td>
<td>4</td>
<td>6</td>
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</tbody>
</table>

**Table 4. Number of the 57 studied sinkholes showing the ranges of diameter and depth**

<table>
<thead>
<tr>
<th>Diameter (m)</th>
<th>1 – 10</th>
<th>11 – 20</th>
<th>21 – 30</th>
<th>31 – 40</th>
<th>41 – 50</th>
<th>&gt; 50</th>
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<td>Total</td>
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<td>7</td>
<td>13</td>
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<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>10</th>
<th>11 – 20</th>
<th>21 – 30</th>
<th>31 – 40</th>
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</tr>
<tr>
<td>43, 44, 45, 46, 50, 53, 54</td>
<td>57</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Total</td>
<td>32</td>
<td>12</td>
<td>11</td>
<td>1</td>
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</table>

**Table 5. Status of the studied 57 sinkholes**

<table>
<thead>
<tr>
<th>Status of the sinkholes and their rims</th>
<th>Filled by soil</th>
<th>Collapsed walls</th>
<th>Recent collapse</th>
<th>Existing roof</th>
<th>Deep Cracks</th>
<th>Recently developed</th>
<th>Active</th>
<th>Inactive</th>
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</thead>
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<td>Sinkhole No.</td>
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<td>8, 16</td>
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<td>10</td>
<td>5</td>
<td>2</td>
<td>2</td>
<td>33</td>
<td>24</td>
</tr>
</tbody>
</table>

* Shows ground water, ** Rejuvenated sinkhole
3. Geological Setting

The geological setting of the studied area, including geomorphology, stratigraphy, and tectonic and structural geology, are briefed hereinafter based on Hamza (2007), Sissakian and Mohamed (2007), and Fouad (2007), respectively. The geological map is shown in Fig. 6.

3.1. Geomorphology

The most common geomorphological unit in the studied area is Solution Origin. Within this unit, the existing sinkholes are the most significant form Hamza (2007), Sissakian and Al-Mousawi (2007), Sissakian et al. (1986, 2021). The indication of the karstification process on the surface is the sinkholes (Fig. 1), and in the subsurface is the treatment of Haditha Dam’s foundation (Sissakian et al., 2021). The wide plateau, which is developed on the top of the Middle Member of the Euphrates Formation (Hamza, 2007) is another geomorphological unit development due to weathering of the softer rocks of the Upper Member of the Euphrates Formation (Fig. 7a) forming typical karst margin plain (Monroe, 1970), Bare karst (Lowe and Waltham, 1950), and mesa (Fig. 7b) and butte (Fig. 7a) forms. Weathering and erosion are active phenomena in the studied area, as witnessed by the existence of the wide plateau, buttes (Fig. 7a), mesas (Fig. 7b), and the presence of the highly fissured bedrocks as appear in some of the sinkholes (Fig. 8a). Weathering and erosion of the fill materials (Fig. 8b) of some Rejuvenated sinkholes (Nos. 21, 34, 42, 53; Fig. 1) is another indication of the activity of these processes.

3.2. Tectonics and Structural Geology

Tectonically, the studied area is within the Inner Platform of the Arabian Plate (Fouad, 2015). The only surface structure near the area is the Anah anticline, which is located northwest of the area with the E – W trend. Joints, fissures, and undulations are common in outcrops and sinkholes (Fig. 7a). Locally, the rims of some sinkholes are collapsed along the joints and/or are enlarged (Fig. 7b). The rose diagram of the measured joints is presented in Fig. 3b and the used data is in Table 2.

![Diameter – Depth Relation of the Active (Blue) and Inactive sinkholes (Orange)](image1)
![Diameter – Depth Relation of the Studied Sinkholes Group A (Blue) and Group B (Orange)](image2)

**Fig. 4.** Diameter – Depth relation of the studied sinkholes, a) Active and Inactive sinkholes, b) Group A and Group B
Fig. 5. a) Active sinkhole (No. 21), note the infill valley (Iv) and the Fissure (Fr), b) Inactive sinkhole (No. 23), note the accumulated soil in the floor, infill valley (Iv), and the half-blind valley (Hbv)

Fig. 6. Geological map of the studied area (after Sissakian and Fouad, 2015)

3.3. Stratigraphy

The exposed geological formations in the studied area are presented in Table 6.
Table 6. Stratigraphic column of the exposed geological formations in the studied area (After Sissakian and Fouad, 2015)

