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The coastal fog and ecological balance for plants in the Jizan region, Saudi Arabia



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ABSTRACT

Fog water collection provides a sustainable resource for watering of crops. The Jizan region is one of the smallest states in the Kingdom of Saudi Arabia (KSA) but very rich with unique flora, fauna, landscape diversity, and occurrence of fog. According to satellite data from the period between (1991–2021) the average visibility in this fog belt varied between 5 m and 100 m. Specific relief properties, such as elevation contrast, present rare space for flora preservation and sustainable fog utilization and use in the watering of crops. Some results showed that number of foggy days is not equal and can be divided in three big cycles. It was estimated that 8×10^{13} L, or 80 m^3 of fresh water from fog per year, could be used for drinking and partly for farming in Jizan region from settlements Al Araq and Al Gandla, city of Jizan, Al Madaya, Al Mubarakiyah, Muwassam. This amount of water varied through time. The last observational period had large amount of water, 10×10^{13} L or 100 m^3 . The main methodologies used in this research were advanced GIS (Geographical Information Systems), Remote Sensing (RS), and numerical analysis. Satellite data were downloaded from National Oceanic and Atmospheric Administration (NOAA) and Landsat 8 and 9 satellite missions. This kind of alternative water may produce stability for three main plants in Jizan region, palm, wheat and olive. Typical arid regions in KSA can be transformed by water used from the fog.

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1. Introduction

Fog presents an important phenomenon around the world that leads to water accumulating near the earth's surface. Fog has different origin at different latitudes and longitudes. Fog reduces vis-

ibility to less than 1 km and in rare situations to less than 10 m (Menut et al., 2014). There is a lot of equipment installed around the world for the collection of fog. In Nepal, the first fog use started in 1997 at elevations higher than 2000 m. Although Nepal has an area with huge amount of rain, there are also some periods of drought. The Nepal government is trying to find alternative water resources (MacQuarrie et al., 2001). High elevation regions in Chile can produce large amount of water from fog. The research in the 90's showed that in most humid months, minimum amount of water is 10 L/m^2 , average $30\text{--}40 \text{ L/m}^2$ and maximum 300 L/m^2 (Schemenauer and Cereceda, 1994).

The quality of fog collectors plays an important role in droplet capturing. It is sometimes difficult to divide fog, haze, or dew droplets. It depends on the season and weather conditions at the moment of capturing. The tubular surfaces may produce bigger collection of fog than open space fields even if the materials of fog collectors are different (Seo et al., 2016). Fog and dew have recently been of huge importance, especially for agricultural and

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economy sector. Water scarcity is one of the major threats to humanity in the 21st century due to water pollution. Fog and dew present potential water resources in the future. The current fog and dew harvesting technologies are low yielding, with great potential for improvements. The main concern is in the threat of biological and heavy metal contamination. Any use of water from fog and dew must include better chemical analysis of water (Kaseke and Wang, 2018; Zhuo, 2022).

In Ebro river basin (Spain) the Accumulated daily crop evapotranspiration (ETc) generally provides good estimates of cumulative soil water depletion between irrigation of well drained soils. The water from fog is additional water for crops watering. The 10 % of total amount of water was from fog (Moratiel et al., 2016). Production of vegetables and fruit for fresh consumption in arid regions is of enormous importance. There are many methods for watering crops. In greenhouses with evaporative cooling during the warm months of the year in Riyadh (KSA), two different greenhouses: one traditional and one modified, both equipped with a pad and fan system, have been compared in terms of productivity and water use with main focus on water use for cooling. The second type of cooling system is very similar to fog collectors (Tsafaras et al., 2021).

Dew and fog have a big potential for use in Europe. In the Netherlands, the dew budget per year varies between 230 mm and 800 mm maximum. In this budget, 20 % of water belong to the water from fog (Jacobs et al., 2006). With the help of Geographical information system (GIS) and Remote Sensing (RS), dew potential was estimated in Serbia. The average estimated dew potential for the territory of Serbia is 20–40 mm·year⁻¹ for the south of the country, 15 mm·year⁻¹ for the north, 30–50 mm·year⁻¹ for the central region, and 20–30 mm·year⁻¹ for the east. It was concluded that the amount of this type of water resource is not significant but enough for partial use in the agricultural sector. 25 % of the amount of water from dew belongs to fog (Valjarević et al., 2020). Water scarcity associated with depletion and ecological degradation of global freshwater resources, leads to intensive consideration of increase in utilization of non-conventional sustainable resources such as dew or fog (Tomaszkiewicz et al., 2016). Lekouch et al., (2012) performed systematic measurements in the arid region of Morocco at Mirleft (43 m to 200 m from the coast for a year (May 1, 2007–April 30, 2008) and Ouassksou 240 m, 8 km from the coast for three summer months (July 1–September 30, 2007). The harvesting of water from dew is a process very similar to the harvesting water from fog. Dew is a frequently observed meteorological phenomenon and its importance to the water balance in arid and semi-arid regions has been recognized. The maize crops in northwest China were watered with water from dew. In the cultivation period this type of water has been used as additional water (Yokoyama et al., 2021; Yu et al., 2022).

