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CASE STUDY

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Remote sensing supported analysis of the effect of wind erosion on local air pollution in arid regions: a case study from Iğdır province in eastern Türkiye

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Abstract

PM pollution is one of the most important environmental problems worldwide. One of the sources of PM pollution, which has a negative impact on human health, is dust that enters the atmosphere, especially in arid regions. Iğdır Province, located in the east of Anatolia, has an arid climate character and was selected as the most polluted province in Europe in 2021 and 2022 (in terms of $PM_{2.5}$ pollution). In this study, the effect of wind erosion-induced dust on air pollution in Iğdır province was investigated. We think that local wind erosion during the summer season (May–September) in the province is effective on PM pollution. Because there are no industrial activities, vehicular traffic, fuel consumption and volcanic activities that cause PM pollution in the summer season around Iğdır. On the other hand, Türkiye's second largest wind erosion area and the other two wind erosion areas are located here, and dust storms are quite frequent. The causes of local wind erosion, which is one of the main factors in air pollution in the summer period, were investigated from a geographical perspective and various data sets were utilized. Then, wind erosion sites were examined and their regional distributions were indicated. Research findings on wind erosion sites were supported by remote sensing techniques (quartz index, aerosol density, etc.). All the data obtained support the idea that wind erosion is a dominant factor in the high level of PM pollution during the summer season in this area. Because the number of days with strong winds during this period is quite high and EU, WHO and national PM limit values are exceeded almost every day.

Keywords Arid region, Wind erosion, Air pollution, Iğdır province

Introduction

Air pollution is a global environmental problem that impacts the environment and human health (Manisadilis et al. 2020; Shaddick et al. 2020). It is shaped by the joint effects of natural (climatic, topographical, geomorphological, geological, etc.) and anthropogenic (increasing population, transportation, industry, construction, agricultural activities, etc.) processes (Şahin et al. 2020). Ozone (O_3), carbon monoxide (CO), nitrogen dioxide (NO_2) sulfur dioxide (SO_2) and particulate matter (PM) are the most important sources of air pollutants (Kamal et al. 2006; Altıkat 2020a). PM (Table 1) is generally divided into PM_{10} and $PM_{2.5}$ according to its aerodynamic diameters (Liang et al. 2017). Substances with aerodynamic diameters smaller than 10 µm are labeled PM_{10}, and those with diameters smaller than 2.5 µm are categorized as $PM_{2.5}$ (Manisadilis et al. 2020). Although common PM sources include volcanic eruptions (Mather et al. 2003; Stewart et al. 2022), industrial activities

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Table 1 Types and sizes of PM (Source: Manisadilis et al., 2020)

PM type		PM diameter [μm]
Particulate contaminants	Smog	0.01–1
	Soot	0.01–0.8
	Tobacco smoke	0.01–1
	Fly ash	1–100
	Cement dust	8–100
Biological contaminants	Bacteria and bacterial spores	0.7–10
	Viruses	0.01–1
	Fungi and molds	2–12
	Allergens (dogs, cats, pollen, household dust)	0.1–100
Types of dust	Atmospheric dust	0.01–1
	Heavy dust	100–1000
	Settling dust	1–100
Gases	Different gaseous contaminants	0.0001–0.01

or other anthropogenic processes (Sousa et al. 2008; D'Amato et al. 2010; Jun et al. 2014), wind-eroded dust is also an important source (Gilette and Passi 1988; Saxton 1996; Zobeck and Van Pelt 2005; Parajuli et al. 2019; Chang et al. 2021).

Wind erosion, which affects more than 500 million hectares worldwide and causes significant soil losses (Lal 1990; Grini et al. 2003), is a weathering process that occurs on bare/dry soils in areas where strong winds blow and cause serious environmental problems (Zobeck and Van Pelt 2005). In particular, insufficient/irregular rainfall, high temperature differences, strong winds, severe evaporation and destruction of vegetation are the main aetiologies of wind erosion (Karaoğlu 2014). Wind erosion, which occurs in arid-semi-arid climates with an average annual precipitation of less than 300 mm, causes very small soil particles (dust) to enter the atmosphere (Çanga 1995). These particles interrupt plant growth (Farmer 1993), cause disruptions and accidents in transportation (Skidmore 1994), carry germs (Leathers 1981) and cause PM pollution by being suspended in the air (Hagen et al. 2010). Wind erosion-induced PM with a diameter of less than 10 μm (PM_{10} and $PM_{2.5}$) is one of the main causes of air pollution (Saxton 1996; Karaoğlu 2014). Therefore, studies on the relationship between dust and PM pollution have been conducted (Mallone et al. 2011; Al-Hemoud et al. 2018; Liu et al. 2021).

Dusts, which are mixed into the atmosphere by wind erosion, cause significant environmental problems in the near or distant environment (Zobeck and Van Pelt 2014). For example, these dust lead to various diseases by entering the lungs through the respiratory tract (Karaoğlu 2014). Some studies have shown that these dust can remain suspended in the air for weeks after being blown by the wind and can be carried far away. Dust from the Great Sahara Desert, for instance, has been reported to have traveled to North America (Gatz and Prospero 1996), the Caribbean (Delany et al. 1967), South America (Talbot et al. 1990) and Europe (Goudie 1978). Türkiye, located between latitudes 36° and 42° in the northern hemisphere, is also a country affected by global dust transport (Şengün and Kıranşan 2012; Dündar et al. 2013). However, the impact of local dust sources on the air pollution of the country is also quite high (Oğuz and Dündar 2014; Kıranşan and Şengün, 2018).

Iğdır (Fig. 2) was recorded as the city with the most polluted air in the European region in terms of $PM_{2.5}$ in 2021. It has the highest PM content in Europe with an annual average of 66.2 μg/m^3 (https://www.iqair.com/world-air-quality-report). This annual average value is considerably higher than WHO and EU standards (Table 7). Air pollution in Iğdır exceeds both WHO and EU limit values throughout the year. It is one of the least populated cities in Türkiye with approximately 200,000 people and is in one of the least developed provinces. Therefore, no industrial activities or vehicle traffic that would cause such high levels of air pollution are present in the city. Although PM pollution is intense in the winter season in the province, this is largely due to meteorological conditions (high pressure, inversion, etc.) and the use of poor-quality fuel (Altıkat 2019). The fact that PM pollution is also high in the summer (Fig. 1) shows that factors other than those mentioned above are at work. In addition to global dust transport, the idea that the local wind erosion problem also affects PM pollution increase in the summer season comes to the fore. In fact, previous studies have revealed that high temperatures and severe evaporation, low rainfall and low humidity, improper land use and overgrazing trigger wind erosion in Iğdır and, therefore, wind erosion sites have developed

Fig. 1 **a** A day with high particulate matter pollution in Iğdır (view of the Iğdır Plain from the slopes of Mount Ararat (Greater Ararat), 30/06/2022). **b** A clean air day in Iğdır (view of the Iğdır Plain from the slopes of Mount Pamuk, 25/9/2022)

at many points (Karaoğlu 2014, 2018a; Karaoğlu et al. 2018). Although Doğru et al. (2015), Argun et al. (2019) and Altıkat (2020b) partially addressed the wind erosion problem, they did not focus on wind erosion with local dynamics on air pollution in the province.

Therefore, in this study, the effect of wind erosion on the air pollution of Iğdır Province was revealed from a geographical perspective supported by remote sensing techniques. For this purpose, firstly, the causes of wind erosion are mentioned, then the temporal and spatial distribution of the effect of wind erosion on PM pollution is emphasised. In addition, in previous studies, annual or winter season air pollution has been analysed. However, in this analysis, only summer season air pollution was analysed for the first time. In addition, it is tried to contribute to the literature by revealing the effect of wind erosion-induced dust on PM pollution.

Study area and data sources

Study area

Iğdır, the focus of our research, is a city located on the Iğdır Plain in the easternmost part of Türkiye. The city borders Armenia to the north and northeast, Azerbaijan (Nakhchivan Autonomous Republic) to the southeast and Iran to the south (Fig. 2). The area where the city is located on a wide plain with very high volcanic mountains to the south (Fig. 2). The most important of these mountains is the Greater Ararat, whose height is 5137 m. The city is separated from Armenia by the Aras River, which flows through the north. Iğdır Province, with an average elevation of approximately 840 m, is the city with the lowest elevation in the East Anatolian region. Iğdır is located in the tectonic Sürmeli Depression, which is a closed depression surrounded by mountains. Approximately 200,000 people live in Iğdır, one of the least developed cities in Türkiye.

Previous studies

Many studies have been carried out on air pollution in Iğdır Province. For example, Doğru et al. (2015) examined the winter season and annual air pollution changes from 2007 to 2014, focusing on the effect of meteorological parameters. Aydın (2018) looked at the effect of natural and anthropogenic processes on air pollution in Iğdır Province and stated that the main problems were the result of poor-quality fuel consumption, topographical conditions and climatic characteristics. Koç (2018), in his study, questioned the relationship between the city's air pollution and the spatial development of the city, but he stated that there was no connection

Fig. 2 Location map of Iğdır Province

between the two parameters. Additionally, Koç and Koç (2018) analyzed the effects of meteorological processes on the air pollution of the city and found a correlation with climatic processes. Altıkat (2019) examined the relationship between PM_{10} pollution and meteorological parameters in Iğdır Province. Argun et al. (2019) discussed the effect of urban structures on urban air pollution and made some suggestions for pollution prevention. Güçük et al. (2019) investigated the sources of air pollution in Iğdır province and proposed various solutions. In another study, Altıkat (2020a) examined the relationship between particulate pollution and other pollutants in Iğdır Province, finding a positive correlation between NO_2, NO and NO_x pollutant values and PM_{10} values. Şahin et al. (2020) investigated the areas where air pollution may be intense in the city center and its districts by applying the AHP technique. Finally, Altıkat (2020b) developed a prediction model for air pollution in the city by using different parameters and artificial neural networks.

