Effects of the Karkheh Dam construction on haze generation due to geomorphological changes (in the Khuzestan Province, Southwest of Iran)

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ABSTRACT

An important factor for occurrence of dust storms is the construction of the Karkheh Dam in the Khuzestan province of Iran. It has reduced the annual mean of flow discharge in the Karkheh River from 120 to 50 m³/s and dried lands around river. The area of dried lands is 90.17 km² around river and 333.45 km² in the Hawr-al-Azim wetland. The Rosgen method, Fluvial-12 software, Shulits equation showed instability of the plan, cross sections of river and longitudinal slope of river, respectively, around Pay-e-pol hydrometric station (the upstream of river). After dam construction, extreme erosion occurred in this part of river. The type of sediment is clay and silt with D₅₀ ≈ 8 μm. The eroded sediment settles in downstream of river (around Hamidiyeh hydrometric station) and the Hawr-al-Azim wetland. The wind can easily lift these particles especially from May to July. Because of size of these particles, the haze concentration increased from 25% to 45% in dust storms. After construction dam, the dust storm days increased to 90 days in 2008. By increasing the stability of the river, the dust storms reduced from 2011. The annual volume of generated haze by geomorphological characteristic changes is almost 3 x 10⁷ m³.

Key words: Fluvial-12 software, haze and dust storm, river geomorphology, the Karkheh Dam, the Rosgen method, the Shulits equation

HIGHLIGHTS

- Identifying the relationship between haze generation and changes in river morphological characteristics.
- Identifying the difference between haze and dust storms.
- Identifying the effects of dam construction on river morphological characteristics.
- Identifying the effects of dam construction on haze generation.
- Identifying the effects of river topographic instability on haze generation.

INTRODUCTION

The environmental aspects of implemented projects are important for people who live in around of them. In the Middle East, common projects between neighbor’s countries have serious effects on environment (because of competition between them). Human activities and construction of large dams in Iran and Iraq exacerbated the destructive effects on environment. For example, the area of the Hawr-al-Azim wetland reduced to one-third (from 307,000 hectares in the 1970s to 102,000 hectares now). Reducing the area of wetlands causes haze and dust storms. Haze can displace in thousands of kilometers and decrease air quality very much. Based on Supplementary Material, Table A2, haze concentration reaches to 21–80 times the allowable amount in the world (35 μg/m³). The Karkheh Dam was built in 1999 on the Karkheh River. The Karkheh River falls to the Hawr-al-Azim wetland. By variations of river geomorphological characteristics and reduction of river discharge, thickness of fine particles’ layer and area of dry lands increase in the Hawr-al-Azim wetland and downstream of river. By decreasing of flow discharge, the width of river reduced and by increasing of stability of river, the length of river meanders decreased (river meanders became straight reaches). The reduction of width and length of river increased area of dry lands. The topsoil layer of these lands is composed of fine-grained soils (clay and silt). These soils were suspended sediment that gradually settled in the river. After the soil dried, water content and shear strength of fine-grained soils reduced considerably and the wind could easily erode them (Adib et al. 2018).
From 2005, haze storms began and polluted air considerably. These storms increased each year and today people can not live in some regions (Figure A4). Lung and heart diseases harmed to people and native people immigrated to other regions (Maleki et al. 2016). As mentioned, a source for haze is developed changes in river geomorphological characteristics by new dams (Adib et al. 2018). The change of geomorphological characteristics of rivers are an interesting matter for river engineers.

Ashmore (2013) researched about braided rivers. He observed that changes of flow and sediment characteristics can develop braided in rivers. Legleiter (2014) studied about importance of place of hydraulic structures and its effect on changes of geomorphological characteristics. For this purpose he applied geo statistics technique. Saleh et al. (2013) illustrated which changes of flow discharge and water surface elevation are dependent to geomorphological characteristics and river slope. Their case study was a branch of the Seine River of France.

Delhomme et al. (2013) studied about formation of oxbow lakes. They considered the Caloosahatchee River in South Florida as case study. Li et al. (2008) calculated gravel transport and changes of geomorphology characteristics in the Fraser River Gravel Reach of British Columbia. They used a two-dimensional hydraulic model. Also, the following researchers studied about the changes of river geomorphological characteristics (Frascati & Lanzoni (2010); Zámolyi et al. (2010); Lazarus & Constantine (2013); Constantine et al. (2010); Güneralp & Marston (2012); Smith et al. (2016); Haghigi et al. (2014); Casado et al. (2016); Termini (2016); Wei et al. (2016); Jing et al. (2013)). Researchers evaluated the effects of dam construction on these characteristics Yang et al. (2014); Csiki & Rhoads (2014); Arnaud et al. (2015); Wang et al. (2018); Smith & Mohrig (2017).