Their data show that 15 sites in Morocco can collect water from dew or fog. In this research, it was difficult to separate dew from fog water. In the semi-arid region in Baku (Azerbaijan), according to research, water is being collected from fog, drizzle and dew. The results in this investigation showed significant level of dew, fog and drizzle. In the collector, rain participated with 84 mm; dew: 15 mm; fog: 6 mm; drizzle: 13 mm (Beysens and Meunier, 2016). In the arid Central Namib desert, rainfall is rare, but fog occurs frequently-120 times a year. In central Namib, fog occurs with the temperature inversion. Fog particles are unusually bigger than the average. The fog in Namibia belongs to low layer stratus and may present important resource of additional water in this semi-arid territory (Spirig et al., 2021). The water in Saudi Arabia is of vital significance. Water scarcity in this part of world may produce a lot of consequences for Saudi Arabian society in the future. Rainfall is important in the planning of the budget of water resources. According to 47 meteorological active stations from

the period of 1965–2010 and with the use of IDW (Inverse Distance Weight) and Kriging methods, the average amount of precipitation was estimated.

The impact of climate change and worldwide crisis of potable water give opportunity for the investigation of new alternative water resources. In the territory of KSA there was a lot of research investigating water from fog. The data used from National Oceanic and Atmospheric Administration (NOAA) were modified and new Fog Potential Index was established. It was found that wind velocity has got twofold impact on the formation of fog; (i) for a lower wind velocity up to a certain threshold value, fog formation increases with velocity as old condensed moist air is continuously replaced by new moist air, and (ii) for a higher wind velocity (beyond the threshold value), fog formation decreases with velocity due to disturbance in the formation of fog. This theoretical model was used and experimentally checked in Asir region of KSA (Alam Imteaz et al., 2011). The main problem for collecting water from fog or dew is how to calculate the water evaporation rate. Cooling systems and kinds of material can present one important thing for water utilization. Mathematical and theoretical models must be used to improve the knowledge about fog properties (Kassem, 1994). Monthly and yearly water balance is crucial for bird existence. Three typical birds were selected as protected objects of water supplement scheme. The water supplement in wet year was nearly 20 % less than that in extremely dry year. The water balance in the Yellow River Delta wetland must be analyzed permanently and additional water collected for a better ecological balance (Yu et al. 2021). Climate change also acts as a main ecological driver of hydrological balance. Surface runoff and balance of water present one of the most significant elements in ecological balanced wetlands formations (Lee et al., 2020). The moisture of vegetation in semi-arid and arid regions presents one of the most vulnerable elements in the water and ecological balance. >75 % of the land in these regions is supported by additional waters (Li, 2020).

In this research, the palm, wheat, and olive may survive using additional water from the fog. The coastal fog in the Jizan region presents an important ecological driver for plants in coastal and hilly regions. This water can be used in the summer and autumn periods for watering palms, and olives, and partly for the wheat.

2. Fog water collection

Fog normally exists in places where tropical, temperate, and arid regions exist. Fog is a phenomenon of thick cloud formation of tiny water droplets gathered from the atmosphere and found in a state of suspension close to the earth's surface. It prohibits visibility more than mist and reduces visibility to below 1 km (Park et al., 2013). Fog droplet sizes range approximately from 1 to 30 μm (Schemenauer and Cereceda, 1992). A droplet has a low fall velocity of approximately 1 cm/s to 5 cm/s. Generally, fog formation occurs when the air cools below its dew point or by increasing the dew point through adding the vapor water to the air (Fessehaye et al., 2014). In addition, fog formation can be classified according to the physical formation process or where the fog was formed (Eugster, 2008). In fog formation, suspended water particles are carried away by the wind and when obstructed, they collect to form larger water droplets. The deposition of water droplets on the obstacle increases and ultimately rolls down to the earth's surface due to gravity.