Materials and methods

In this study, the causes of wind erosion on Iğdır Plain will be explained first, and then, the erosion sites will be introduced. In the last stage of the study, the relationship between erosion and PM pollution will be the focus. Due to the climatic character of Iğdır Province, heating systems (stoves, radiators, etc.) are operated between October and April. Therefore, this period is when fuel-induced PM pollution is high. At this time, drought is not evident due to decreased evaporation and increased precipitation (Figs. 4 and 5). Therefore, the period from May to September, when heating systems do not operate and drought and wind erosion are evident, was the focus of this study. For the data, the years 2019, 2020, 2021 and 2022 (only May and June of this year) were selected as the sample period. For this purpose, various maps (topography, lithology, wind speed, 3D view, precipitation distribution, etc.) were produced in the ArcGIS 10.5 program using various data sets. In addition, temperature, precipitation and Thornthwaite water balance graphs were drawn for Iğdır Province with the data obtained from the General Directorate of Meteorology (https://www.mgm.gov.tr/veridegerlendirme/il-ve-ilceler-istatistik.aspx), and the drought status of the region was indicated using figures. In addition, field studies were carried out in wind erosion areas at different times, and sample photographs were taken. Remote sensing techniques were also utilized in the study.

Remote sensing methods

The ASTER L1T dataset was downloaded from https://earthexplorer.usgs.gov and processed in ENVI 5.3 for optical remote sensing. Pre-processing steps included radiometric calibration of all ASTER bands. Shortwave and visible bands were stacked for internal average reflectance correction. After atmospherically correcting thermal infrared bands with thermal atmospheric correction, emissivity normalization was applied with thermal data extraction with Kelvin degree on thermally corrected TIR data. Using these calibration and correction operations, the study area was clipped to create a region of interest.

Quartz index b13/b12 was used only for quartz bearing zones, and QRI index (b10/b12) *(b13/b12) was employed for quartz bearing rocks. Following the application of these indices (Q-QRI-TempK in RGB), a false colour combination was generated for desertification detection in the study area.

Sentinel-5P AER AI Aerosol index data from 2019 to 2022 for the months of June, July, August and September was obtained for the study area. Satellite images of dusty days detected with catalog browsing in the EO Browser app on ESA (https://apps.sentinel-hub.com/eo-browser/) were later downloaded to process them for dust activity in the area being investigated.

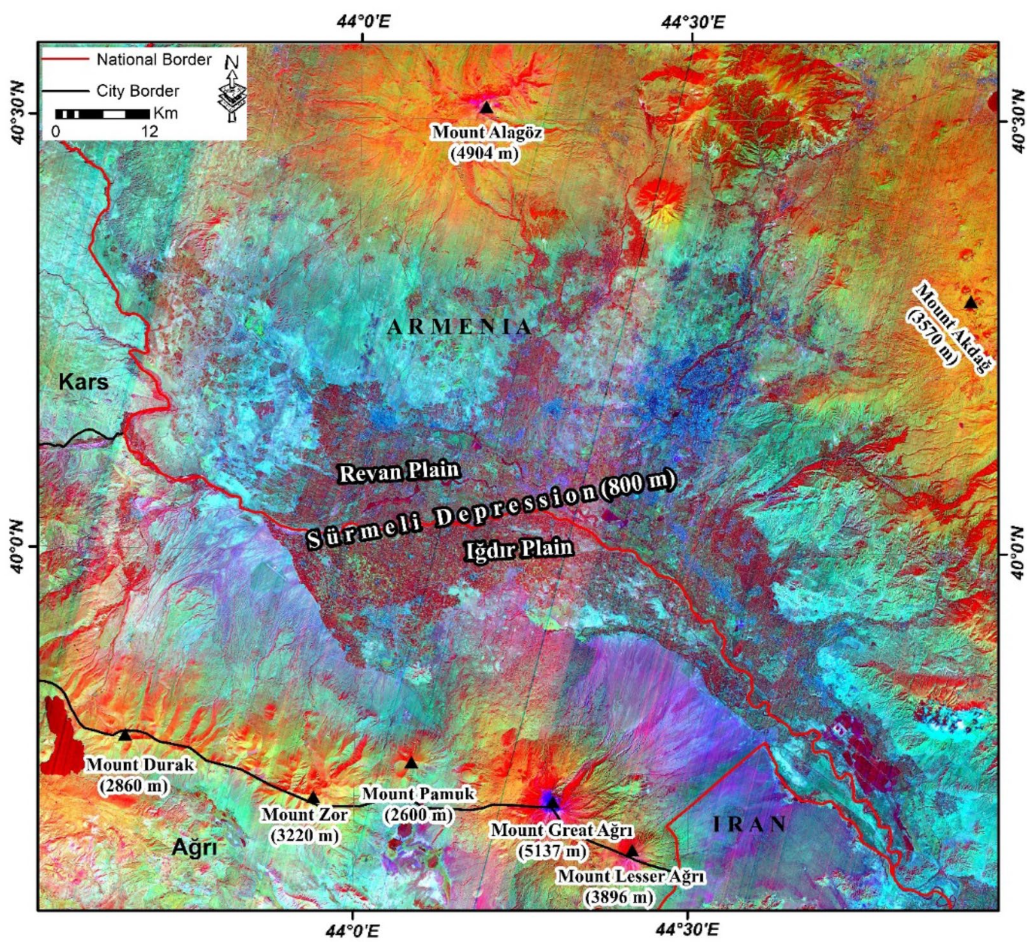

Fig. 3 General view of the Sürmeli Depression (Map created with landsat-8 satellite imagery. Thermal-2, SWIR-2 and B1 in RGB/FCC. The colours represent the lithologies; yellow and orange represent rocks, navy blue basin deposits and light blue alluvial deposits.)

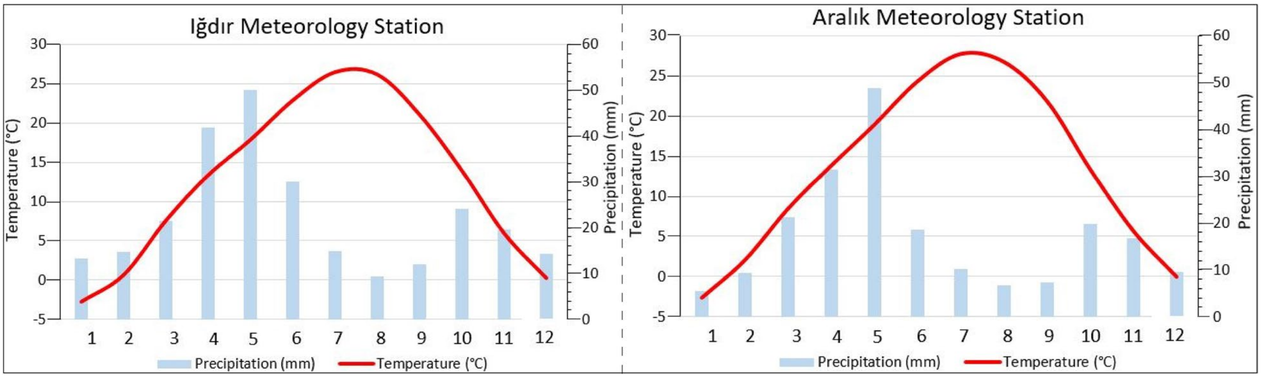

Fig. 4 Temperature and precipitation graphs of Iğdır and Aralık Meteorological Stations (Data taken from the Turkish State Meteorological Service, Iğdır station directorate)

Results

Processes creating wind erosion on Iğdır Province

Climatic processes

The main factor causing wind erosion in any region is climatic characteristics, with temperature, precipitation and wind as the main drivers.

Iğdır Province was established in the south of a large tectonic depression in the east of Anatolia. This depression area, known as the Sürmeli Depression, is divided into two by the Aras River the south is called Iğdır Plain and the north is designated Revan Plain (Şimşek 2018). The south, west and north of this northwest-southeast trending depression with an elevation of approximately 800 m are surrounded by high volcanic mountainous areas. Greater Ararat (5137 m) and Lesser Ararat (3896 m) (both peaks of Mount Ararat), Mount Pamuk (2600 m), Mount Zor (3220 m) and Mount Durak (2860 m) are located in the south of this depression. Additionally, Kandil Mountain (3200 m) is in the southwest of the depression, Alagöz Mountain (4904 m) is in the north and Akdağ (3570 m) in the northeast (Fig. 3). Therefore, the relative elevation difference between the depression and the mountainous belt surrounding it is at least 1800 m. This elevation difference has caused the climatic characteristics of the Iğdır Plain and its surroundings to be different.

Due to this difference in elevation, Iğdır is characterized by a micro-climate with temperature, precipitation and wind characteristics different from those of the severe continental climate in its immediate vicinity. According to data from the Iğdır Meteorological Station, the average annual temperature is 12.8 °C; and it is 13.4 °C according to data from the Aralık Meteorological Station to the east of the plain (Table 2; Fig. 4). Annual mean temperature values are 4.7 °C in Kars (1768 m), 6.2 °C in Ağrı (1640 m) and 5.7 °C in Erzurum (1890 m), which are the closest cities to Iğdır (Fig. 2) (https://www.mgm.gov.tr/veridegerlendirme/il-ve-ilceler-istatistik.aspx). These numbers show that Iğdır plain has higher temperatures than those of the surrounding areas.