Also, researchers studied about fine dust storms and factors that generate them. Alizadeh-Choobari et al. (2014) researched about relation between wind of 120 days and fine dust storms in the Sistan province in southeast of Iran. They illustrated that sources of dust are in Iran and along its borders. Rezazadeh et al. (2013) showed that dust storms occur in four regions of the Middle East. Hamidi et al. (2014) simulated the severe dust event of 3–8 July 2009 in the Middle East by the WRF–DuMo model. Abbsi et al. (2019) observed that the prevailing wind direction is north to south for wind of 120 days in the Sistan province. The dust concentration increases from north (the Registan of Afganestan) towards south (the Sistan in Iran). In the Khuzestan province, Maleki et al. (2016) investigate about effects of fine particles in dust storms on health of people while MalAmiri et al. (2022) studied these effects for coarse particles in dust storms.

Also, researchers studied about dust storms in the Middle East countries such as Sabbah et al. (2018) in Kuwait and Bodenheimer et al. (2019) in North Africa and Arabian Peninsula.

These researchers considered the hydraulic and geological aspects of the geomorphological features of the rivers and did not pay attention to the relationship between haze and dust storms and these features. Also, other scientists studied about effective factors on dust storms but did not consider river geomorphological characteristics. Unfortunately, they evaluated effects of dust storms instead of hazes. These phenomena are different and diameter of dust particles is larger than diameter of hazes. Therefore, environmental effects of these two phenomena are different too. Because of small diameter of hazes, they can harm to lungs of people very much and their destructive effects on environmental is very dangerous (Maleki et al. 2016). Dust masks can not prevent from passage of hazes while these masks are suitable for dusts. Since haze storms are very important problem for people who live in the Khuzestan province and developed changes in river geomorphology by construction of the Karkheh Dam have the fundamental role in this hazard, author of this paper evaluated relation between these changes and haze generation. For this purpose, different components of river geomorphology changes are measured and calculated by observations and suitable methods.

The fundamental differences between this study and other studies are two matters. (a) Evaluating effects of instability of river geomorphological features (developed by dam construction) on occurrence of dust storms, (b) Determine percentage of haze (the particles with diameter less than 2.5 μm) in dust storms by considering dam construction effects on river geomorphological features.

The Khuzestan province has five large dams and 12 small dams. These dams have caused many changes in the river features and these changes have many effects on environment, nature and people. Therefore, studies that consider different aspects of dam construction effects are necessary for the Khuzestan province.

The novelties of this research are:

1. Investigation about relation between dam construction and reduction of flow discharge with the area of dried lands around river
2. Investigation about relation between changes in geomorphological characteristics (such as instability of plan, longitude profile, cross sections and slope of the river) with changes of width and length of river. The changes of width and length of river determines the area of dried lands in the river.
3. Determining the percentage of haze in dust storms based on soil grain size curve in dried lands
4. Extracting the relationship between changes in geomorphological characteristics and changes in sedimentation and erosion in the river and the number of dust storm days
5. Investigation about relation between wind velocities with dust storm concentrations

MATERIALS AND METHODS

Case study
The area and population of the Khuzestan province are 66,532 km² and 4,710,509 (in 2016). This province locates in southwest of Iran and Iraq and the Persian Gulf locate in west and south of it respectively. Its Longitude is between 47° 42’ and 50° 39’E and latitude is between 29° 58’ and 32° 58’N. Half of the oil and gas of Iran belongs to this province and it has the huge steel and cement plants. Six major rivers of Iran locate in this province (the Karun, Karkheh, Dez, Marun, Zohreh, Jarahi Rivers) and this province is center of agricultural in Iran.

The Hawr-al-Azim wetland is case study of this study. The Karkheh River and two tributaries of the Tigris are Iranian and Iraqi sources of water supply in this wetland. Because of construction of the Karkheh Dam, changes of geomorphological characteristics are observed in the reach between Pay-e-Pol hydrometric station (downstream of the Karkheh Dam) and Hamidiyeh hydrometric station (with length 214 km, mean width 188 m, greatest width 658 m and least width 32 m). The downstream of the Karkheh River has been illustrated in Figure 1.