Fog harvesting is a process of gathering water using unconventional means i.e., using fog as a medium for collecting water. Fog harvesting systems need key characteristics including a physical transformation process through the fog collectors and mesh types. Fog collectors are simple devices which provide a barrier to wind

with suspended water. A fog collector in its simplest form has a frame which supports a section of mesh in a vertical plane usually; large collectors, for example, can be 12×6 m in length and width, respectively (Schemenauer and Cereceda, 1994). The construction of a fog collector is simple and shown in Fig. 1. Generally, large operational fog collectors are made of two supporting posts and cables on which the mesh is suspended. Additional support may be given to increase the robustness of the mesh. Additional supports are required to keep it intact against the wind.

Standard Fog Collectors (SFCs) can be designed using indigenously available materials or imported materials for the mesh. These collectors are mounted on the previously selected fog site based on topography, altitude, and defined elevation. Generally, SFC is made up of a 1 m^2 , double-layered polypropylene mesh having an approximately 35 % shade coefficient. The large fog collector (LFC) has been widely used for fog collection. LFCs and SFCs have the same principles but differ in size. The mesh is directly stretched over a rigid frame in SFCs whereas in the LFC, a frame made of cables supports the mesh; this mesh is kept under tension by erecting two vertical posts.

The water collection rate of a typical fog collector depends upon many parameters, such as wind speed, the liquid water content in the fog, density of available water droplets in the fog, the size of the mesh and arrangement of the mesh material in the fog collector. According to the (Ju et al., 2013), small-sized water droplets must be transferred without external force for continuous and efficient fog formation. The erection of fog collectors needs critical attention in selecting the location. The collectors are normally fitted in a position perpendicular to the wind direction at a suitable mounting height to obtain optimum water collection. A fence may be provided to protect it from mishandling by birds and animals.

An efficient fog collection mechanism can result in enhanced water collection. Many researchers have devised fog collector mechanisms to optimize the water collection. Fog collectors are devised using the differences in surface wettability to enhance water collection. (Thickett and Neto, 2011; Bagheri, 2018) devised atmospheric water collectors using biomimetic surface coatings by dewetting of polymer films. Drop formation mechanisms involving different velocities of water drop motion on a conical copper wire