When the precipitation values of Iğdır Plain are analyzed, the total annual precipitation is revealed to be 265.8 mm. This value is very close to the annual precipitation amount of 250 mm used in defining the desert climate limit (Türkeş 2012). On the other hand, the precipitation values of the Aralık Meteorological Station located in the east of the plain reflect the desert precipitation regime with a total annual precipitation of 205.2 mm (according to Karaoğlu 2018a, this value is 244.2 mm) (Table 2, Fig. 4). Average annual precipitation values are 506 mm in Kars, 524 mm in Ağrı and 429 mm in Erzurum, which are the closest cities to Iğdır (https://

Table 2 Annual mean temperature and annual total precipitation values of Iğdır and Aralık Meteorological stations (I.m.s. = Iğdır meteorology station, A.m.s. = Aralık meteorology station; Data taken from the Turkish State Meteorological Service, Iğdır station directorate)

Months parameters		1	2	3	4	5	6	7	8	9	10	11	12	Total
Temperature (°C)	I.m.s	− 2.7	0.7	7.6	13.4	17.9	22.9	26.5	26.2	21.1	14	6	− 0.3	12,8
	A.m.s	− 2.6	2.1	8.5	13.9	19	24.4	27.8	26.8	21.9	13.4	5.7	0	13,4
Precipitation (mm)	I.m.s	13.5	14.7	21.4	42	50.1	30	14.9	9.4	12.1	24.1	19.5	14.3	265.8
	A.m.s	5.5	9.3	21.2	31.5	48.9	18.6	10.1	6.6	7.4	19.7	16.8	9.6	205.2

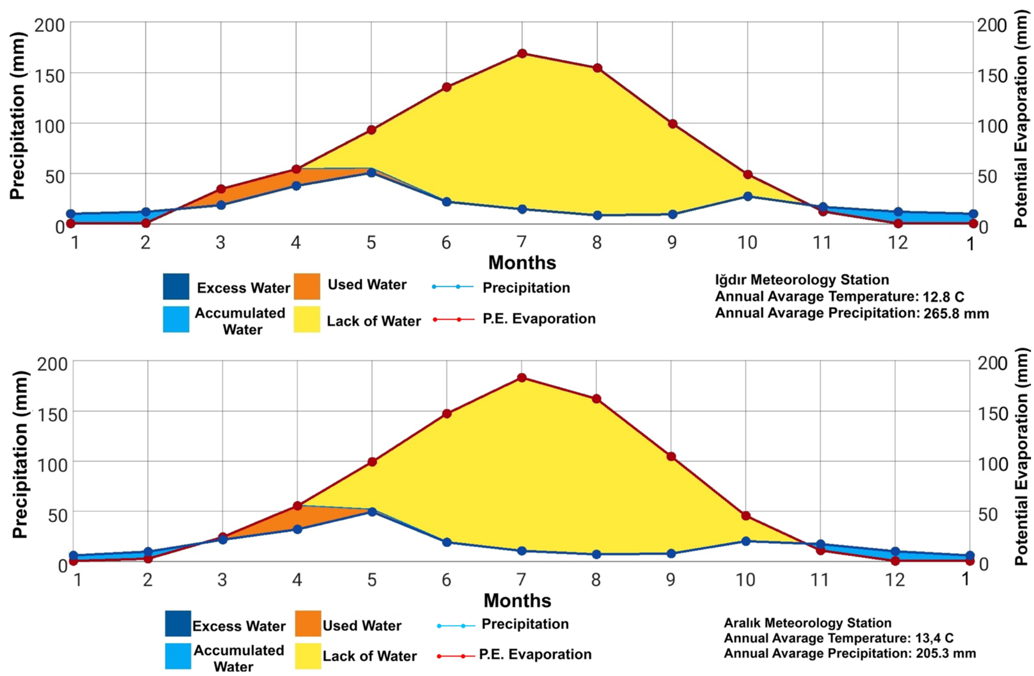

Fig. 5 Thornthwaite water balance graphs drawn according to Iğdır and Aralık Meteorological Station data

www.mgm.gov.tr/veridegerlendirme/il-ve-ilceler-istatistik.aspx). Iğdır's annual precipitation is below that of Türkiye (650.5 mm) and the Eastern Anatolia Region (579.4 mm) (Karaoğlu 2010). Like the temperature parameter, precipitation characteristics also prove that Iğdır Plain has a different climatic structure compared to that of its surroundings. For this reason, Iğdır Plain is considered an arid/semi-arid climate island in the east of Anatolia (Çölaşan 1960; Demircan 2022, 2023). Such ecosystems can become very sensitive to wind erosion and being destroyed as a result of human activities (Karaoğlu 2018c).

These climatic parameters of Iğdır Plain reflect the fact that the plain is characterized by a high average annual temperature and low annual precipitation compared to its surroundings. In particular, the increasing temperature values starting from May and the coinciding decrease in precipitation cause severe drought in the summer period until October. In fact, the Thornthwaite water balance graphs drawn with the data from the Iğdır and Aralık Meteorological Stations show that there is a serious water deficit between May and October (Fig. 5). This water deficit causes the vegetation cover to dry out early and the soil cover to be unprotected against wind erosion.

In addition to these climatic data, in extant studies, Iğdır Plain has been reported as arid according to the Erinç precipitation efficiency index (Aydin et al. 2019), semi-arid according to the De Martonne drought index (Bölük, 2016), arid according to the Köppen-Geiger climate classification (Öztürk et al. 2017), semi-arid according to the Thornthwaite climate classification (Bölük, 2016) and very arid according to the Aydeniz climate type (Şensoy and Ulupınar 2007). In addition, Türkeş (2012) has stated Iğdır is the driest station in Türkiye and that its tendency towards desertification is quite high (Türkeş 1999). Avcı (2005) also emphasised that Iğdır Plain is one of the few natural steppe areas of Anatolia due to drought. The ebucehil bush (*ephedra distachya*), which is found on the foothills of Mount Ararat and is a typical desert plant, grows only in Iğdır in Türkiye (Akkemik 2018). All these parameters show that drought is an important problem on Iğdır Plain (Karaoğlu 2011) and that there are temperature and precipitation values that foster wind erosion. As a matter of fact, Karaoğlu (2012, 2014, 2018a) stated that wind erosion affects different parts of the Iğdır Plain.

Wind speeds are quite low on the Iğdır Plain due to high pressure conditions in the winter season. However, when the pressure conditions change as of May, wind speeds increase which can trigger wind erosion. A wind speed of 8 m per second is sufficient for erosion to develop (Mesozi et al. 2015). This means that wind with a speed of 8 m per second can cause erosion when other conditions are appropriate. On Iğdır Plain, the number of wind events with this speed increases between May and October (especially in June and July) when drought is evident (Table 3).

Table 3 Number of windy days with a speed above 8 m per second from 2019 to 2021 (Data taken from the Turkish State Meteorological Service, Iğdır station directorate)

	May	June	July	August	September
Iğdır Station	38 days	44 days	38 days	28 days	12 days
Aralık Station	50 days	64 days	51 days	44 days	39 days
Airport Station	81 days	86 days	86 days	77 days	65 days

In addition to winds with a speed of 8 m per second, strong winds and storms (Table 4) increased between May and October causing serious deflation and sandstorms in the erosion areas located on the plain (Fig. 6). Due to the topographical character of the plain, PM aerated by erosion cannot be discharged out of the plain and increases PM pollution by accumulating. Table 4 reflects the list of strong winds (> 17.2 m/s = storm; > 20.8 m/s = strong storm; > 24.5 m/s = full storm; > 28.5 m/s = very strong storm) blowing between May and October from 2019 to 2022. As the table reveals, wind speed, like temperature and precipitation parameters, creates a favorable environment for erosion on Iğdır Plain.

Topo-lithological features

Although wind erosion is caused by climatic processes, regional topography and lithology also indirectly affect its development. The structure of the topography (the character and direction of the mountains, relative elevation difference, etc.) has an indirect influence on the climatic features (Çetin and Meydan 2023) that lead to erosion. In addition, the structure of the lithology affects erosion processes. For example, loose and unconsolidated rock is more susceptible to wind erosion than hard and resistant rock, which has led to the development of wind erosion areas on loose/soft alluvial fans on Iğdır Plain.

Türkiye, due to its latitudinal position, is in the belt of the Westerly Wind Belt within the global wind systems. Therefore, the amount of precipitation is relatively higher on the mountain slopes facing west and southwest. However, the topographical structure of the Sürmeli Depression prevents these winds from bringing precipitation to Iğdır Plain. Moist winds from the west, which develop due to global wind circulation, deposit abundant precipitation (approximately 700 mm) on the mountainous belt located in the south and west of the Iğdır Plain[1] (Nişancı 1979). However, the north/northeast slopes of these mountains and the plain center receive less precipitation (Demircan 2022). Due to these and other factors, Iğdır is the province with the lowest amount of rainfall in Anatolia (Erinç 1953; Karaoğlu 2010, 2011). On the other hand, Yerevan, which shares the same depression with Iğdır, has a higher annual rainfall (Çölaşan 1960) amount (357 mm) (https://tr.climate-data.org/asya/ermenistan/erivan/erivan-1347/). The reason for this is that Yerevan was established on the slope of the mountains facing the humid winds coming from the west. Because of the geographical position of the region, mountain fronts facing west and southwest (Yerevan) receive more precipitation than those facing east and northeast (Iğdır) (Çölaşan 1960) (Fig. 7). Due to the effect of topography on precipitation characteristics, the areas of wind erosion located on Iğdır Plain cannot receive enough precipitation. These areas are developed on the back slopes of the mountains that prevent moist winds (Fig. 7).

The foehn winds caused by the topography also make the Iğdır Plain arid and hot compared to its surroundings (Nişancı 1979). The air masses descending rapidly from the mountains towards the plain floor (Figs. 7, 9a) warm up adiabatically and increase the temperature of the plain. As the amount of moisture decreases in the heated air, the air becomes drier. Due to the elevation difference, the drying effect of the winds is quite evident, especially on the slopes of Greater Ararat and Mount Zor facing the Iğdır Plain (Demircan 2022). The location of the wind erosion areas in the south of the plain corresponds to the areas where the foehn winds develop.

The lithology that affects the wind also influences the erosional processes secondarily. The distribution of wind erosion sites on the Iğdır Plain reveals these areas correspond to the foothill plains accumulated as colluvial deposits (alluvial fans) (Fig. 8). Since the soils in these areas are under arid climate conditions, they have a sandy structure as seen in most of the arid regions (Warren 2007). Since these areas are also floodplains, they are covered with loose and fine material and show sandy soil characteristics due to the effects of climate (Çelebi 1981; Sevim and İstanbulluoğlu 1985; Sevim 1999). In addition, according to prior research, since the sand grains belonging to the rivers are round, they have higher mobility in the subsequent processes (Erinç, 1963). The fact that the sands in the erosion areas are loosely textured, round and largely devoid of vegetation cover shows that they have suitable characteristics for wind erosion. The dryness of the sandy soils in these areas causes weak bonds (cohesion) between particles and weak aggregation; therefore, these soils become vulnerable to wind erosion (Warren 2007; Karaoğlu 2014). For example, in the studies conducted in the wind erosion areas of Aralık and Küllük, the soil was found to be very sensitive to wind erosion

[1] As of late spring, the effect of the west winds gradually decreases. Especially in the summer season, the air masses that penetrate over the Persian Gulf can occasionally cause precipitation in the region. However, most of the precipitation in the summer season is convectional precipitation due to local warming. The effect of these precipitation is quite limited.