The Hawr-al-Azim wetland locates in Iran and Iraq between 30° 58’- 31° 50’N and 47° 20’- 47° 55’E. In Iran, area of this wetland was 64,100 hectares in 70s but today, its area is 29,000 hectares. Also, total of its area (in Iran and Iraq) was 307,000 hectares in 70s and is 102,000 hectares now. This wetland locates in the North of Azadegan Plain and its distance from Ahvaz (center of the Khuzestan province) is 80 km. it is in southwest of Ahvaz. Changes of the land cover in the Hawr-al-Azim wetland from 1973 to 2000 are showed in Figure 2 (UNEP 2001).

An important reason for reduction area of lakes and marshes is construction of the Karkheh Dam in 1999 (Adib et al. 2018).

The utilized data
This study used different categories of data such as meteorological data, hydrometric data, surveying data, soil data and satellite images. The used data and their features (the source of data, type of data, the location and years of data collection and application of data in this study) are illustrated in Table 1. These data and their statistical analysis are stated in Supplementary Material, Appendix.

Fluvial-12 software
Fluvial-12 software was developed by Chang in 1972. This model is an unsteady model for erodible channels and can simulate channel bed scour and fill, width variation, and changes in bed topography induced by the curvature effect (Chang 1988; Adib...
et al. (2019). This software uses different total load equations (for example The Yang (1973) equation). Yang (1973) developed the following unit stream power equation for sand transport:

$$\log C_{ts} = 5.435 - 0.286 \log \frac{\omega d}{v} - 0.457 \log \frac{U^*}{\omega} + \left( 1.799 - 0.409 \log \frac{\omega d}{v} - 0.314 \log \frac{U^*}{\omega} \right) \log \left( \frac{V_S}{\omega} - \frac{V_{cr} S}{\omega} \right)$$

(1)

where:

- $C_{ts}$: Total sand concentration in ppm by weight
- $\omega$: Sediment fall velocity
- $d$: Sediment particle diameter

**Figure 2** | The changes of land cover in the Hawr-al-Azim wetland from 1973 to 2000. (a) 1973 Area = 8,926 km² (b) 2000 Area = 1,296.9 km² (UNEP 2001).
ν: Kinematic viscosity
$U^*$: Shear velocity
S: Energy or water surface slope
VS: Unit stream power
$V_{cr}$: average flow velocity at incipient motion

The dimensionless critical average flow velocity is:

$$\frac{V_{cr}}{\omega} = \frac{2.5}{\log(U^*d/\nu) - 0.06} + 0.66 \quad \text{for} \quad 1.2 < U^*d/\nu < 70$$  \hspace{1cm} (2)

$$\frac{V_{cr}}{\omega} = 2.05 \quad \text{for} \quad U^*d/\nu > 70$$  \hspace{1cm} (3)

**RESEARCH METHODOLOGY**

Figure 3 shows the research methodology flowchart in this study.

**RESULTS AND DISCUSSION**

Results of this study are:

1. Determination of the river bed and deposited sediment height in 1999, 2012 and 2013 by observed data (prepared by surveying)
The surveying distinguished that severe erosion occurred from Pay-e-Pol to Abdol Khan while sedimentation occurred from Abdol Khan to Hamidiyeh. The changes of the bed river in three hydrometric stations are illustrated in Table 2.

In the upstream of considered reach (from Pay-e-Pol to Abdol Khan), Table 2 shows that severe erosion occurred after 1999 but sediment deposition occurred from 2012 (the average of erosion height is 1.9 m from 1999 to 2012 and the average of sedimentation height is 0.05 m from 2012 to 2013). The river bed and longitudinal profile are almost stable from 2012 while river plan is unstable. Also in the downstream of considered reach (from Abdol Khan to Hamidiyeh), Table 2 shows that severe sedimentation occurred after 1999 but slightly erosion occurred from 2012 (the average of sedimentation height is 0.36 m from 1999 to 2012 and the average of erosion height is 0.09 m from 2012 to 2013). The bed river and longitudinal profile are almost stable from 2012. Because of the relative stability of the geomorphological features of the river after 2013, this study considered the period 2004–2014 for evaluating dam construction effects on haze and dust storms.