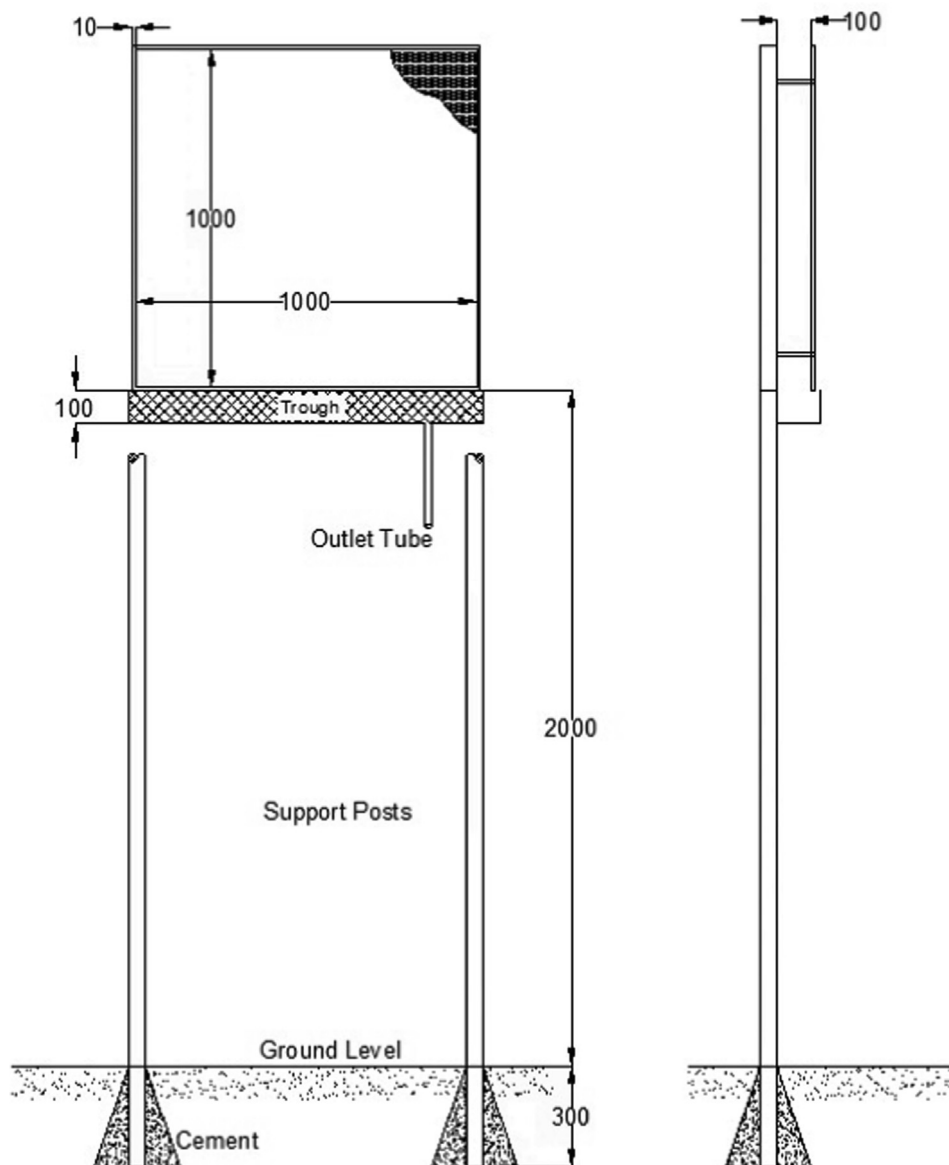


Fig. 1. Standard fog collector (Schemenauer and Cereceda, 1994).

having different wettability have been studied in order to enhance water collection. Various studies comparing single driving forces and double driving forces on clamshell and barrel drops have also been studied. The mesh is an extremely important part of the fog collector as the collection of water depends upon the mesh characteristics. Generally, the mesh is attached to the frame and remains open to environment thus directly exposed to the atmosphere. When the wind brings the foggy air in contact with it, the fog droplets are deposited on the mesh, combined to form larger droplets, and finally, run down as water into the reservoir (Klemm et al., 2012; Friesen et al., 2018). Water is not only crucial but like additional element for agriculture, industry, land, and forest. It is important too for ecological balance in vulnerable regions (Ai et al. 2022; Mora, 2017).

3. Methodology

3.1. Case study of Jizan region

Saudi Arabia comprises almost 80 % of the territory of the Arabian Peninsula. The data from the research conducted within the period between 1978 and 2009 showed changes in recent climate. The first gridded datasets represent a very dry (40–80 mm) area over the world's largest sand desert (Rub Al-Khali). The regions in the middle and north of Saudi Arabia have precipitation (80–150 mm) whereas the wettest (>150 mm) region is in the southwest of the Peninsula. The highest temperature in the last century (>27 °C) was measured over the Rub Al-Khali. The maximum, mean, and minimum temperatures have increased significantly by 0.71, 0.60, and 0.48 °C per decade (Almazroui et al., 2012). The climate of KSA is classified as an arid zone according to Köppen-Geiger climate classification (Peel et al., 2007). The main focus was placed on the spatial and temporal variations of mean temperature and temperature extremes, wind speed and direction, and relative humidity (Patlakas et al., 2019).

It is of utmost significance to find the climate regions of Saudi Arabia. With the help of cluster analyses, techniques and meteorological data from 56 stations, results were satisfying. The results analyzed in this investigation are compared with traditional methods. The factor cluster analysis is better than any traditional method and may give a precise conclusion about temperature and precipitation in Saudi Arabia (Ahmed, 1997). After a detailed analysis of CO₂, it was concluded that developing countries consumed almost 67 % of non-renewable energy in the last few decades. This ecosystem of xeric shrubs exists in the belts of coastal fog between the eastern and western parts of the Arabian peninsula. It follows the coast of Oman southward from Masirah Island and reaches 120 km inland. From here, it continues as a very narrow strip only 5 km wide along the coast of Yemen and up to 50 km wide to the Tihamah plain along the Red Sea coast of Saudi Arabia. In this region, especially in Saudi Arabia, the rainfalls are less than 200 mm. In this region, although it rarely rains, fog provides moisture sufficient to nurture a great deal of grassland, shrubs and thick woodland. This coastal strip is of particular importance and with enough occurrence of fog. The fog progressively becomes weak in inland regions. In Jizan region, fog may occur in hilly and mountainous areas. Jizan region occupies the territory of 11,671 km². According to the last census from 2017, this region has 1,676,655 inhabitants. The density of population is 130/km². The capital city of the region is also called Jizan. This region has shorelines of 300 km along the southern part of the Red Sea. It borders Yemen in the south, the region Al Bahah in the north, and the region Asir in the east (Fig. 2); (Youssef et al., 2015). This region includes over 100 islands in Farasan area in the Red Sea. There are many protected animals and trees. The southern and western areas of the