Table 4 Winds with a speed above 17.02 m per second according to the measurements of the Iğdır, Aralık and Airport Meteorological Stations (2019–2022 was selected as the sample; Data taken from the Turkish State Meteorological Service, Iğdır station directorate)

Date	Wind direction	Wind speed (m/sn)	Meteorology station	Date	Wind direction	Wind speed (m/sn)	Meteorology station
2 May 2019	WSW	19.0	Airport	24 June 2020	S	20.6	Airport
3 May 2019	WSW	18	Airport	28 June 2020	SW	30.4	Airport
9 May 2019	E	18.5	Airport	11 August 2020	NNW	23.7	Airport
12 May 2019	W	19.0	Airport	13 August 2020	NNW	17.5	Airport
20 May 2019	NW	18.5	Airport	9 May 2021	N	26.2	Airport
21 May 2019	NE	19.5	Airport	9 May 2021	NW	17.5	Iğdır
25 May 2019	SW	26.2	Airport	9 May 2021	WNW	17.3	Aralık
25 May 2019	SSW	19.0	Iğdır	17 May 2021	W	18.0	Airport
26 May 2019	NNW	28.3	Airport	22 May 2021	SSE	19	Airport
26 May 2019	NW	18.5	Iğdır	22 May 2021	W	22.2	Aralık
26 May 2019	NW	17.2	Aralık	23 May 2021	ENE	20.6	Airport
6 June 2019	WNW	22.1	Airport	2 July 2021	WNW	19.0	Airport
6 June 2019	NNW	19.0	Aralık	5 July 2021	NNW	24.2	Airport
8 June 2019	E	19.0	Airport	5 July 2021	NNW	17.3	Aralık
15 June 2019	SSE	18.5	Airport	6 July 2021	N	19.0	Airport
20 June 2019	S	17.5	Airport	9 July 2021	SSW	19.5	Airport
26 June 2019	W	15.9	Airport	28 July 2021	W	22.1	Airport
28 June 2019	SW	17.2	Aralık	29 July 2021	SW	22.0	Aralık
29 June 2019	WNW	19.5	Aralık	29 July 2021	NW	19.5	Airport
5 July 2019	WNW	19.5	Airport	1 June 2021	W	20.0	Aralık
8 July 2019	NNW	20.6	Airport	2 June 2021	WNW	18.5	Airport
13 July 2019	NW	19.5	Airport	4 June 2021	W	18.5	Airport
5 August 2019	NW	17.5	Airport	6 June 2021	NW	17.4	Aralık
24 August 2019	NNW	19.5	Airport	7 June 2021	NNW	20.6	Airport
26 August 2019	WNW	21.1	Airport	9 June 2021	SW	24.2	Airport
28 August 2019	NNW	18.0	Airport	9 June 2021	WSW	20.1	Iğdır
30 August 2019	WSW	21.6	Airport	13 June 2021	WNW	25.7	Airport
2 Sept. 2019	NNW	19.5	Airport	23 June 2021	NW	18.5	Airport
17 Sept. 2019	NNW	18.5	Airport	27 June 2021	NW	18.5	Airport
21 Sept. 2019	NNW	22.6	Airport	12 August 2021	SW	21.6	Airport
21 Sept. 2019	NW	18.9	Aralık	13 August 2021	SW	19.5	Airport
28 Sept. 2019	NW	21.1	Airport	14 August 2021	W	24.2	Airport
1 May 2020	WSW	18.0	Airport	23 August 2021	NW	21.1	Airport
7 May 2020	NW	18.0	Airport	2 Sept. 2021	WSW	23.7	Airport
21 May 2020	SW	17.5	Airport	2 Sept. 2021	SSW	18.2	Aralık
22 May 2020	W	20.6	Airport	3 Sept. 2021	N	18.0	Airport
23 May 2020	NNW	17.5	Airport	20 Sept 2021	N	20.6	Airport
25 May 2020	ESE	25.5	Airport	25 Octo. 2021	N	21.1	Airport
25 May 2020	E	17.5	Iğdır	11 May 2022	W	22.6	Airport
28 May 2020	WSW	19.5	Airport	15 May 2022	WSW	20.6	Airport
12 July 2020	SSE	18.5	Airport	19 May 2022	W	22.6	Airport
13 July 2020	SW	19	Airport	20 May 2022	W	18.7	Aralık
14 July 2020	WSW	20.1	Airport	23 May 2022	NNW	20.1	Airport
17 July 2020	NNW	19.5	Airport	1 July 2022	N	21.1	Airport
17 July 2020	W	17.8	Aralık	2 July 2022	SW	25.2	Airport
18 July 2020	WNW	19	Airport	4 July 2022	S	22.6	Airport
19 July 2020	SSW	20.5	Aralık	4 July 2022	SSW	20.6	Aralık
20 July 2020	W	19	Airport	9 July 2022	N	23.1	Airport

Table 4 (continued)

Date	Wind direction	Wind speed (m/sn)	Meteorology station	Date	Wind direction	Wind speed (m/sn)	Meteorology station
4 June 2020	WNW	18.5	Airport	11 July 2022	NE	18.5	Airport
8 June 2020	WNW	19.0	Airport	12 July 2022	NW	22.6	Airport
10 June 2020	W	19.5	Airport				
13 June 2020	WNW	24.7	Airport				
21 June 2020	WNW	19	Airport				

Fig. 6 **a** and **b** Sandstorms in the December wind erosion area east of the Iğdır Plain. **c** Sandstorms in the foothills of Mount Ararat south of the plain (14/8/2021, taken from south of Iğdır Plain). **d** and **e** Localised sandstorms in the Suveren wind erosion area (25/9/2022, taken from Iğdır University Şehit Bülent Yurtseven Campus). **f** View of the same area in windless and clear weather (25/9/2022, taken from Iğdır University Şehit Bülent Yurtseven Campus). (photo **a** and **b** are from the archives of Mücahit Karaoğlu)

(Çelebi 1981; Sevim and İstanbulluoğlu 1985; Sevim 1999; Karaoğlu et al. 2018).

The topographical structure of the Iğdır Plain also affects wind direction and speed (Kaya and Öztürk 2013; Şahin et al. 2020), which in turn influence PM pollution. In particular, when the dominant directions of local winds (Tables 3, 4) with a speed of over 8 m per second are examined, it is seen that the dominant direction is NW and the second dominant direction is SW (Fig. 9b). The winds blowing from the northwest hit the mountainous belt in the south of the plain (Fig. 9a), and sufficient airflow cannot occur because this slows down their speeds (Koç, 2018). Since there are high mountainous belts surrounding the plain in these directions,

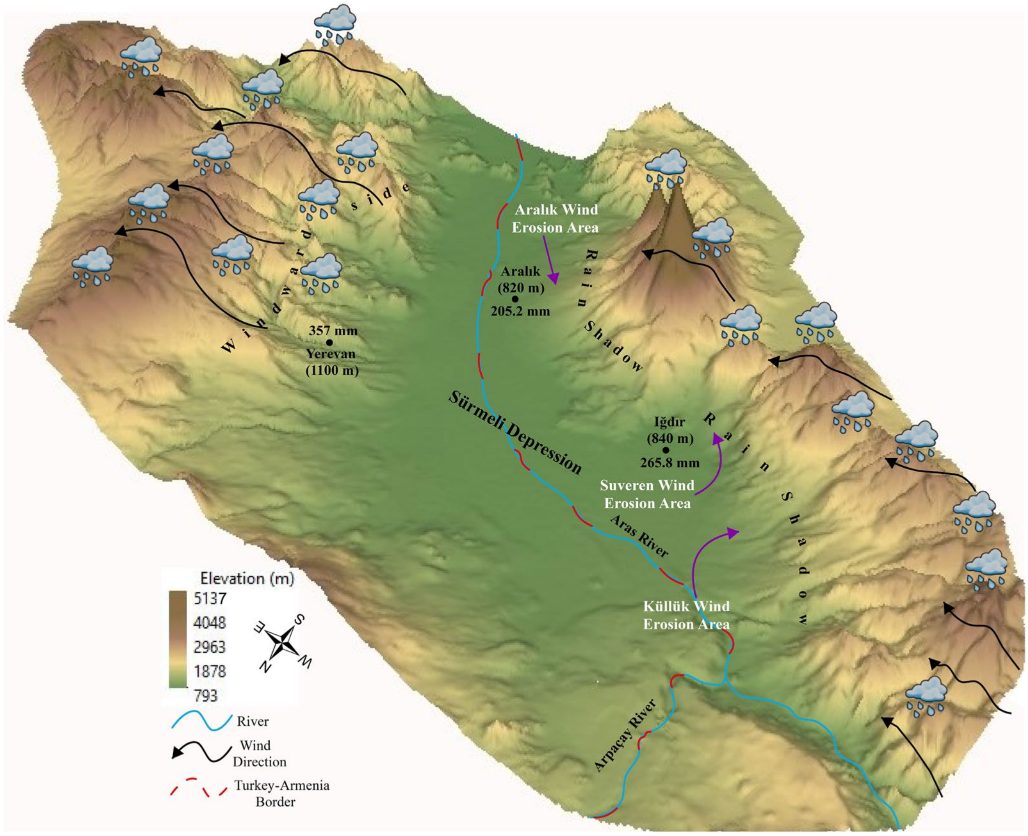

Fig. 7 The effect of topography on precipitation distribution around Sürmeli Depression. (The Iğdır Plain is in the shadow of the mountains that prevent moist winds coming from the west and southwest. Although Yerevan is in the same depression, it was established on the west and southwest facing the front of the mountains. Therefore, Yerevan receives more precipitation than Iğdır)

the general wind system in the plain is not capable of dispersing air pollution. Koç (2018) stated in his study that PM pollution increased due to wind obstruction during periods when the prevailing wind direction was NW. In addition, Altıkat (2019) found that PM pollution decreases when the prevailing wind direction turns to the SW. Finally, the NW sector winds change direction by hitting the mountain slopes in the south of the plain, causing these winds to affect the erosion areas as a belt (Fig. 9a).