2. Determination of stability of different cross sections of river by the Fluvial-12 software:

For calibration of the Fluvial-12 software, dominant discharge for transportation of suspended sediment was determined. For this purpose, it is utilized sediment-discharge rating equation. This equation was determined for three hydrometric stations. To derive these equations, this study used the sediment rating curves that prepared by the KWPA from 1999 to 2014 (Figure A6).

Table 2 | The changes of the bed river (measured by surveying) in three hydrometric stations

<table>
<thead>
<tr>
<th>Hydrometric station</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Bed level 1999 (m)</th>
<th>Bed level 2012 (m)</th>
<th>Bed level 2013 (m)</th>
<th>Dif. bed levels 2012–1999 (m)</th>
<th>Dif. bed levels 2013–2012 (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pay-e-Pol</td>
<td>E 48° 15’</td>
<td>N 33° 7’</td>
<td>103.08</td>
<td>99.961</td>
<td>100.11</td>
<td>−3.119</td>
<td>0.149</td>
</tr>
<tr>
<td>Abdol Khan</td>
<td>E 48° 23’</td>
<td>N 31° 50’</td>
<td>28.72</td>
<td>28.016</td>
<td>27.966</td>
<td>−0.704</td>
<td>−0.05</td>
</tr>
<tr>
<td>Hamidiyeh</td>
<td>E 48° 26’</td>
<td>N 31° 30’</td>
<td>9.166</td>
<td>10.594</td>
<td>10.474</td>
<td>1.428</td>
<td>−0.12</td>
</tr>
</tbody>
</table>
These equations for different hydrometric stations are:

\[ y = 0.0364x^{2.357} \]  for Pay-e-Pol  
\[ y = 0.0362x^{2.38} \]  for Abdol Khan  
\[ y = 0.1651x^{2.487} \]  for Hamidiyeh

where:

- \( x \): Discharge (m\(^3\)/s)
- \( y \): Sediment discharge (Ton/day)

By these equations, the dominant discharge is almost equal to 400 m\(^3\)/s. The best equation for calculation of the changes of cross sections of this river is Yang (1973–1986) equation (determined by calibration of the Fluvial-12 software). Table 3 and Figure 4 illustrate results of calibration for different hydrometric stations.

The Fluvial-12 software runs for different discharges after 2014. A sample of results of this software has been illustrated in Table 4.

In the upstream cross sections of the river, the change in height of their various points is negligible. These sections eroded very extremely from 1999 to 2004 (after construction of dam). Top soil eroded and transported to downstream. Therefore, armoring layers are against flow. These layers are very resistant and flow can not erode them. Because of extreme erosion, the depth and width of the upstream cross sections increased and flow velocity decreased. Therefore, sedimentation has occurred in recent years in this part of river.

In the downstream of reach, sedimentation occurred from 1999 to 2004 (after construction of dam). Deposited sediment has very fine particles. Resistance of these particles is negligible against erosion. Because of deposition of sediment in this part of river, the depth and width of the downstream cross sections decreased and flow velocity increased. Therefore, a small flow discharge can erode these particles and erosion is independent of flow discharge. Also, the elevation changes at different points in different cross sections of the river indicate that sedimentation occurs upstream of the river while erosion occurs downstream of the river. The surveying illustrates this subject from 2012 to 2015 in three hydrometric stations (Table 2).

3. Evaluation of stability of different river reaches by the Rosgen method (developed by Rosgen 1994) and the Shulits equation:

The Rosgen method evaluate stability of plan and cross sections of river. For this purpose, it considered sinuosity coefficient, width/depth ratio, entrenched ratio (the ratio of the width of the flood-prone area to the surface width of the bank full channel) and slope of river.

By the Rosgen method, different reaches of river were classified. For this purpose two different years after construction of dam were considered (2004 and 2014). Results of the Rosgen method are: Type B of river increased between Pay-e-Pol to Abdol Khan considerably. This type is a stable type in plan and cross sections. Also, type E (has stable plan and cross sections)

| Table 3 | Results of calibration the Fluvial-12 software from 2004 to 2014 |
|---------------------------------|----------------|----------------|----------------|
| Hydrometric station             | Pay-e-Pol     | Abdol Khan     | Hamidiyeh      |
| Max difference between observation and calculation (cm) | 16            | 10             | 20             |
| Average difference between observation and calculation (cm) | 4.18          | 5.43           | 10.08          |
Figure 4 | Results of calibration the Fluvial-12 software from 2004 to 2014. (a) Pay-e-Pol (b) Abdol Khan (c) Hamidiyeh (for flow discharge = 400 m³/s).
increased with very high percentage in total of river. Conversely, type C (has unstable floodplains) decreased with very high percentage in total of river. Type F (has unstable plan and cross sections) increased at close to Pay-e-Pol and decreased at other parts of river. The main result of the Rosgen method shows that river is unstable at close to Pay-e-Pol and stable at other parts. The Shulits equation that shows stability of longitudinal slope of river, confirms main result of the Rosgen method.

