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

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ABSTRACT

The construction of the Karkheh Dam is an important factor contributing to the occurrence of dust storms in the Khuzestan Province of Iran. It has reduced the annual mean flow discharge in the Karkheh River from 120 to 50 m³/s and dried land around the river. The area of dried land is 90.17 km² around the river and 333.45 km² in the Hawr-al-Azim wetland. The Rosgen method, Fluvial-12 software, and Shulits equation demonstrate the instability of the plan, cross sections and longitudinal slope of the river, respectively, around Pay-e-pol hydrometric station (upstream of the river). After dam construction, extreme erosion occurred in this part of the river. The type of sediment is clay and silt with $D_{50} = 8 \mu m$. The eroded sediment settles downstream (around Hamidiyeh hydrometric station) and the Hawr-al-Azim wetland. The wind can easily lift these particles especially from May to July. Because of the size of these particles, the haze concentration increased from 25% to 45% in dust storms. After construction of the 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 $3 \times 10^7$ m³.

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

HIGHLIGHTS

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

INTRODUCTION

The environmental aspects of implemented projects are important for people who live in and around them. In the Middle East, common projects between neighboring countries have serious effects on the environment (because of competition between them). Human activities and construction of large dams in Iran and Iraq have had destructive effects on the 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 over thousands of kilometers and significantly decrease air quality Table A2 (Supplementary Material) shows that 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. As a result of variations of river geomorphological characteristics and reduction of river discharge, the thickness of a fine particle layer and area of dry lands in the Hawr-al-Azim wetland and downstream of the river increased. By decreasing flow discharge, the width of the river was reduced and by increasing the stability of the river, the length of river meanders decreased (river meanders became straight reaches). The reduction of the width and length of the river increased the 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, the water content and the 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 cannot live in some regions (Supplementary Material, Figure A4). People have suffered from lung and heart diseases and 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 braided rivers. He observed that changes of flow and sediment characteristics can develop braided rivers. Legleiter (2014) studied the importance of place of hydraulic structures and its effect on changes of geomorphological characteristics. For this purpose he applied geostatistical techniques. Saleh et al. (2013) illustrated which changes of flow discharge and water surface elevation are dependent on geomorphologic characteristics and river slope. Their case study was a branch of the Seine River of France.

Delhomme et al. (2013) studied the formation of oxbow lakes. They considered the Caloosahatchee River in South Florida as a 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 changes in river geomorphological characteristics (Frascati & Lanzoni (2010); Zámaryi et al. (2010); Lazarus & Constantine (2013); Constantine et al. (2010); Güneralp & Marston (2012); Smith et al. (2016); Haghjhi et al. (2014); Casado et al. (2016); Termini (2016); Wei et al. (2016); Jing et al. (2013)). Researchers have evaluated the effects of dam construction on these characteristics, including Yang et al. (2014); Csiki & Rhoads (2014); Arnaud et al. (2015); Wang et al. (2018); Smith & Mohrig (2017).

Also, researchers have studied fine dust storms and factors that generate them. Alizadeh-Choobari et al. (2014) researched the relation between the wind of 120 days and fine dust storms in the Sistan Province in southeast 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. Abbasi et al. (2019) observed that the prevailing wind direction is north to south for the wind of 120 days in the Sistan Province. The dust concentration increases from north (the Registan Desert of Afghanistan) towards south (the Sistan Province in Iran). In Khuzestan Province, Maleki et al. (2016) investigated the effects of fine particles in dust storms on the health of people while MalAmiri et al. (2022) studied these effects for coarse particles in dust storms.

Also, researchers have studied dust storms in the Middle East countries such as Sabbah et al. (2018) in Kuwait and Bodenheimer et al. (2019) in North Africa and the 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. Also, other scientists studied factors affecting dust storms but did not consider river geomorphologic characteristics. Unfortunately, they evaluated the effects of dust storms instead of hazes. These phenomena are different and the diameter of dust particles is larger than the diameter of hazes. Therefore, environmental effects of these two phenomena are different too. Because of the small diameter of hazes, they can do much harm to people’s lungs and their destructive effects on the environment is very dangerous (Maleki et al. 2016). Dust masks cannot prevent the passage of hazes while these masks are suitable for dust. Since haze storms are a very important problem for people who live in the Khuzestan Province and changes in river geomorphology by the construction of the Karkheh Dam have a fundamental role in this hazard, this paper has evaluated the 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: (a) it evaluates the effects of instability of river geomorphological features (developed by dam construction) on occurrence of dust storms; and (b) it determines the percentage of haze (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 the 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. It investigates the relation between dam construction and reduction of flow discharge with the area of dried lands around the river
2. It investigates the 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 determine the area of dried lands in the river.
3. It determines the percentage of haze in dust storms based on soil grain size curve in dried lands
4. It extracts the relationship between changes in geomorphological characteristics and changes in sedimentation and erosion in the river and the number of dust storm days.
5. It investigates the relation between wind velocities with dust storm concentrations.