As seen in Table 4, strong winds with a speed of over 17.02 m per second blow quite frequently in Iğdır Plain. For example, it was recorded that 101 strong winds blew in the summer of 2019–2022 (Table 4). This data is very important in terms of the fact that there are winds with sufficient speed and frequency to disperse PM pollution in the summer. Therefore, it is expected that the air will be cleaned at least on the days when storms occur. However, this is prevented by the fact that strong winds are blocked due to the topographical structure of and cause localized erosion on the plain. The winds in question cause erosion in the erosion areas on the plain, and dust are mixed into the air from a very large area (Fig. 6); therefore, instead of cleaning the air, these winds turn into a process that leads to air pollution due to the topography. In addition, as can be seen in Fig. 18, although the number of days with strong winds decreases in August and September, PM pollution is intense in these months. This is again due to the accumulation of PM affected by the topographical structure of the area.

Although fast winds blow on the Iğdır Plain, the blockage of the wind due to the local topography causes the wind speed to slow down considerably, especially in the Iğdır City center (Fig. 10). Although the multi-story buildings in the city center have an effect on this, the main reason is the prevailing wind direction and topography. Since the city center is located in a small half bowl (formed by topography), this is the area with the lowest wind speed (Fig. 10). Therefore, PM mixed into the air by wind erosion accumulates and causes air pollution in the city center, especially in the summer period. Güçük et al. (2019) and Şahin et al. (2020) stated in their study that PM pollution in the Iğdır Plain is mostly experienced in the city center.

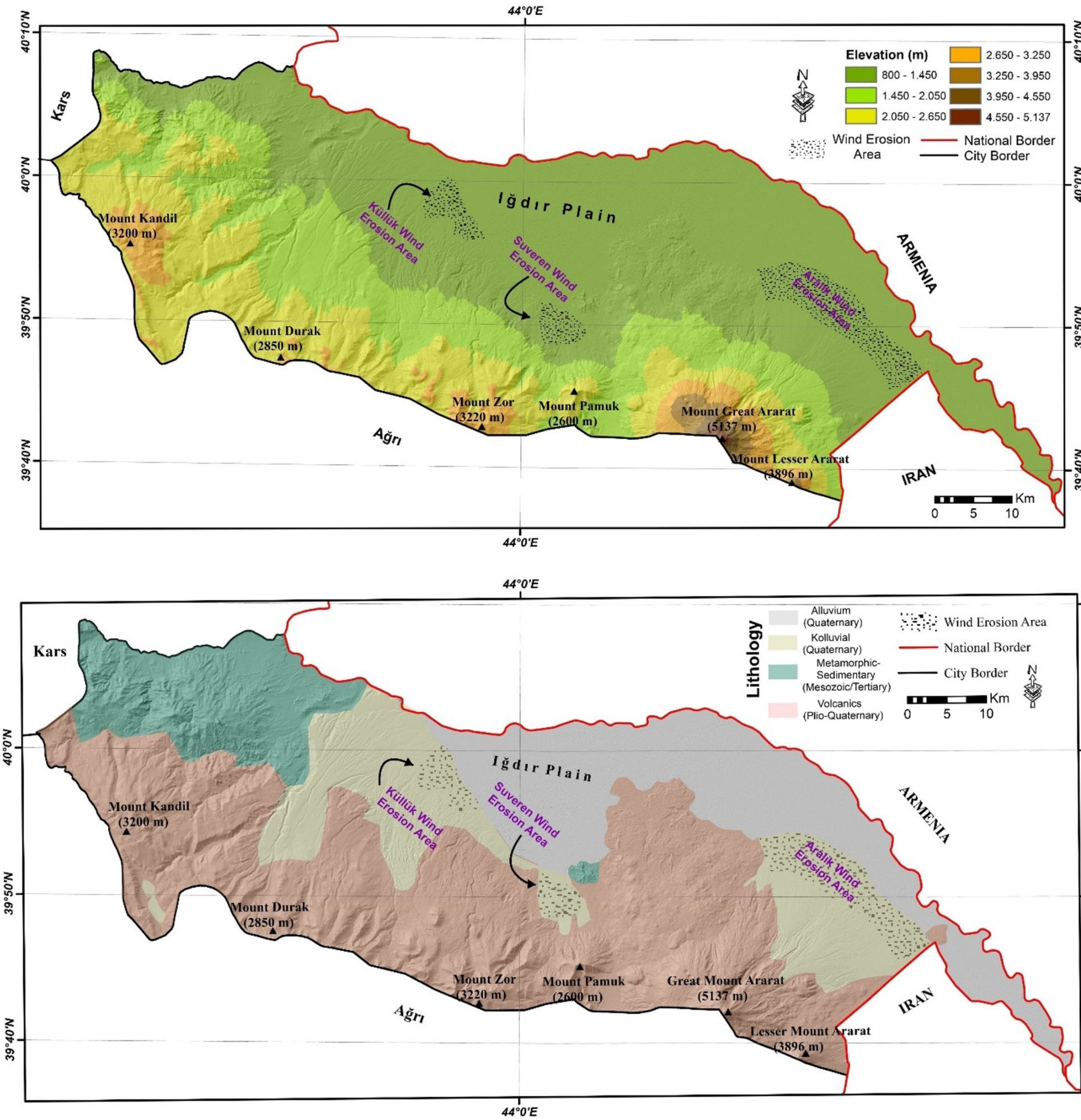

Fig. 8 Topography (top) and general lithology (bottom) maps of the Iğdır Plain and surrounding (Lithology data were obtained from field observations)

Anthropogenic processes

Vegetation is very important in preventing erosion (Okin and Gilette 2001). Therefore, human-induced destruction of vegetation is one of the causes of wind erosion (Karaoğlu 2018b). In particular, incorrect agricultural activities, overgrazing of livestock, as well as the cutting of shrubs and grasses as fuel accelerate erosion as these activities destroy vegetation (Karaoğlu 2014, 2018c). Therefore, wind erosion in semi-arid countries, such as Türkiye, is largely due to anthropogenic processes (Karaoğlu 2018c), and this type of erosion is also called accelerated erosion or human erosion (Çelebi 1981; Saxton 1996; Karaoğlu 2014). Since the effect of land management on wind erosion is recognized (Li et al. 2007), it is necessary to plan land use in semi-arid areas. From this point of view, incautious animal husbandry activities and the destruction of pastures are the main anthropogenic problems for the Iğdır

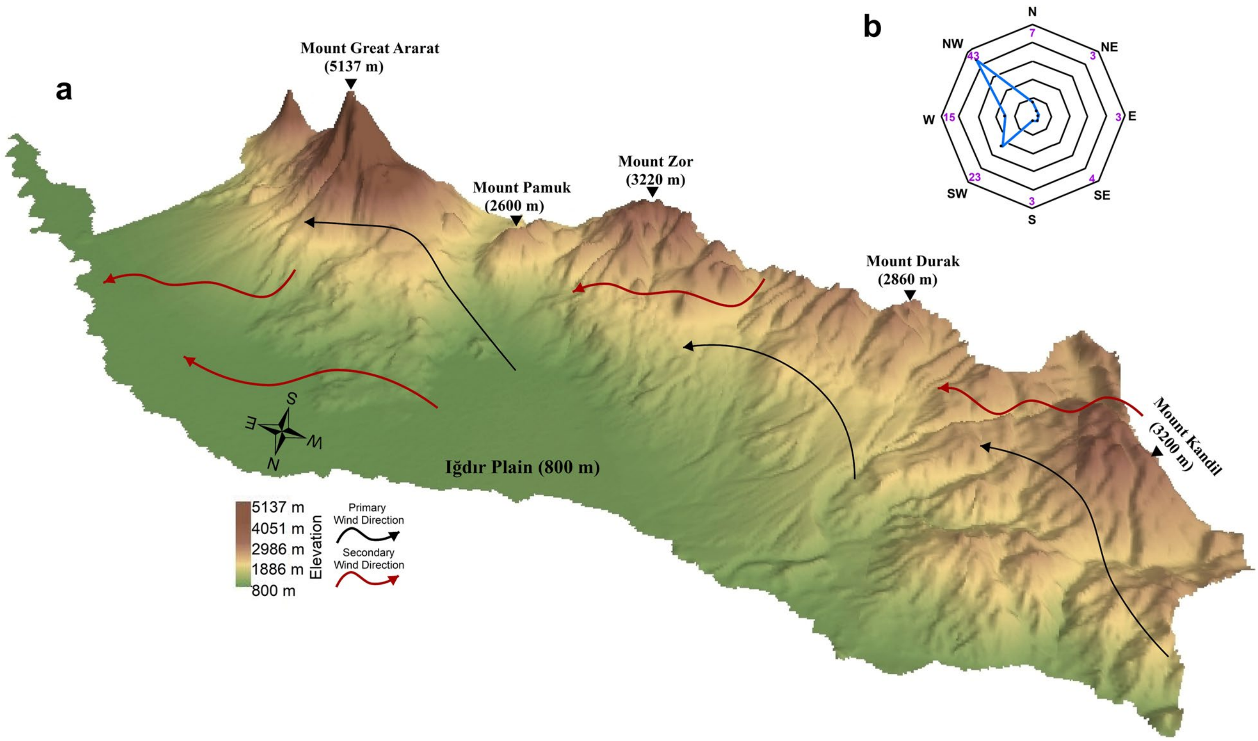

Fig. 9 **a** 3D view of the Iğdır Plain and directional characteristics of the prevailing winds. **b** Diagram of winds with a speed above 17.02 m per second on the plain. (All stormy days of the summer period of the selected 3 years are shown)

Plain. 49% of the population in Iğdır Province lives in rural areas, and the potential for animal production is quite high (Ertürk and Yılmaz 2013). Overgrazing due to livestock breeding also causes the erosion areas to remain unprotected.