region are considered the lowest being between 0 and 500 m. The altitudes of northern and eastern parts are between 500 and 2,400 m. The average temperature in this region is 24.2 °C. The coastal belts of Jizan region are the part of Tihamah region with the maximum temperatures of 40 °C in July and 31 °C in January. Very high humidity in coastal region of Jizan produces large number of foggy days throughout the year. Average precipitation is extremely low and less than 75 mm per year (Youssef et al., 2012). Economically, the region is divided into three parts. The lowest part near the Red Sea belongs to plains and is suitable for the production of fruit and vegetables. It is followed by the Alhazoun forest district which consists of some areas with rich pasture. The region with the highest elevation belongs to Al-Sarawat mountains inland, which rises up to 3,000 m. The geomorphological properties of Jizan are extremely different. The slopes of Jizan are between 0° and maximum up to 74°. The specific relief of KSA and Jizan region give possibility for dew use. Jizan city is differentiated into two zones; Jizan salt dome to the west and sabkha deposits to the east. The Jizan region has near-surface sediments with overlying salt rocks which are greater than those of sabkha zone. Three zones have different elevation belts. The first zone covers low land near the Red Sea, the second is hilly area and the third is mountainous area (Alhumimidi, 2020). The southwestern region of Saudi Arabia indicated deficit of measurable precipitation in the used period (Abo-Monasar and Al-Zahrani, 2014). The aridity in KSA in central and southwest regions including Asir and Jizan may cause big consequences on inland and groundwater resources. The main problem in coastal regions is high percent of soil and nitrate in groundwater wells (Lloyd, 1986). Favorable atmospheric and topographical conditions can give some amount of water collected from fog. In the period between 2006 and 2007, in Asir region KSA, measurements in April were 6.2 L/m² per day minimum, 24 L/m² maximum. In the same month in the Abha city, 3.3 L/m² per day was collected. The average water production in the same city for three months (December, November, January) was 11.5 L/m² per day. The best results for fog collection are between elevations of 2,260 m to 3,200 m (Al-hassan, 2009). 27 cities in KSA have the potential for deriving water from fog. In a similar research, the instruments for collecting fog water showed that 80 % of the cities in the north and a part of cities in the south have potential for fog harvesting. The maximum amount of water collected in this detailed research was 22.9 L/m² per day and 7.25 L/m² in a 2-h period. It was found that there was a high probability of fog when the relative humidity was higher than 95 %. The results of the chemical analysis showed small content of Fe but not in a serious doze. Fog-prone regions may use fog as supplement water in dry areas (Gandhidasan and Abualhamayel, 2007). Collecting water from fog is not only possible in arid or semi-arid areas but also in hyper arid regions. The Atacama Desert is the oldest and driest non-polar desert on Earth. Millions of years of hyper aridity enabled salt accumulations through atmospheric deposition. In the research of position and properties of soil in desert Atacama, the region southwest of Antofagasta, Chile has two locations for fog occurrences through the year. In this soil profiles, sulfates are the dominant salts showing a downward transition from gypsum to anhydrite that is accompanied by an increase of highly soluble salts and a decrease of sulfate δ³⁴S and δ¹⁸O values. These layers may collect fog through the year but at the depth bigger than 40 cm. The two lower sites situated on the distal parts of inactive alluvial fan deposits were subject to occasional fog occurrences (Arens et al., 2021). The experiment of 11 weeks, showed that in the south part of the desert of Atacama a better chance for fog occurrences exists in the open, rather than closed space. According to the results from this research, it was concluded that salted soil has a better possibility for fog collection (Andrew et al., 2002).