MATERIALS AND METHODS

Case study

The area and population of the Khuzestan Province in 2016 were 66,532 km² and 4,710,509, respectively. This province is located in southwest Iran, with Iraq to the west and the Persian Gulf to the south. 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 huge steel and cement plants. Six major rivers of Iran are located 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 the case study for this study. The Karkheh River and two tributaries of the Tigris are Iranian and Iraqi sources of water supply in this wetland. Because of the 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 is 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, the area of this wetland was 64,100 hectares in the 1970s but today its area is 29,000 hectares. Also, total of its area (in Iran and Iraq) was 307,000 hectares in the 70s and is 102,000 hectares now. This wetland locates in the North Azadegan Plain and its distance southwest from Ahvaz (center of the Khuzestan Province) is 80 km. Changes of the land cover in the Hawr-al-Azim wetland from 1973 to 2000 are shown in Figure 2 (UNEP 2001).

An important reason for the reduction in area of lakes and marshes was the 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 the Supplementary Material.

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:

\[
\log C_{ts} = 5.435 - 0.286 \log \frac{\omega d}{v} - 0.457 \log \frac{U^*}{\omega} + \left(1.799 - 0.409 \log \frac{\omega d}{v} - 0.314 \log \frac{U^*}{\omega}\right) \log \left(\frac{V_S}{\omega} - \frac{V_{cr}S}{\omega}\right) \tag{1}
\]

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 km\(^2\); (b) 2000 Area = 1,296.9 km\(^2\) (UNEP 2001).
Table 1 | The used data and their features

| Data          | Type     | Source                                | Location (years of data collection) | Description                                                                 |
|---------------|----------|---------------------------------------|-------------------------------------|-----------------------------------------------------------------------------|
| Wind          | Meteorological | Iran Meteorological Organization | The Bostan synoptic station (2004–2014) | The wind data were used for determine the prevailing wind direction and relation between wind velocity and dust concentration |
| Dust          | Meteorological | Iran Meteorological Organization | The Bostan synoptic station (2004–2014) | The dust data were used for determine the relation between wind velocity and dust concentration |
| Dust storm days | Meteorological | Iran Meteorological Organization | The Bostan synoptic station (1996–2017) | The dust storm days data were used to determine the relation between number of dust storm days with the instability of geomorphological features and dam construction effects |
| Surveying     | Surveying | The Khuzestan Water & Power Authority (KWPA) | The Karkheh River (1999, 2004, 2012, 2013 and 2014) | The surveying data were used for evaluating sedimentation and erosion in the river, changes in cross sections and slope of river. The Fluvial-12 software, Rosgen method and Shulits equation used these data. |
| Satellite images | Satellite images | Landsat images 7 & 8 | The Karkheh River and its floodplain (2004 and 2014) | The satellite images were used for evaluating changes in the sinuosity coefficient, length and width of river and plan of river and its floodplain. The Rosgen method used these images. |
| Flow discharge | Hydrometric | KWPA                                   | The Pay-e-Pol hydrometric station (1955–2014) | The flow discharge data were used for calculating the area of dried lands after dam construction. The Fluvial-12 software used these data. |
| Soil          | Soil     | KWPA                                   | The Karkheh River and its floodplain (1999–2014) | The soil data were used for extraction of the soil grain size curve and sediment rating curves and relations. These data were used to determine percentage of haze in dust storms. |

$v$: 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:

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

(2)

$$
\frac{V_{cr}}{\omega} = 2.05 \quad \text{for} \quad U^*d/v > 70
$$

(3)

**RESEARCH METHODOLOGY**

Figure 3 shows the research methodology flowchart for this study.

**RESULTS AND DISCUSSION**

**Determination of the river bed and deposited sediment height in 1999, 2012 and 2013 by observed data**

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 river bed in three hydrometric stations are illustrated in Table 2.