\[ S_x = S_0 e^{-ax} \]  (The Shulits equation)  

where:
- \( S_x \): Slope at distance x from base point
- \( S_0 \): Slope at base point
- a: Slope variation coefficient

Results of the Shulits equation in 2004 and 2014 are.

Figure 5 shows that instability of longitudinal slope at close to Pay-e-Pol hydrometric station.

4. Evaluation of changes of river geomorphological characteristics by satellite images:

The landsat 7 & 8 images show that river divided to 5 zones. These zones are shown in Figure A1. The lengths of zones are 27.604, 32.334, 53.028, 51.373 and 53.304 km respectively. The obtained results from these images are (Table 6).

Based on Table 6, the ratio of displaced length to total length in the upstream of river (zone 1) is more than other zones. Therefore, plan of the upstream of river is unstable (the results of the Rosgen method and Shulits equation show this subject too). This ratio is low for the downstream of river. But values of displacement are high for the downstream of river (because soil of this part is fine grain and soil strength is low. This soil contains eroded sediments at the upstream of river that settle at the downstream). The changes of sinuosity coefficient and length of meanders are (Table 7).

The sinuosity coefficient of the upstream of river is low (see Zone 1 in Table 7). Therefore, the upstream of river is unstable and this fact was compatible with results of displacement of different parts of river, the Rosgen method and Shulits equation. The sinuosity coefficient of different zones of river increased from 2004 and stability of river is increasing (see Zones 1, 2, 3

### Table 4 | A sample of results of the Fluvial-12 software

<table>
<thead>
<tr>
<th>Section</th>
<th>Discharge (m³/s)</th>
<th>Max sedimentation height (cm)</th>
<th>Max erosion height (cm)</th>
<th>Average of change the height cross section (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pay-e-Pol</td>
<td>130</td>
<td>51.8</td>
<td>–9</td>
<td>7.15</td>
</tr>
<tr>
<td>Pay-e-Pol</td>
<td>5,523</td>
<td>51.8</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Hamidiyeh</td>
<td>130</td>
<td>165</td>
<td>–323</td>
<td>–10</td>
</tr>
<tr>
<td>Hamidiyeh</td>
<td>5,523</td>
<td>166</td>
<td>–322</td>
<td>–10</td>
</tr>
</tbody>
</table>

### Table 5 | The length and percentage of length changes of different types of river (the Rosgen method)

<table>
<thead>
<tr>
<th>Type of river</th>
<th>Total length 2004 (Km)</th>
<th>Total length 2014 (Km) (Percentage of length changes)</th>
<th>Length between Pay-e-Pol to Abdol Khan 2004 (Km) (Percentage of length changes)</th>
<th>Length between Abdol Khan to Hamidiyeh 2004 (Km) (Percentage of length changes)</th>
<th>Length between Abdol Khan to Hamidiyeh 2014 (Km) (Percentage of length changes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>58.842</td>
<td>68.777 (16.88%)</td>
<td>39.953 (32.26%)</td>
<td>28.634</td>
<td>28.824 (0.7%)</td>
</tr>
<tr>
<td>C</td>
<td>65.999</td>
<td>4.637 (– 92.97%)</td>
<td>4.637 (– 91.12%)</td>
<td>13.806</td>
<td>0 (– 100%)</td>
</tr>
<tr>
<td>E</td>
<td>16.93</td>
<td>74.089 (337.62%)</td>
<td>5.326</td>
<td>34.407</td>
<td>39.682 (241.97%)</td>
</tr>
<tr>
<td>F</td>
<td>72.267</td>
<td>71.885 (– 0.53%)</td>
<td>18.383</td>
<td>31.939 (73.74%)</td>
<td>53.884</td>
</tr>
</tbody>
</table>
Table 7 shows that the length of meanders is decreasing. Therefore, meanders become straight reaches and the length of river is decreasing.