In the first quarter of the twentieth century, the Iğdır Province, when it formed its administrative, economic and social organization, increased its population with migration from the Caucasus, Iran and other nearby regions, and its population rose to 3716 in 1927 (Yulu and Doldur 2023; https://www.tuik.gov.tr/). Until the 1950s, in addition to the increase in births, the population grew larger with the people coming from the villages evacuated due to the Mount Ararat rebellion (Güner 1993). Additionally, as a result of the settlement of Turks brought from Bulgaria in Iğdır (Hun 2018), the population increased to 7836 in 1950 (https://www.tuik.gov.tr/). After the 1990s, the population continued to rise above its capacity as a result of migration from rural areas. Iğdır was transformed into a province with an administrative change in 1992, public investments increased and the opening of the Dilucu border gate in 1993 revitalized Iğdır economically. According to TÜİK data, the population of the city increased from 24,352 in the 1980s to 35,858 in 1990 and 59,880 in 2000. Today, its population is around 200,000.

Population growth in Iğdır has also created many problems, especially erosion and air pollution. For example, the number of multi-story buildings has increased with urbanization and green areas have gradually decreased. Studies have shown that there are 200,000 dust particles in 1 cm^3 air mass in the city center, but this value decreases to 100,000 in green areas, such as parks (Erol 2014). This parameter shows the importance of green areas in preventing PM pollution.

The city of Iğdır, which is referred to as "*Green Iğdır*" in historical sources, has lost this characteristic to a great extent today. An Arab geographer describing Mount Ararat in the Middle Ages stated that the mountains of the region were covered with lush forests (especially Mount Ararat) (Erinç 1953). In his book "Transcaucasia and Ararat" (1877), James Bryce, a US jurist, traveler, politician and historian who climbed to the summit of Mount Ararat in 1876, stated that the nomads in the region used birch trees as fuel. The gradual decrease in vegetation cover in the region has paved the way for wind erosion.

Most of the people living on the Iğdır Plain and in the mountainous areas, especially in the villages built on barren soil, are engaged in animal husbandry. When the population of the villages is compared with that of the area of agricultural lands, it is seen that agricultural lands are insufficient. In addition, there is no equality in the

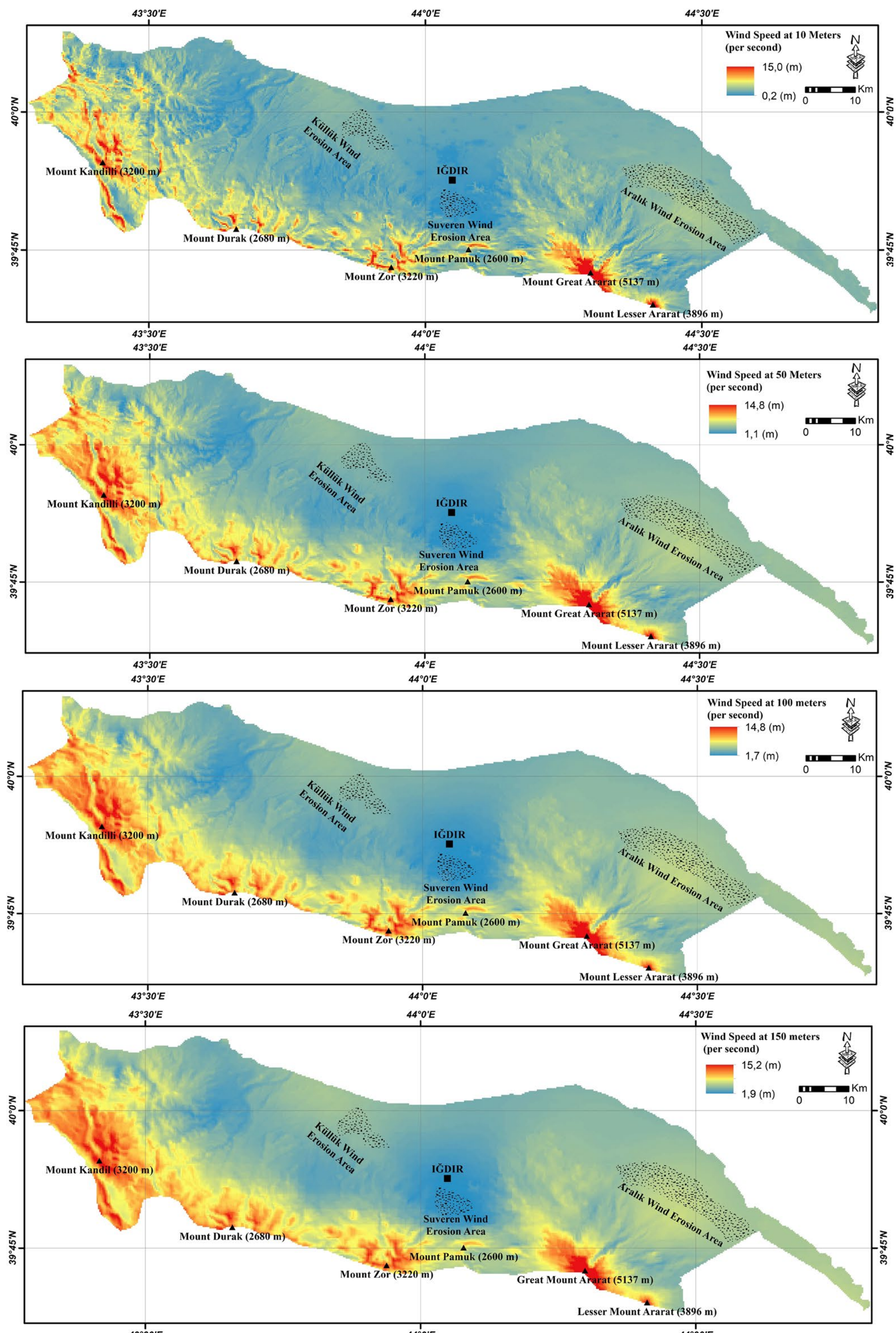

Fig. 10 Average wind speed map of the Iğdır Plain (Source: https://globalwindatlas.info/)

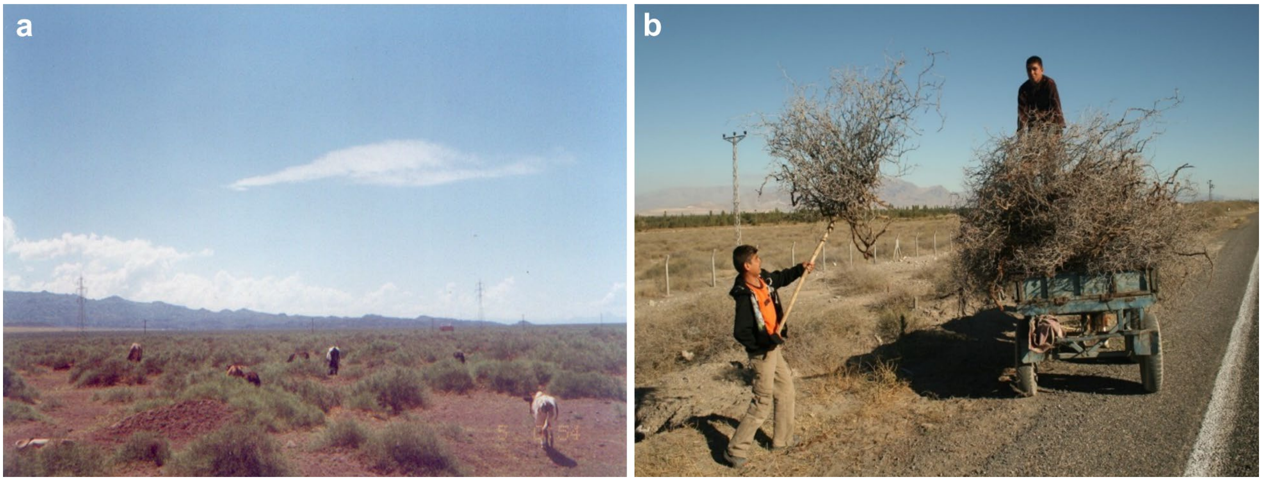

Fig. 11 **a** Animal husbandry activity in the Aralık wind erosion area. **b** Local people collecting bushes for fuel supply in the same area (photos from the archives of Mücahit Karaoğlu)

distribution of land. This causes the people of the region to turn to animal husbandry activities (Güner 1993, 1995; Severli et al. 2022). However, since one of the main problems of farmers is the inadequacy of pastures (Ertürk and Yılmaz 2013), there is grazing on pastures above the carrying capacity. The pasture area of the province is approximately 1,223.31 km^2. Since the total surface area of the province is 3,664 km^2, pasture areas cover approximately 33.3% of the surface area. The number of registered cattle in Iğdır has varied over the years: 41,324 (2002), 65,962 (2013), 157,426 (2020) and 100,400 (2021); the number of ovine animals has generally increased: 548,055 (2002), 502,177 (2013), 1,279,203 (2020) and 1,402,380 (2021) (Ertürk and Yılmaz 2013; Iğdır Tarımsal Yatırım Rehberi 2022). With these values, Iğdır Province is 10th on the list of the highest number of ovine animals among the 81 provinces of Türkiye (https://www.tuik.gov.tr/). This data shows that there is intense livestock pressure on pasture areas on and around the Iğdır Plain. Although there are transhumance migrations from the Iğdır Plain to other provinces, the arid vegetation on the plain has been largely destroyed. For this reason, people engaged in animal husbandry on the plain go to the mountainous belt surrounding the plain from the south for transhumance activities in the summer season.

There is a gradual migration from the villages on the Iğdır Plain to the plateaus in the mountainous areas. Animals, which are fed in the stables on the plain until the beginning of March, are taken out of their winter shelters and grazed in the areas around the village as the weather warms up (Güner 1995). This early grassing inhibits the development of vegetation that prevents erosion. As of the first week of April, the animals are taken to the foothills of the mountains in the south, and grazing is carried out in this area for approximately 1–1.5 months. Towards the middle of May, the animals are taken to the plateaus (Güner 1995). Some of the areas used as pasture before moving to the plateaus correspond to wind erosion areas today. In particular, the foothills between Mount Durak and Mount Pamuk are the scene of intensive grassing activities before and after returning from the plateaus. In these areas, both early grazing and overgrazing accelerate the erosion process by destroying the vegetation cover. Additionally, large, deep-rooted grasses/shrubs, such as Ebucehil shrub (*ephedra distachya*), Astragalus and Acantholimon, in the pastures are cut and the vegetation cover is destroyed (Figs. 11, 14b). This has resulted in serious anthropogenic pressure on pasture areas, leading to accelerated erosion. For example, due to the harmful behaviours in the Aralık wind erosion area, the area was closed to livestock and the vegetation was partially protected.