In the upstream of the 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 erosion height is 1.9 m from 1999 to 2012 and the average sedimentation height is 0.05 m from 2012 to 2013). The river bed and longitudinal profile are almost stable from 2012 while
the river plan is unstable. Also in the downstream of the considered reach (from Abdol Khan to Hamidiyeh), Table 2 shows that severe sedimentation occurred after 1999 but slight erosion occurred from 2012 (the average sedimentation height is 0.36 m from 1999 to 2012 and the average erosion height is 0.09 m from 2012 to 2013). The river bed 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.

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

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

These equations for different hydrometric stations are:

\[ y = 0.0364x^{2.357} \text{ for Pay-e-Pol} \quad (4) \]
\[ y = 0.0362x^{2.38} \text{ for Abdol Khan} \quad (5) \]
\[ y = 0.1651x^{2.1487} \text{ for Hamidiyeh} \quad (6) \]

where:

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

| Hydrometric station | Longitude | Latitude | Bed level 1999 (m) | Bed level 2012 (m) | Bed level 2013 (m) | Diff. bed levels 2012–1999 (m) | Diff. bed levels 2013–2012 (m) |
|---------------------|-----------|----------|-------------------|-------------------|-------------------|-----------------------------|-----------------------------|
| Pay-e-Pol           | E 48° 15’ | N 33° 7’ | 103.08            | 99.961            | 100.11            | –3.119                      | 0.149                       |
| Abdol Khan          | E 48° 23’ | N 31° 50’| 28.72             | 28.016            | 27.966            | –0.704                      | –0.05                      |
| Hamidiyeh           | E 48° 26’ | N 31° 30’| 9.166             | 10.594            | 10.474            | 1.428                       | –0.12                      |
x: Discharge (m³/s)
y: Sediment discharge (Ton/day)

By these equations, the dominant discharge is almost equal to 400 m³/s. The best equation for calculation of the changes of cross sections of this river is the Yang (1973) equation (determined by calibration of the Fluvial-12 software). Table 3 and Figure 4 illustrate results of calibration for different hydrometric stations. Figure 4(a)–4(c) was prepared by calibration of the Fluvial-12 software in three hydrometric stations.

The Fluvial-12 software ran for different discharges after 2014. A sample of results from 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 the dam). Top soil eroded and transported downstream. Therefore, armoring layers are against flow; these layers are very resistant and flow cannot 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 the river.

In the downstream of the reach, sedimentation occurred from 1999 to 2004 (after construction of the dam). Deposited sediment has very fine particles. Resistance of these particles is negligible against erosion. Because of deposition of sediment in this part of the 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. The surveying illustrates this from 2012 to 2013 in three hydrometric stations (Table 2). Results of the Fluvial-12 software show that the downstream cross sections are unstable while they are stable in the upstream. Because of occurrence of severe droughts in the Khuzestan Province and flood control by the Karkheh Dam, the reduction of flow discharges is significant. The annual mean 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 standard deviation of flow discharge in these periods was 18 and 7 m³/s, respectively. After construction of the dam, the largest range of flow discharges is 500–600 m³/s (with 34% of the total number of flow discharge data in this range). Therefore, the probability of deformation of the downstream cross sections is low.

Evaluation of stability of different river reaches by the Rosgen method and Shulits equation

The Rosgen method (developed by Rosgen 1994) evaluates the stability of the plan and cross sections of a 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.

Using the Rosgen method, different reaches of river were classified. For this purpose two different years after construction of the dam were considered (2004 and 2014). Results of the Rosgen method are (Table 5): river type B 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) increased with very high percentage in all of the river. Conversely, type C (has unstable floodplains) decreased with very high percentage in all of the river. Type F (has unstable plan and cross sections) increased close to Pay-e-Pol and decreased in other parts of the river. The main result of the Rosgen method shows that the river is close to Pay-e-Pol and stable at other parts. The Shulits equation, which shows stability of the longitudinal slope of the river, confirms the 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

### 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      |
Results of the Shulits equation in 2004 and 2014 appear in Figure 5 which shows the instability of the longitudinal slope close to Pay-e-Pol hydrometric station.