5. **Calculation of area of lands around of river that were dried by construction of dam:**

By decreasing of peak flood discharge after 1999, the area of floodplain decreased considerably (especially for small return period). For example, peak flood discharges with 2 years return period are 1739 and 130 m$^3$/s before and after construction of
dam. For flood with 2 years return period, reduction of left floodplain area is 45.82 km² (94.63%); reduction of right floodplain area is 44.35 km² (89.66%) and reduction of total floodplain area is 90.17 km² (92.12%). Because of occurrence of severe droughts, effects of dam construction and value of flow discharge in recent years, the percentage of reduction of floodplain area is almost 95%.

6. Calculation of area of lands of the Hawr-al-Azim wetland that were dried by construction of dam:

After 1999, the annual mean flow discharge in the Pay-e-Pol hydrometric station reduced from 120 m³/s to 50 m³/s. Table 8 shows the frequency of occurrence of different daily flow discharges.

In Iran-side of the wetland, area of this wetland was 64,100 hectares in 70s but today, its area is 29,000 hectares. Since average of flow discharges is less than peak flood discharge with return period 2 years, it can be concluded that 95% (similar to floodplain of river) of reduction of area of the Hawr-al-Azim wetland in Iran-side of the wetland is due to dam construction.

Therefore, construction of dam reduced 0.95 \times (64,100–29,000) = 33,345 hectares of area of the Hawr-al-Azim wetland in Iran.

7. Calculation of volume of haze in dried land (hazes can be displaced by wind)

Average size of sediment particles (D_{50}) is 2.36–28.48 μm. For determine D_{50}, sampling of sediments was done from December 1999 to May 2014 in 12 points around river. The size of sediment particles illustrates that these particles are clay and silt. Therefore, if these particles are displaced by wind, they will convert to haze (no fine dust). After dam construction, the annual mean height of deposited sediment is 9 cm in Hamidiyeh hydrometric station. On the other hand surveying (from 1999 to 2013) illustrates same value in the Hawr-al-Azim wetland. The annual volume of deposited sediment in lands of the Hawr-al-Azim wetland which has been dried by dam is almost 3 \times 10^7 m³. This majestic volume can be displaced by wind and is a potential source for haze generation.

8. Discussion about relation between changes of geomorphological characteristics of river and haze generation in the Hawr-al-Azim wetland.

The Rosgen method, the Shulits equation and satellite images illustrate instability of slope and plan in the upstream of river. Therefore, these parts of river are a potential resource for sediment generation. The erosion of the bed river and river floodplains can generate sediment. Displacement of river causes erosion in floodplains too.

Also, results of the Fluvi-12 software illustrate instability of cross sections in downstream of river. Surveying and the Fluvi-12 software have showed occurrence erosion at recent years in these parts of river. At the end total eroded sediment of river arrives to the Hawr-al-Azim wetland. These sediments are very fine and wind can lift them easily and generate haze.

9. Discussion about relation between haze and dust storm characteristics and effective factors on them.

Table 8 | The frequency of occurrence of different daily flow discharges

<table>
<thead>
<tr>
<th>Discharge (m³/s)</th>
<th>Number of days (Probability) before construction of dam (1955–1998)</th>
<th>Number of days (Probability) after construction of dam (1999–2014)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;5,000</td>
<td>1 (0.01%)</td>
<td></td>
</tr>
<tr>
<td>4,000–5,000</td>
<td>1 (0.01%)</td>
<td></td>
</tr>
<tr>
<td>3,000–4,000</td>
<td>4 (0.03%)</td>
<td></td>
</tr>
<tr>
<td>2,000–3,000</td>
<td>17 (0.11%)</td>
<td></td>
</tr>
<tr>
<td>1,000–2,000</td>
<td>188 (1.19%)</td>
<td></td>
</tr>
<tr>
<td>600–1,000</td>
<td>557 (3.51%)</td>
<td></td>
</tr>
<tr>
<td>500–600</td>
<td>316 (1.99%)</td>
<td>15 (0.27%)</td>
</tr>
<tr>
<td>400–500</td>
<td>530 (3.34%)</td>
<td>35 (0.64%)</td>
</tr>
<tr>
<td>300–400</td>
<td>961 (6.06%)</td>
<td>42 (0.77%)</td>
</tr>
<tr>
<td>200–300</td>
<td>1,815 (11.45%)</td>
<td>245 (4.47%)</td>
</tr>
<tr>
<td>100–200</td>
<td>3,698 (23.33%)</td>
<td>1,096 (20.02%)</td>
</tr>
<tr>
<td>0–100</td>
<td>7,762 (48.97%)</td>
<td>4,042 (73.82%)</td>
</tr>
</tbody>
</table>
The allowable value of particulate matter 10 (PM10) and PM2.5 are 150 and 35 μg/m³, respectively. Table A2 and Figure A4 illustrate the number of dust storms days and dust concentration. At the dust storms, the dust concentration is more than its allowable value. Figure A4 shows number of dust storm days after construction of the Karkheh Dam (after 1999). Due to the instability of the river and the drying up of the lands around the river after the construction of the Karkheh Dam, the number of dust storm days increased from 1999 to 2009. After 2009, these days decreased gradually. Table 2 shows that the river bed and longitudinal profile are almost stable from 2012 and Figure 5 shows that most of the length of river is stable from 2014. Stability of the Karkheh River is an effective factor for reduction of haze and dust storms.