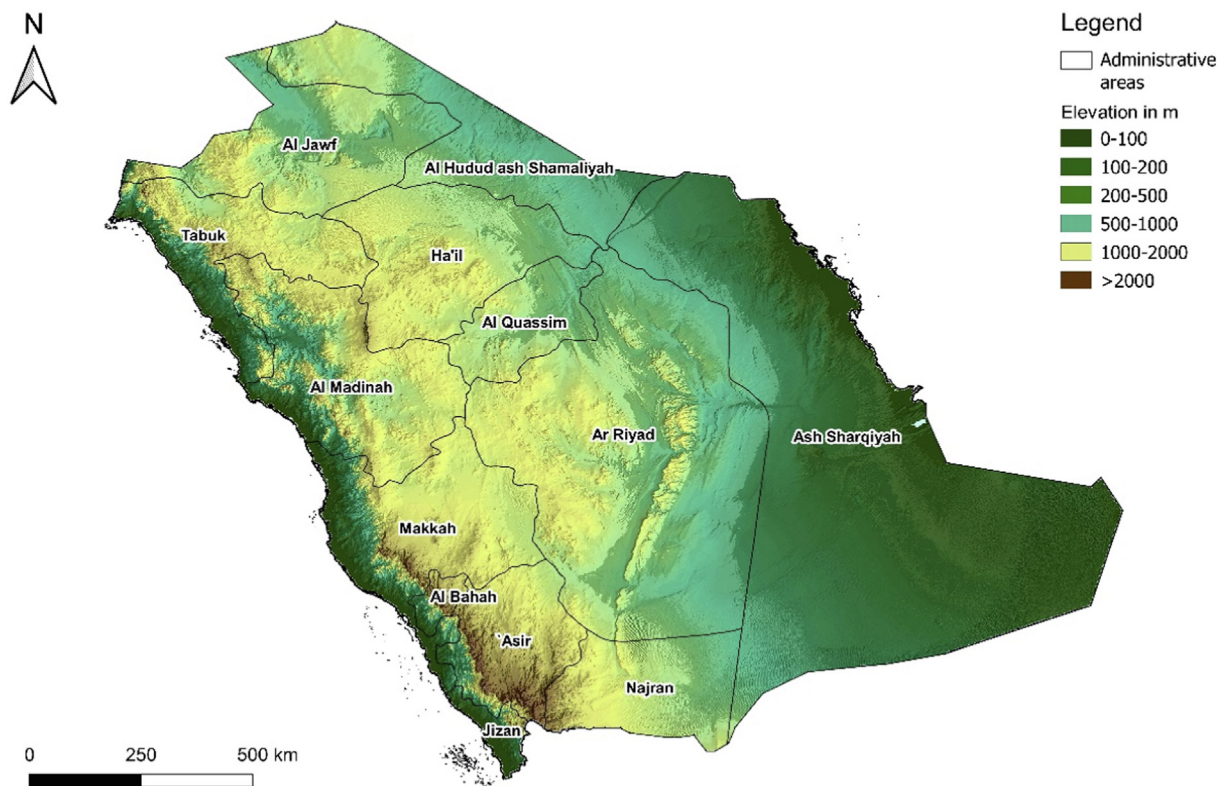


Fig. 2. The Physical map of Saudi Arabia with administrative areas, created by DEM (Digital Elevation Model).

98 % of the KSA is in arid or desert area, with less than 100 mm of precipitation per year. The water collected from fog is of great importance for the KSA. The data from the research on fog properties used in Rayda weather station with two standard fog collectors (SFCs) installed, showed satisfying results. The results indicated that the average amount of water collected by the local mesh was 6.7 L/m² per day and in the other mesh was 5.5 L/m². The highest quantity of water was collected in March and it was 22 L/m² per day. The best results were found in the southwest KSA, especially in the Asir region. This region receives more rainfall through the year than the rest of the country. The fog is formed in the Asir area between December and April, and in the summer months in May and September. The water from fog collection may be a significant resource of additional water throughout the year. Asir region has big mountain and hilly areas and the best results for fog utilization are in the areas between 1800 m and 2000 m. (Algarni, 2018).

After downloading data in DEM (Digital Elevation Model) in resolution of 30 m from the satellite missions Landsat 8 and Landsat 9, it is possible to find precise elevation properties (Wang, 2015). First and foremost, it is necessary to find relief features of Jizan administrative area. The lowest points of 0 m of Saudi Arabia lay near coastal regions of the Red Sea and Persian Gulf. The highest peak is on the Mountain Jabal Sawda, with the elevation of 3133 m. Physical features of Saudi Arabia can be divided into six elevation belts. First belt covers the area between 0 and 100 m and occupies 26 % of the territory. The belt between 100 and 200 m occupies 15 %, the belt between 200 and 500 m 16 %, the belt between 500 and 1000 22 %, between 1000 and 2000 m 17 % and higher than 2000 m 4 % of the territory (Fig. 2).