**Evaluation of changes of river geomorphological characteristics by satellite images**

Landsat images 7 & 8 show that the river is divided into 5 zones. These zones are shown in Figure A1 (Supplementary Material). 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 shown in Table 6.
Based on Table 6, the ratio of displaced length to total length in the upstream of the river (zone 1) is more than other zones. Therefore, the plan of the river upstream is unstable (the results of the Rosgen method and Shulits equation show this result too). This ratio is low for the downstream of the river but displacement values are high (because soil in this part is fine grain and soil strength is low. This soil contains eroded sediments from upstream that settle downstream). The changes of sinuosity coefficient and length of meanders are shown in Table 7.

The sinuosity coefficient of the upstream of the river is low (see Zone 1 in Table 7). Therefore, the upstream is unstable and this fact was compatible with results of displacement of different parts of the river, the Rosgen method and Shulits equation. The sinuosity coefficient of different zones of the river increased from 2004 and stability of the river is increasing (see Zones 1, 2, 3 and 5 in Table 7). Table 7 shows that the length of meanders is decreasing. Therefore, meanders become straight reaches and the length of the river is decreasing.

**Calculation of area of land around the river that was dried by construction of the dam**

By decreasing the peak flood discharge after 1999, the area of floodplain decreased considerably (especially for small return period). For example, peak flood discharges with a 2 year return period are 1739 and 130 m³/s before and after construction.

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

| Section     | Discharge (m³/s) | Max sedimentation height (cm) | Max erosion height (cm) | Average of change in cross section height (cm) |
|-------------|------------------|-------------------------------|-------------------------|----------------------------------------------|
| Pay-e-Pol   | 130              | 51.8                          | -9                      | 7.13                                         |
| Pay-e-Pol   | 5,523            | 51.8                          | 0                       | 20                                           |
| Hamidiyeh   | 130              | 165                           | -323                    | -10                                          |
| Hamidiyeh   | 5,523            | 166                           | -322                    | -10                                          |

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

| Type of river | Total length 2004 (Km) | Total length 2014 (Km) (Percentage of length changes) | Length between Pay-e-Pol to Abdol Khan 2004 (Km) (Percentage of length changes) | Length between Abdol Khan to Hamidiyeh 2004 (Km) (Percentage of length changes) | Length between Abdol Khan to Hamidiyeh 2014 (Km) (Percentage of length changes) |
|---------------|------------------------|------------------------------------------------------|-------------------------------------------------------------------------------|-------------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| B             | 58.842                 | 68.777 (16.88%)                                      | 30.208                                                                       | 39.953 (32.26%)                                                              | 28.634                                                                        | 28.824 (0.7%)                                                                |
| C             | 65.999                 | 4.637 (-92.97%)                                      | 52.193                                                                       | 4.637 (-91.12%)                                                             | 13.806                                                                        | 0 (-100%)                                                                   |
| E             | 16.93                  | 74.089 (337.62%)                                     | 5.326                                                                        | 34.407 (546.02%)                                                            | 11.604                                                                        | 39.682 (241.97%)                                                            |
| F             | 72.267                 | 71.885 (-0.53%)                                      | 18.383                                                                       | 31.939 (73.74%)                                                             | 53.884                                                                        | 39.946 (-25.87%)                                                            |

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

The sinuosity coefficient of the upstream of the river is low (see Zone 1 in Table 7). Therefore, the upstream is unstable and this fact was compatible with results of displacement of different parts of the river, the Rosgen method and Shulits equation. The sinuosity coefficient of different zones of the river increased from 2004 and stability of the river is increasing (see Zones 1, 2, 3 and 5 in Table 7). Table 7 shows that the length of meanders is decreasing. Therefore, meanders become straight reaches and the length of the river is decreasing.

**Figure 5** | Slope changes against distance in 2004 and 2014, calculated by the Shulits equation.
of the dam. For flood with a 2 year 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 the 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%.

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

On the Iran side of the wetland, the area of this wetland was 64,100 hectares in the 1970s but today its area is 29,000 hectares. Since average of flow discharges is less than peak flood discharge with a return period of 2 years, it can be concluded that 95% (similar to floodplain of the river) of reduction of the area of the Hawr-al-Azim wetland on the Iran side of the wetland is due to dam construction.

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

Calculation of volume of haze in dried land (hazes can be displaced by wind)
Average size of sediment particles (D50) is 2.36–28.48 μm. To determine D50, sampling of sediments was done from December 1999 to May 2014 in 12 points around the 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 (not fine dust). After dam construction, the annual mean height of deposited sediment is 9 cm in Hamidiyeh hydrometric station. Surveying (from 1999 to 2013) illustrates the same value in the Hawr-al-Azim wetland. The annual volume of deposited sediment in lands of the Hawr-al-Azim wetland which have been dried by the dam is almost 5 × 10⁷ m³. This majestic volume can be displaced by wind and is a potential source of haze generation.