Tables A1 and A2 also show the relationship between wind velocity and dust concentration. In May, June and July, the wind velocities are more than other months. It has been observed that the dust concentration is higher in these months. Maleki et al. (2016) observed decreasing trend of dust storm days in Ahvaz and dust storm days often occur in May to July. Because of the prevailing wind direction toward North West, the number of dust storm days and dust concentration are more in Ahvaz.

Shahsavani et al. (2012) showed that approximately 25% of the dust concentration is PM2.5 in Ahvaz. Supplementary Material, Figure A2 states, which this ratio can reach 45% after drying the lands around the Karkheh River. These fine particles can easily enter lungs of people and cause various respiratory diseases.

**CONCLUSION**

Considerable changes of geomorphological characteristics and the area of dried lands occurred in the Karkheh River after construction of the Karkheh Dam in 1999. The construction of dam decreased flow discharge very much. The annual mean of flow discharge was 120 m³/s from 1955 to 1998 and it was 50 m³/s from 1999 to 2014 (in the Pay-e-Pol hydrometric station). The Karkheh Dam reduced significantly flow discharge at floods (especially floods with small return periods). This subject decreased the area of floodplain more than 90% while the changes in geomorphological features was governing factor for reduction of width, length and area of river. This study used appropriate methods for evaluating instability in river. These methods include the Fluvial-12 software for instability of river cross sections, the Rosgen method for instability of river plan and the Shulits equation for instability of river slope. These instabilities increased the volume of eroded sediments. These sediments deposited at the Hawr-al-Azim wetland and the downstream of the Karkheh River. On the other hand reduction of flow discharge of the Karkheh River dried vast area of the Hawr-al-Azim wetland (33,345 hectares of the Hawr-al-Azim wetland has been dried by construction of dam). Surveying in the Hawr-al-Azim wetland illustrated that annual mean height of deposited sediment is almost 9 cm. Therefore, annual mean volume of deposited sediment in lands of the Hawr-al-Azim wetland which has been dried by dam is almost $3 \times 10^7$ m³.

Average diameter eroded sediments from river and its floodplain is very small (2.36–28.48 μm). Developed shear stress by wind can lift and displace them easily. The sediments with diameter less than 2.5 μm convert to haze in air. Because of increasing fine grain sediments after dam construction, the percentage of hazes increased in dust storms (from 25% in 1999 to 45% now). In the other hand, the number of dust storms days increased after dam construction. After stabilizing the slope, plan and cross sections along most of the river in recent years, the number of these days reduced. Because of the prevailing wind direction, the haze and dust storms move towards the Khuzestan province and haze and dust concentration increases in central regions of this province such as Ahvaz (similar to the results of Abbasi et al. 2019).

Hazes are a source of danger for environment and human socials Maleki et al. (2016). The Iranian energy ministry must release water from the Karkheh Dam. Released water from dam can reduce area of dried lands in the Hawr-al-Azim wetland. Also, for reduction of erosion, this ministry must fix up the sides of the river by suitable structures. Of course, implementation of these actions needs to great investments. Middle East governments for overcoming this natural hazard needs to financial and technical assistance of other countries (especially developed countries).

**ACKNOWLEDGEMENTS**

The author of this article thanks the Khuzestan Water & Power Authority (KWPA) and Iran Meteorological Organization for providing the data needed for this research.

**DATA AVAILABILITY STATEMENT**

Data cannot be made publicly available; readers should contact the corresponding author for details.
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First received 4 July 2021; accepted in revised form 20 October 2021. Available online 29 October 2021