<table>
<thead>
<tr>
<th>Formation</th>
<th>Age</th>
<th>Thick. (m)</th>
<th>Main Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nfayil</td>
<td>M. Miocene</td>
<td>12-25</td>
<td>The formation consists of three cycles, each cycle consists of soft green marl and limestone. This formation forms a wide plateau in the west and small isolated hills west and south of Haditha town. Upper Member: Consist of highly brecciated dolostone and dolomitic limestone, massive, and hard; overlain by highly deformed thinly well bedded undulated limestone. Middle Member: Consists of chalky like dolostone, and hard, limestone is well bedded, hard to very hard, and two soft marl beds. Lower Member: Consists of a basal conglomerate and limestone. The pebbles of the conglomerate are derived from the Anah Formation and range in size up to 1 m. The limestone is thickly bedded - massive, hard to very hard.</td>
</tr>
<tr>
<td>Euphrates</td>
<td>Lower Miocene</td>
<td>20-30</td>
<td>The formation consists of thickly bedded to massive, cavernous, jointed, and hard to very hard limestone. The joints are enlarged in form of caves and caverns, which are filled by Tera Rosa.</td>
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<tr>
<td></td>
<td></td>
<td>5–15</td>
<td></td>
</tr>
<tr>
<td>Anah</td>
<td>U. Oligocen</td>
<td>12–20</td>
<td>The formation consists of thinly well bedded limestone, fairly hard to hard.</td>
</tr>
<tr>
<td>Shurau and</td>
<td>L. Oligocen</td>
<td>8–12</td>
<td>The formations consist of thinly well bedded limestone, fairly hard to hard.</td>
</tr>
<tr>
<td>Sheikh Alas</td>
<td></td>
<td></td>
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</tbody>
</table>

The red line represents unconformity which facilitates the ground water circulation.

Fig. 7. a) Bare karst (Sinkhole No. 22) and karst margin plain in the background with a Butte (B), b) Mesa (M) developed within the Upper Member of the Euphrates Formation, note the oblique joints (Sinkhole No. 18).

Fig. 8. Highly Fissured rocks of the uppermost part in sinkhole No. 56 B weathering and erosion of infilling materials in a sinkhole R called Paleo Karst (No.34) leading to the re-opening of the sinkhole; called Denuded karst (Rejuvenated sinkhole) and a typical circular sinkhole in the background

4. Results
From analyzing the collected data, the following results were achieved.

4.1. Karstification

The karstification process is still active in the studied area, as was seen in the field from recently developed sinkholes (Fig. 10) and/or rejuvenated sinkholes (Fig. 8b), which is the re-opening of a “closed karst” and hence is called “denuded karst” (UNESCO, 1972). The karstification in the subsurface; however, is also still active, this is confirmed by the considered actions in the treatments of the Haditha Dam’s foundation (Sissakian et al., 2021).

4.2. Karst Types

The main types of sinkholes in the studied area are of two types: 1) Solution sinkhole or collapse sinkhole where the roof is collapsed due to the dissolution of the limestone beds below the surface leading to the development of the sinkhole (Fig. 7 a), which is also called “Exposed karst” (Quinlan, 1978). This type can engulf the inflow of rainwater during heavy rain showers through one or more fissures (Fig. 1). 2) Cryptokarst where the karst is developed in the limestone beneath a mantle of its residual clayey soil (Fig. 5 b), we have called this type “Inactive sinkhole”. This type cannot engulf the rainwater during rain showers; however, when are then the access water will flow out by one or more shallow valleys. They are also called “Paleo karst” and when reopened, they are called “Denuded karst” (Monroe, 1970).

4.3. Karst Forms

We recognized eight different sinkhole forms, which were developed in the studied area:

1) Circular-basin form, is the main form found in the area (Figs. 5a and b). 2) Circular-conical form, this has a circular aperture with inclined walls either inside or outside (Fig. 11b). 3) Circular-cylindrical form, this has mainly circular aperture with vertical or steeply inclined walls (Fig. 5a). 4) Elongated form, this is developed along vertical joints (Fig. 9a). 5) Kidney form, this is developed due to conjugation of two or more sinkholes leading to one large sinkhole. 6) Circular-Irregular form, this is developed due to collapsing of the rims, or infilled by Quaternary sediments, and exposed again due to weathering and erosion (Fig. 8b). 7) Oval form, this is developed due to the total removal of parts of the rims between two sinkholes; accordingly, two or more neighboring sinkholes are conjugated together, forming one enlarged sinkhole (Fig. 11a). Conjugated form, this shows a small partition between two neighboring sinkholes (Fig. 11c), they will conjugate after the partition is removed due to weathering and erosion.