Wind erosion areas

Due to the abovementioned reasons, wind erosion areas have developed in different parts of the Iğdır Plain. Especially in the south of the plain, erosion areas are seen as a belt on the slopes of the mountainous belt (Fig. 6). From west to east, we find the Küllük Wind Erosion Area, the Suveren Wind Erosion Area and the Aralık Wind Erosion Area.

Aralık wind erosion area

The Aralık wind erosion site (Figs. 8, 11, 12), located in the borders of the district of Aralık, east of the city center of Iğdır, is the second largest wind erosion site

Fig. 12 **a** Large dryland area covered with arid shrubs in the Aralık wind erosion site (11/9/2021). **b** Stony desert in the same area (11/9/2021). **c** Dune cover in the same area (photo c from the archives of Mücahit Karaoğlu)

in Türkiye (Özdoğan 1976; Karaoğlu 2012, 2014). This erosion area is about 8 km wide and 20 km long (Çelebi 1981) and affects the district center of Aralık and 9 villages (Karaoğlu 2018a). The erosion area located on the NE and E slopes of Mount Ararat is one of the important desertification areas of Türkiye. Although it has been partially protected by EU-funded projects, wind erosion continues to be a major problem in the region.

The Aralık wind erosion area is the largest PM source area for the Iğdır Plain. The dune cover (Fig. 12c), which develops due to severe drought, is lifted by winds and affects a large area, especially the district center of Aralık (Fig. 6). The winds blowing in the summer season carry the dust to the provincial centre of Iğdır. Human structures in the region suffer significant damage due to wind erosion (Fig. 13), and many settlements have been subjected to sand invasion in the past.

Küllük wind erosion area

This wind erosion site was first described by Karaoğlu et al. (2018). It is located on the northern slopes of Mount Zor and Mount Durak in the south of the Iğdır Plain (Figs. 8, 14). Its N–S width is short, but its E–W extension is quite long. The erosion site, which developed on the loose river sediments originating from Mount Zor and Mount Durak, is the second largest erosion site in Iğdır. The results of chemical analyses of the soils in the erosion area show that they are very sensitive to erosion (Karaoğlu 2018a).

Suveren wind erosion area

In addition to the erosion sites mentioned in the literature on the Iğdır Plain, there is a small wind erosion site on the northern slopes of Mount Pamuk (Fig. 8). The area, which has similar geomorphological and climatic characteristics to the other erosion sites, is a region where ovine breeding is intensively carried out. Dust (Fig. 6d, e), which is blown from this erosion site, especially on days with strong winds, causes dust clouds around Iğdır University Şehit Bülent Yurtseven Campus. Detailed studies are needed to define this area as an erosion site. For this reason, this area is indicated as a possible erosion site in this study.

Remote sensing results

In this study, remote sensing technologies were utilized to explain the relationship between wind erosion and air pollution. Firstly, quartz analysis was applied to show that wind erosion areas are potential desertification areas (Fig. 15). As a result of the quartz analysis, it was found that the wind erosion areas in the south of the Iğdır Plain have high sand content (Fig. 15). In particular, the Aralık wind erosion site has quartz in the density seen in desert

Fig. 13 **a**–**c** Settlement area covered by sand in the Aralık Wind Erosion Area. **d** Irrigation canal covered by sand (photos from the archives of Mücahit Karaoğlu)

regions. This data confirms that wind erosion sites are important PM source sites due to their dense sand cover.

In the study, the amount of aerosol around the Sürmeli Depression was mapped using satellite images. The dates 4/7/2021, 10/8/2021, 31/08/2021, 2/6/2022, 4/6/2022 and 6/6/2022 were selected for the sample. The aerosol density in the atmosphere was high on the selected dates (Fig. 16). The Sürmeli Depression, where the Iğdır Plain is located, corresponds in particular to an area where the amount of aerosol is intense in a line extending from the NW–SE. The reason for this is wind erosion and PM accumulation due to the bowl structure.

Discussion

The climatic characteristics of the Iğdır Plain and the data compiled from the literature show that the region has a desert-semi-desert character with arid ecosystem characteristics. In fact, according to data from the Ministry of Environment, Urbanisation and Climate Change of the Republic of Türkiye, the Iğdır Plain and its surroundings are in the high-risk group in terms of desertification (Fig. 17). In addition, Demircan (2022) stated that the average temperature of Iğdır province has increased by 1.2 °C since 1960. Therefore, this climatic parameter has led to the development of wind erosion areas in the region.

The Iğdır Plain is a low depression in eastern Anatolia where important wind erosion sites have developed due to climatic (wind, temperature, precipitation), topographical (position and extension of mountains), lithological and anthropogenic (overgrazing, vegetation destruction, fuel supply) factors (Figs. 3, 8). For example, the Aralık wind erosion area is the second largest erosion site in Türkiye. The strong winds in these erosion areas are among the factors that cause PM pollution on the plain. Tables 3 and 4 show that strong winds blow on the Iğdır Plain, especially in the summer season when drought is evident. Figure 16 shows that there is an intense aerosol accumulation on the plain in the summer season, as seen in the selected sample times. When the data of the air pollution measurement points located on the plain on these dates are examined, Table 5 shows that the national PM_{10} limit value of 50 μg/m^3 (Table 6) was exceeded.

In addition, considering the presence of strong winds (Tables 3, 4) before and after the dates in question, the wind movements increased the aerosol density. In fact, Fig. 18 shows that when there are strong winds between the dry months of May and September, PM_{10} pollution exceeds the limit values in these months and the number of days when the limit values are exceeded in these months is quite high. All these parameters confirm that

Fig. 14 **a** General view of the Küllük wind erosion site. **b** Ovine husbandry activity in the Küllük wind erosion site (photos taken from north of Küllük wind erosion area, 21/11/2022)

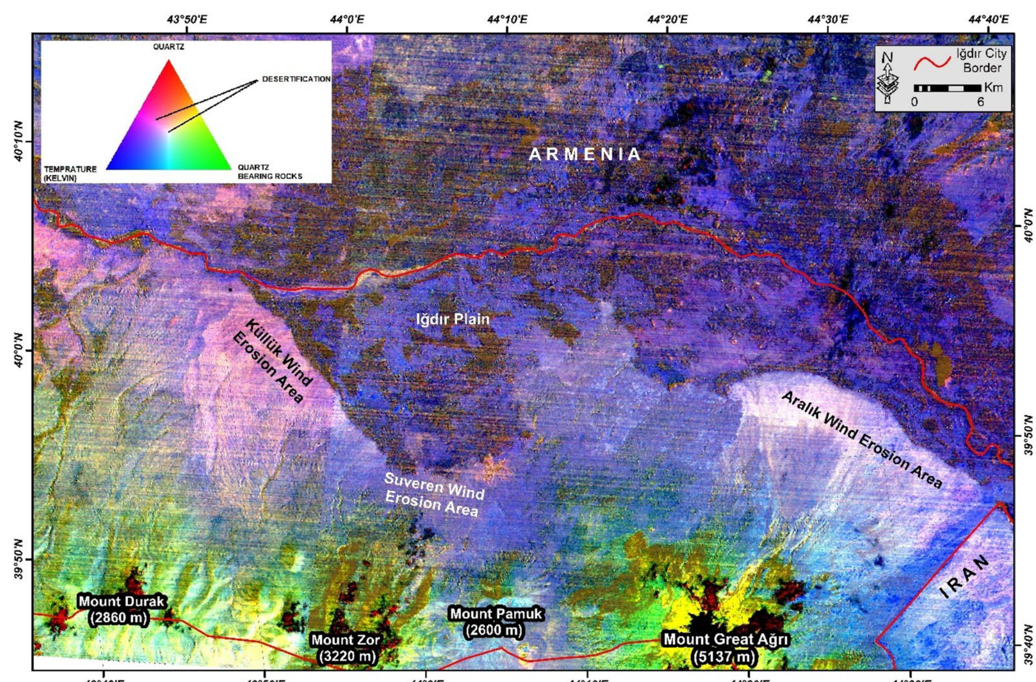

Fig. 15 Quartz analysis map of the Iğdır Plain (ASTERL1T Quartz indice b13/b12 in Red, siliceous rocks (b10/b12)*(b13/b12) in Green, Temperature in Kelvin in Blue Band math/Band ratio combination method) and its immediate surroundings (as can be seen in the map, wind erosion areas have a high degree of desertification)