The drainage network of Saudi Arabia is typically arid with low river flow. The densest network is distributed near the areas of the mountains Jabas Sawda (3,133 m) and Jawan (3,091 m). The directions of drainage network occupy south-west parts of the country. Another parts of dense drainage network in Saudi Arabia are close

to the plate Najd and mountains Jabal Dukhaum (2,630 m), Jabal Idgis (2,160 m) and Jabal Zalma (1,258 m); (Fig. 3). The regions in which there aren't any drainage networks belong to Rub Al Khali and An Nufud Al Kabir deserts (Saleh, 1985).

4. Results and discussion

4.1. General physical properties of jizan region

All digital analysis is conducted and approved in QGIS 3.16.5. The coastline belt of Red Sea has the lowest point of 0 m, whereas the highest point has the elevation of 2624.5 m and belongs to Asir Mountain. The Jizan region can be divided into four independent elevation belts. The first belt is between the elevation of 0 m to maximum 656.1 m. This belt covers 10,905 km² or 93.4 % of the territory, the belt between 656.1 m and 1312.3 covers the area of 357 km² or 3.1 %. The following belt with the elevation between 1312.3 m and 1968.4 m has the territory of 227 km² or 1.9 %, and the highest belt between 1968.4 m and 2624.5 m covers the area of 182 km² or 1.6 %. Generally, the relief properties showed zones between four independent areas. First zone is plate and relatively low areas in the north and south. This zone belongs to the Red Sea coastal areas (see Fig. 4).

The city of Jizan is at the distance of 46 km from hilly areas. At the same time, the distance to mountain areas is 63.9 km. The north coastlines of the Red Sea in the Jizan region are at the distance of 29 km from hilly areas. The central coastlines are at the distance of 55 km from hilly and 71 km from mountain areas.

4.2. Drainage network of Jizan region

After downloading the data from Earthdata (<https://earth-data.nasa.gov/>) the DEM (Digital Elevation Model of ASTER Global