4.4. Karst’s Rims and Walls

The rims and walls of the studied karts are statistically classified into six classes (Table 5), which are described briefly hereinafter. 1) Sinkholes filled with soil, this type is very common (26 sinkholes) and are considered an inactive sinkhole (Figs. 5a and 5b). 2) Sinkholes with collapsed rims, this type is also very common (20 sinkholes), the size of the collapsed blocks ranges in size from ≤ 1 to 3 m³ (Fig. 8b). 3) Sinkholes with recent collapse, this type is common (10 sinkholes), and it depends on the depth and diameter of the sinkhole (Fig. 11a). 4) Sinkholes with the existing roof, this type is very rare (5 sinkholes), the main part of the collapsed roof can still be seen in the sinkhole (Fig. 12b).
Fig. 9. a) Vertical and oblique joints (Sinkhole No. 18), note Butte and Mesa in the background, b) the collapsed rim of a sinkhole (No.19) along vertical joints.

Fig. 10. a) Bayan sinkhole (No.56) developed on 20 September 2012, b) Najy sinkhole (No. 57) discovered on 11 November 2021.

Fig. 11. a) An enlarged sinkhole (No. 24), b) a conical form sinkhole (No. 15) (photographed from the bottom, the long diameter is 15 m), c) a conjugated sinkhole (No. 17).

Fig. 12. a) Recent collapse, note the color difference between old (O) and recent (R) collapses, and existing pipe to pump out the ground water (Sinkhole No. 43) b) Existing roof in a sinkhole (ER) (it is called Salman Rossa Sinkhole, No. 31), c) Deeply cracked sinkhole (No. 18) (reddish-brown arrows).
Sinkholes with deep cracks, this type is very rare (2 sinkholes), although cracks are essential for the development and enlargement of sinkholes, they are very rare (Fig. 12c). Recently developed sinkhole, only two sinkholes were recently developed (Fig. 10). From interviewing the local people, apart from the mentioned 2 sinkholes, none of the existing sinkholes are known to be developed recently, at least in the past (80 –100) years.

4.5. Cenote Karst

This sinkhole shows ground water on the floor (Monroe, 1970). In the studied area, two sinkholes of this type were found (Nos. 43 and 56, Table 5). The groundwater in Sinkhole No. 43 (Figs. 1 and 12a) was used to irrigate the cultivated plants and a water pump was installed. However, due to a recent collapse, the cultivation in the sinkhole was abandoned. In sinkhole No. 56 (Fig. 13), emitted vapor was seen during the carried field check on 16 December 2022.

4.6. Diameter and Depth of the Studied Sinkholes

The diameters and depths of the studied sinkholes (Table 4) were plotted in two diagrams (Figs. 4a and b). In both cases, no clear relation was found between both variables.

4.7. Concentration of Sinkholes

The concentration of the studied sinkholes (Fig. 2) shows that the concentration of the developed sinkholes in the Euphrates Formation are more than those in the Nfayil Formation.

4.8. Rose Diagrams

Three rose diagrams were constructed (Fig. 3). The three diagrams show excellent coincidence with the trend and developed shear and tension joints within the Anah anticline, which is the nearest surface fold in the studied area. It is located 70 km northwest of the studied area (Sissakian and Fouad, 2015).

5. Discussion

The karstification process in the studied area is still active and has caused damage to the infrastructure and life losses. We have discussed the main impacts on the infrastructure and the life losses.

- **Haditha Dam:** It is located on the Euphrates River with length and height of 9064 m and 57 m, respectively. The earthfall parts of the dam are: 3310 m on the right abutment, 4985 m on the left
abutment, and 580 m in the river channel (Sissakian et al., 2021). This abnormal length is to protect
the dam from the effect of the active karstification and accordingly increase the dam’s safety.

- **Haqlaniyah Rock-slabling Plant:** This is a special plant to slab large rock blocks into different
sizes using giant circular saws. Because the site is highly karstified (near sinkholes Nos. 21–24),
the saws were out of their centers due to settlement of the ground; accordingly, the plant was
abandoned (Fig. 13b and c).

- **Life losses:** Three persons were found dead when their car was found fallen in a sinkhole (No. 31,
Fig. 1) in 1960. The sinkhole was called “Salman Rosa” referring to the oldest dead person.