Table 6 | The range of displacements and percentages of displaced length in left and right river banks from 2004 to 2014

| Zone | Bank | Range of displacement (m) to left | Percentage of displaced length to left | Range of displacement (m) to right | Percentage of displaced length to right |
|------|------|-----------------------------------|----------------------------------------|-----------------------------------|------------------------------------------|
| 1    | Left | 18.52–191.89                      | 17.07%                                 | 46.43–242.03                      | 12.2%                                    |
| 2    | Left | 5.08–149.09                       | 29.55%                                 | 15.89–75.84                       | 4.55%                                    |
| 3    | Left | 10.78–118.85                      | 13.79%                                 | 0                                  | 0                                        |
| 4    | Left | 35.42–381.3                       | 5%                                     | 156.63                            | 2.5%                                     |
| 5    | Left | 22.77–305.41                      | 6.12%                                  | 0                                  | 0                                        |
| 1    | Right| 52.33–143.98                      | 7.32%                                  | 7.87–233.22                       | 19.51%                                   |
| 2    | Right| 112.02–197.64                     | 4.55%                                  | 8.91–350.97                       | 18.18%                                   |
| 3    | Right| 128.11–284.1                      | 5.17%                                  | 10.85–43.95                       | 6.9%                                     |
| 4    | Right| 104.39                            | 2.5%                                   | 150.11–252.55                     | 5%                                       |
| 5    | Right| 77.19                             | 2.04%                                  | 0                                  | 0                                        |

Table 7 | The changes of sinuosity coefficient and length of meanders from 2004 to 2014

| Zone | Number of meanders | Average meander length (m) | Average sinuosity coefficient |
|------|---------------------|-----------------------------|------------------------------|
|      | 2004 | 2014 | 2004 | 2014 | 2004 | 2014 |
| 1    | 19  | 17   | 1,404.27 | 1,184.72 | 1.27 | 1.35 |
| 2    | 20  | 19   | 1,603.08 | 1,713.7  | 1.4  | 1.54 |
| 3    | 24  | 26   | 1,662.72 | 1,631.94 | 1.9  | 2.01 |
| 4    | 14  | 14   | 3,148.26 | 3,155.38 | 2.1  | 2.09 |
| 5    | 17  | 17   | 2,939.29 | 2,851.18 | 1.79 | 1.84 |
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 the instability of the slope and plan in the upstream of the river. Therefore, these parts of the river are a potential resource for sediment generation. The erosion of the bed river and river floodplains can generate sediment. Displacement of the river causes erosion in floodplains too.

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

Relation between haze and dust storm characteristics and effective factors on them

The allowable values of particulate matter 10 (PM10) and PM2.5 are 150 and 35 μg/m³, respectively. Table A2 and Figure A4 (Supplementary Material) illustrate the number of dust storms days and dust concentration. In dust storms, the dust concentration is more than its allowable value. Figure A4 shows the 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 (Supplementary Material) 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 a 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 the North West, the number of dust storm days and dust concentration are higher in Ahvaz.

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

CONCLUSION

Considerable changes in geomorphological characteristics and in the area of dried lands occurred in the Karkheh River after construction of the Karkheh Dam in 1999. The construction of the dam decreased flow discharge considerably. The annual mean flow discharge was 120 m³/s from 1955 to 1998 and was 50 m³/s from 1999 to 2014 (in the Pay-e-Pol hydrometric station). The Karkheh Dam reduced flow discharge in floods significantly (especially floods with small return periods).
This decreased the area of the floodplain more than 90% while the changes in geomorphological features was a governing factor for reduction of width, length and area of the river. This study used appropriate methods for evaluating instability in the 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. At the same time, reduction of flow discharge of the Karkheh River dried a vast area of the Hawr-al-Azim wetland (33,345 hectares of the Hawr-al-Azim wetland has been dried by construction of the 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 the dam is almost $3 \times 10^7$ m$^3$.

Average diameter of the eroded sediments from the 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 the dam construction, the percentage of hazes increased in dust storms (from 25% in 1999 to 45% now). Furthermore, 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 has now 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 in Ahvaz (similar to the results of Abbasi et al. 2019).

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

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the author for details.

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