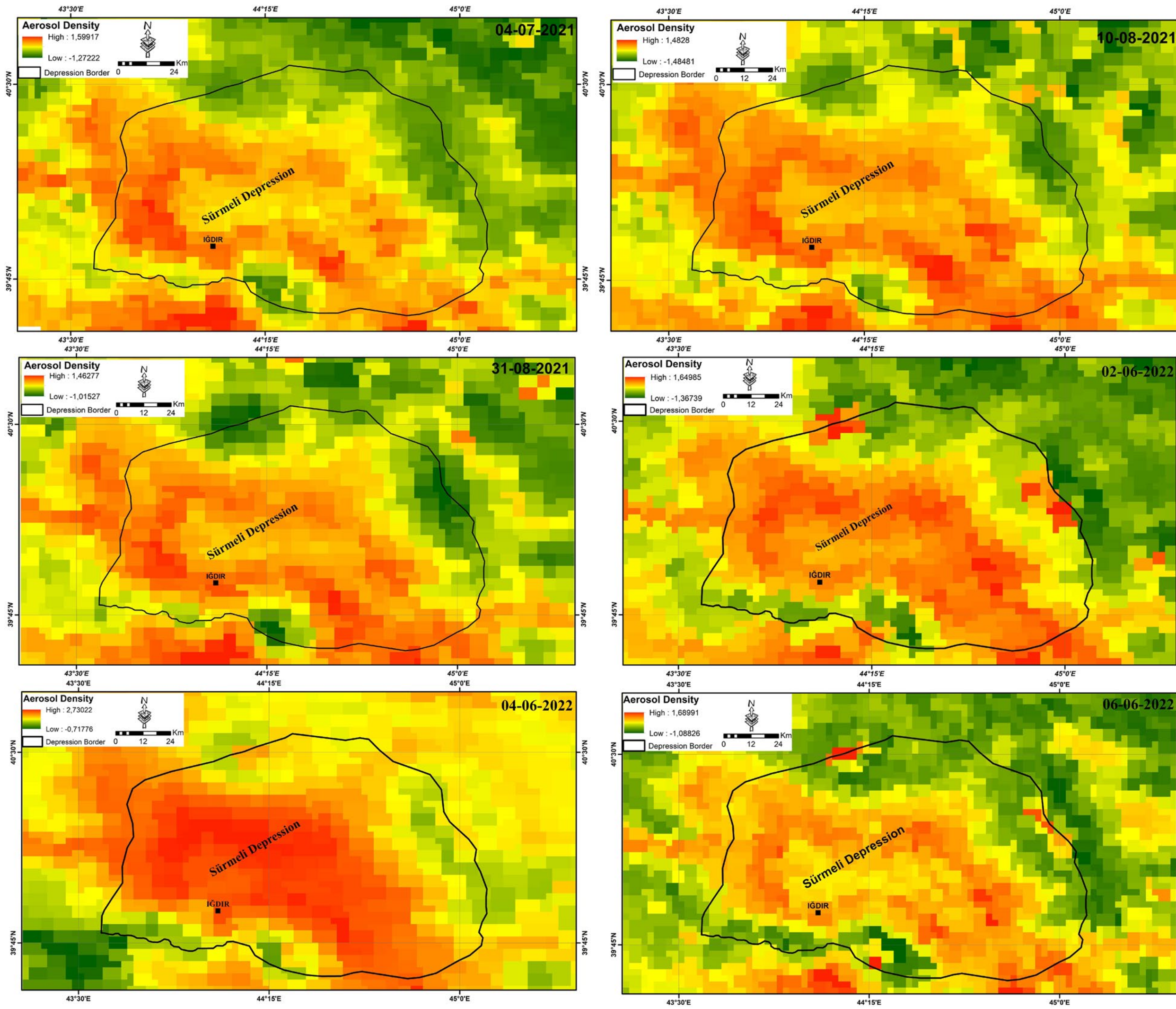

Fig. 16 Maps showing the aerosol density of the Sürmeli Depression and its surroundings, including Iğdır Province, on different dates (there are strong winds on these dates, Tables 4 and 5)

there is a relationship between wind speed, wind erosion, aerosol density and PM_{10} pollution.

Of course, local wind erosion is not the only cause of PM pollution on the Iğdır Plain. The particles originating from the global dust transport system and the dust coming to the plain from the southeast via Nakhchivan also have a determining contribution to the air pollution on the plain. However, the fact that the Sürmeli Depression in particular has a high number of aerosols (Fig. 16) proves the local wind erosion processes act together with the topographical structure. For example, the fact that aerosol density is low in the high areas located in the south, southwest and north of the depression, whereas it is high at the bottom of the depression reveals the effect of topography. However, global dust transport is not always a realised event. High PM pollution is recorded on almost all days (Fig. 18) during the summer seasons on the Iğdır Plain. Therefore, the average PM values in the summer season are high (Table 7). This situation is largely due to local wind erosion.

The presence of high PM pollution in the winter season in Iğdır Province has been reported (Aydın, 2018). However, the high PM pollution in the summer season due to wind erosion causes an increase in the annual average PM pollution. Therefore, the annual averages of both PM_{10} and $PM_{2.5}$ values in Iğdır Province exceed WHO and EU limits (Table 8).

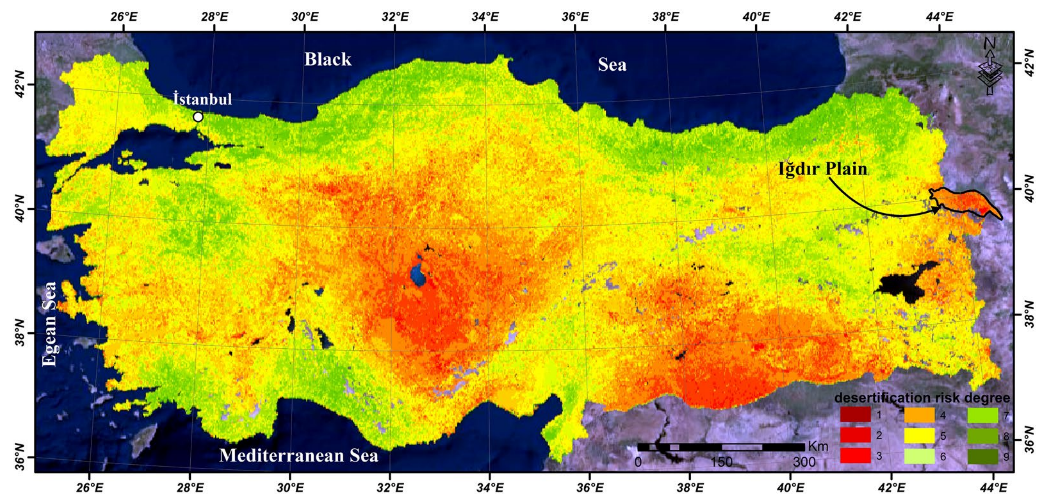

Fig. 17 Desertification risk map of Türkiye and the location of the Iğdır Plain (Source: https://basic.atlas.gov.tr/?_appToken=&metadataId=)

Table 5 PM_{10} pollution values and wind speeds on the reference dates in Fig. 16 (Source: http://sim.csb.gov.tr/SERVICES/airquality)

Date	Station		Maximum wind speed
	Iğdır	Aralık	
4/7/2021	133 μg/m^3	80.93 μg/m^3	18.5 m per second
10/8/2021	94 μg/m^3	59.34 μg/m^3	10.8 m per second
31/8/2021	208.45 μg/m^3	(no data)	9.3 m per second
2/6/2022	(no data)	76.49 μg/m^3	25.2 m per second
4/6/2022	102.90 μg/m^3	141.93 μg/m^3	22.6 m per second
6/6/2022	(no data)	106.98 μg/m^3	15.4 m per second

Table 6 National PM_{10} limit values (Doğru et al. 2015)

Index	PM_{10} (μg/m^3) 24-h mean
Good	0–50
Medium	51–100
Sensitive	101–260
Unhealthy	261–400
Bad	401–520
Dangerous	> 521

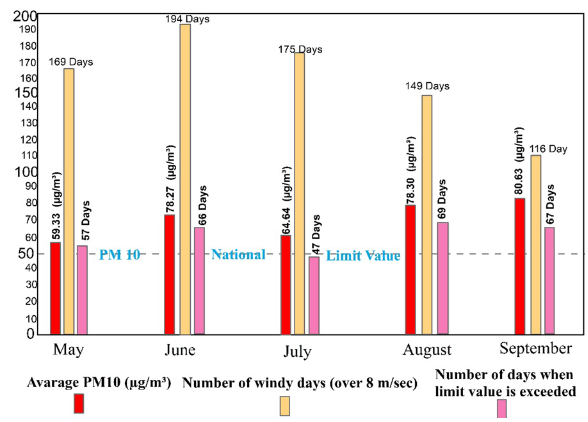

Fig. 18 Monthly average PM_{10} values, monthly number of days with strong winds and number of days when the air pollution limit is exceeded on the Iğdır Plain (the period between May and September of 2019, 2020 and 2021 was accepted as reference. Data taken from the Turkish State Meteorological Service, Iğdır station directorate and http://sim.csb.gov.tr/SERVICES/airquality)

Conclusion

Iğdır, a small city in eastern Turkey with a population of 200,000, is one of the provinces with the highest air pollution worldwide. The air pollution in Iğdır in winter season is largely due to the use of poor quality fuel and high atmospheric pressure (anticyclone) conditions. However, there is no fuel consumption in the summer season and high atmospheric pressure conditions are not observed. This study proved that wind erosion is effective on the high PM pollution in the summer season of Iğdır.

The Sürmeli Depression, where Iğdır is located, is a tectonic depression that is quite low compared to its surroundings due to its topographical structure. Due to this topographical structure, Sürmeli Depression has been hotter and drier than its surroundings. Temperature and aridity have prepared the climatic conditions for the development of important wind erosion areas in the region. In addition to this, lithological structure and anthropogenic processes have been other effective processes in the development of erosion areas. Especially in

Table 7 Average PM values of 2021 (Ulaş, 2022)

$PM_{2.5}$				PM_{10}			
Iğdır		Aralık		Iğdır		Aralık	
Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
23.64 μg/m^3	94.39 μg/m^3	22.05 μg/m^3	44.82 μg/m^3	84.07 μg/m^3	137.28 μg/m^3	61.17 μg/m^3	113.55 μg/m^3

Table 8 PM limit values according to the WHO and EU and 2021 annual averages for Iğdır and Aralık districts (Zeydan 2021; Ulaş 2022)

Parameters	WHO	EU	National	Iğdır	Aralık
$PM_{2.5}$	5 μg/m^3	25 μg/m^3	–	68.1 μg/m^3	37.03 μg/m^3
PM_{10}	15 μg/m^3	45 μg/m^3	50 μg/m^3	119.76 μg/m^3	77.03 μg/m^3

the summer period, which is the dry months, dust mixed into the atmosphere with strong winds causes intense aerosol pollution in Igdir province. This parameter has caused the PM pollution limit values to be exceeded in the summer season as well as in the winter season in Iğdır. Therefore, Iğdır is a province where PM pollution limit values are exceeded throughout the year.

Since the main cause of PM pollution, which affects the Iğdır Plain in the summer season, is the dust caused by wind erosion, the main measure to be taken is to control such erosion. In particular, wind erosion areas should be rehabilitated and greened. Drought-resistant trees should be planted in these areas and the existing vegetation should be protected. In addition, the erosion areas should be closed to livestock activities and destruction by local people should be prevented.

Author contributions

YÖ: research, fieldwork, map production, text writing, editing, methodology. AY: research, fieldwork, editing, text writing. OT: remote sensing, editing. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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