- **Planned school:** A school was planned to be constructed south of Haqlaniyah town. The excavator
was scraping the area to be leveled when a sinkhole was opened (No. 56, Figs. 1 and 10a) due to
the weight of the excavator and caused vibration. The driver was badly injured, and the site was
abandoned. If the sinkhole was not discovered, and the sinkhole opened after the school was
constructed, then the consequences would be a catastrophic event.

- **Development of the Sinkholes:** The Group A sinkholes (Fig. 5) were developed in nearby valleys
where the basal conglomerate of the Euphrates Formation and/or the Anah Formation is exposed
in the valley. The presence of the basal conglomerate will accelerate the circulation of the ground
and surface water; accordingly, the dissolution of the rocks will increase and karstification will
start, leading to the development of sinkholes. For Group B sinkholes, which are developed within
the Nfayil Formation (Figs. 1 and 5) the main reasons for karstification are: 1) the presence of thick
marl beds alternated with thinly bedded and highly fissured limestone, which will increase the
dissolution ability. 2) presence of densely spaced fissures, which have increased the dissolution
ability; therefore, the developed sinkholes are very shallow (1–1.5 m) with very long diameters (up
to 110 m) (Fig. 1) presence of thinly bedded and undulated limestone beds of the uppermost part
of the Euphrates Formation below the Nfayil Formation. These very well thinly bedded and
undulated limestone beds have increased the penetration and circulation of the surface and
groundwater and accordingly, have increased the dissolution ability.

- **Joint and Fissure Directions:** The constructed rose diagrams (Figs. 3b and 3c) show two main
trends of the joints. They are NEE – SSW, and NEN-SSW, they represent tension and shear joints,
respectively; affected by the growth of the Anah anticline with dip directions of the two limbs in
NWN and NWW, respectively. Whereas the two recorded main fissure directions in the sinkholes
are SSE and NEE (Fig. 3a). They slightly deviate from the main joint trends. This can be attributed
to: 1) the fissures are irregular; therefore, their openings may not represent the true direction, which
cannot be seen under the walls of the sinkholes, 2) enlargement of the fissures due to water
circulation has changed the true direction of the fissure.

- **Rejuvenated Sinkholes (Denuded karst):** The presence of this type of sinkholes (Fig. 8b) is a
good indication that the karstification process is still active. Otherwise, the paleo karst would never
be denuded and reopened.

- **Karstification’s Age:** As aforementioned, the karstification process has started since the
Pleistocene and is still active. This age estimation is based on: 1) the presence of residual soil in
the surrounding of some sinkholes (Figs. 5a and 7), 2) the presence of a very thin vinier of soil on
the floor of some sinkholes (Fig. 5b), 3) the presence of alluvial sediments which show clear
indications for weathering and opening of the paleo-karst (Rejuvenation) (Fig. 8b), and 4) The
recognized two recently developed sinkholes (Fig. 10).

- **Tourism:** The densely karstified area with tens of sinkholes (Fig. 2) west of Haqlaniyah town was
used since the fifties of the last century by the local people as a touristic place, to explore some of
the sinkholes, and a golf yard was constructed there. Unfortunately, these interesting activities are
not existing anymore. However, local people are visiting the Salman Rosa sinkhole (Fig. 12 b) for its unique and spectacular shape.

- **Health Care**: In sinkhole No. 43 (Fig. 1), where ground water exists, people were using sulphate water for the treatment of skin diseases. However, this activity is also abandoned due to the recent collapse of the sinkhole (Fig. 12a).

6. **Conclusions**

The karstification process in the Haditha vicinity is still active, as confirmed by the newly developed two sinkholes. The existing sinkholes have different shapes, sizes, and maturities; some are rejuvenated after being filled by alluvial and residual soils. The karstification impact has affected the existing infrastructure, especially the Haditha Dam, Haqlaniyah rock slabbing factory, and life losses too. The major trend of the existing fissures in the active sinkholes is towards SEE, which is almost perpendicular to the main tension joints’ directions (NEE–SWW) of the Anah anticline. The developed sinkholes within the rocks of the Nfayil Formation have large diameters and small depths, whereas those developed in the Euphrates Formation have large depths and diameters.

**Acknowledgements**

This article is performed by joint work between three universities, the University of Kurdistan Hewler (Erbil), University of Anbar (Ramadi), and Al-Karkh University of Science (Baghdad). The authors express their sincere thanks to the responsible authorities in the three universities for their continuous support during the performance of the research.

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