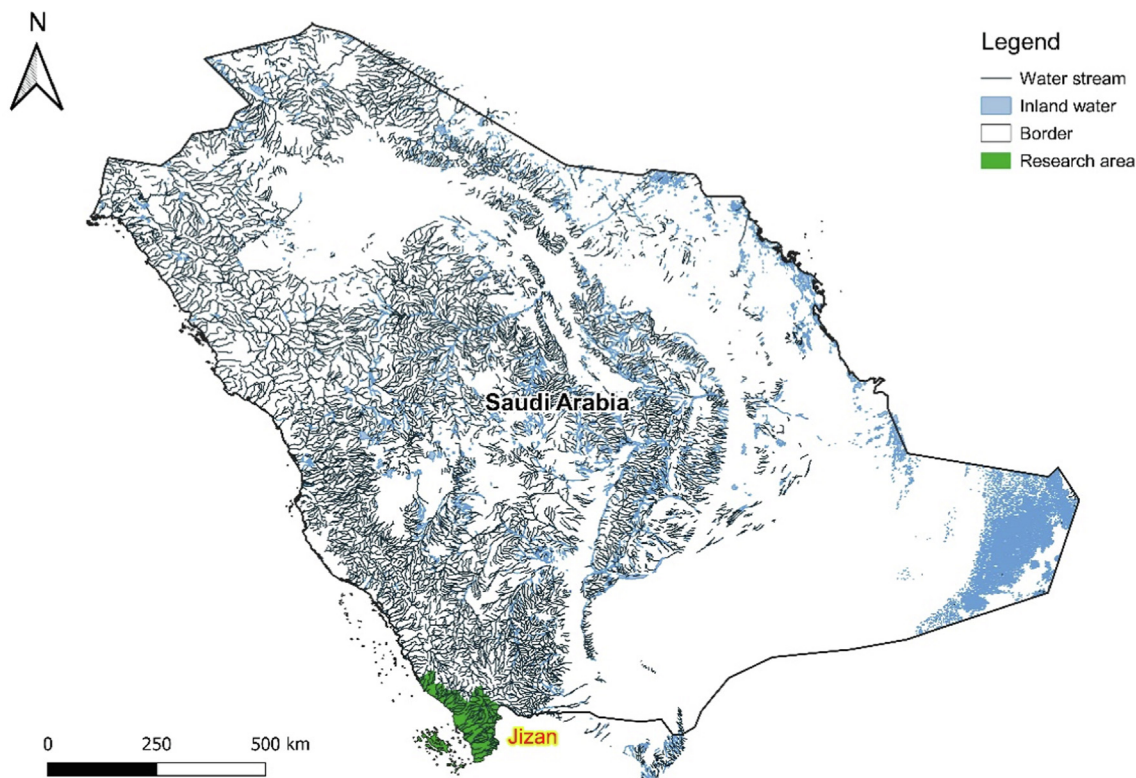


Fig. 3. The position of the Jizan region in Saudi Arabia included a drainage network and inland waters. The drainage network and inland waters in KSA are not permanent.

Digital Elevation Model V003 of 10 m of elevation was downloaded and analyzed. The total number of ASTER DEM granules used in this analysis was 24 (twenty-four). The area of one granule is 500 km². Drainage network was created and analyzed in the software QGIS 3.16.5. The total length of drainage network is 122,810 km. After watersheds and drainage network analysis of Jizan region, conducted in SAGA 0.9 and QGIS 3.16.5, the properties of water streams were found. The total perimeter of drainage network is 16,247 km, and the average density per 1 km² is 0.7. The densest network is situated in southwestern and central north-western quadrants of the Jizan region where the results varied between 0.9 and 1.3 per 1 km². The total number of streams is 17,123 (see Fig. 5). The best results after approved numerical and GIS analysis showed great potential for fog harvesting in the areas between 0 and 100 m of elevation and between the city of Jizan and border of Yemen in the belt close to the Red Sea coastline.

4.3. General fog occurrence in Jizan region

From the standpoint of fog harvesting potential, the investigated territory of the Jizan region is divided into three independent areas (fog occurrences belts). The first area is in the territory northeast from Jizan, close to the settlements Al Araq and Al Gandla. This belt covers 14 % of the territory. The following area is in the areas of Jabal Sawda's mountain and it covers the large territory or 34 %. The settlements Al Heayh and Fayfa belong to this belt. This area has a northwest orientation.

The third belt covers the territory south from the city of Jizan and borders the territory of Yemen. Settlements Jizan, Al Madaya, Al Mubarakiyah, Muwassam are in this belt. It covers 52 % of the territory. The average days with fog in the period between 1991 and 2021 can be divided into seven belts with fog occurrences. In seasonal analysis, only belts with >16 days can be used for fog harvesting and crops watering (Fig. 6). According to long term analysis

water from fog, may be sufficient for watering of palms in south-east part of country and partly for wheat. The volume of water amount is mm 25 or 25 L per 1 km². The coastal areas from north-west to the south-east yearly may produce 30 L of water. This area is covered by palms (Kadri et al., 2022), (see Fig. 6). In south mountain areas it is possible to derive 35 L of water a year this area is covered by wheats. The maximum water from fog is distributed in central and north-east mountain and hilly areas. In these areas are crops with olives (Miri Nargesi et al., 2022) The amount of water per year is 45 L per 1 km².

Summer and winter present good seasons for fog occurrence. In these seasons 10 days will be used for watering of palms in south-east part of country and partly for wheat. The volume of fog amount is 10 mm 10 L per 1 km² (see Fig. 6).

The first belt is the area with no possibility for using water from fog and it covers 6815 km² or 58.4 % of the territory. The belt with (16–20) days covers the area of 1764.8 km² or 15.1 %. The belt with >24 days covers the area of 1733.2 or 14.9 %. The good possibility for fog use have belts with (20–24) days and more than (24 days). These belts together cover 30 % of the territory potentially suitable for fog harvesting (see Table 1; Table 2; Fig. 7). In summer season 10,100 ha can be watered in central and north areas. In Winter season 8,400 ha in central and east areas.

4.4. Seasonal fog occurrence in Jizan region

According to the thirty years' analysis, the results obtained for the spring season are as follows. The belt with (16–20) days with fog during spring time occupies 533.7 km² or 4.6 % of the territory of Jizan. >24 days of fog cover the area of 835.4 or 7.2 %. During summer, the belt of (16–20) days with fog is distributed in the area of mountain Jabal Sawda's and coastal areas of the Red Sea in Jizan region near scrub xeric forest. This belt covers the area of 1049 km² or 8.8 %. The belt > 24 days covers the area of 1047.7 km² or 9 %. In

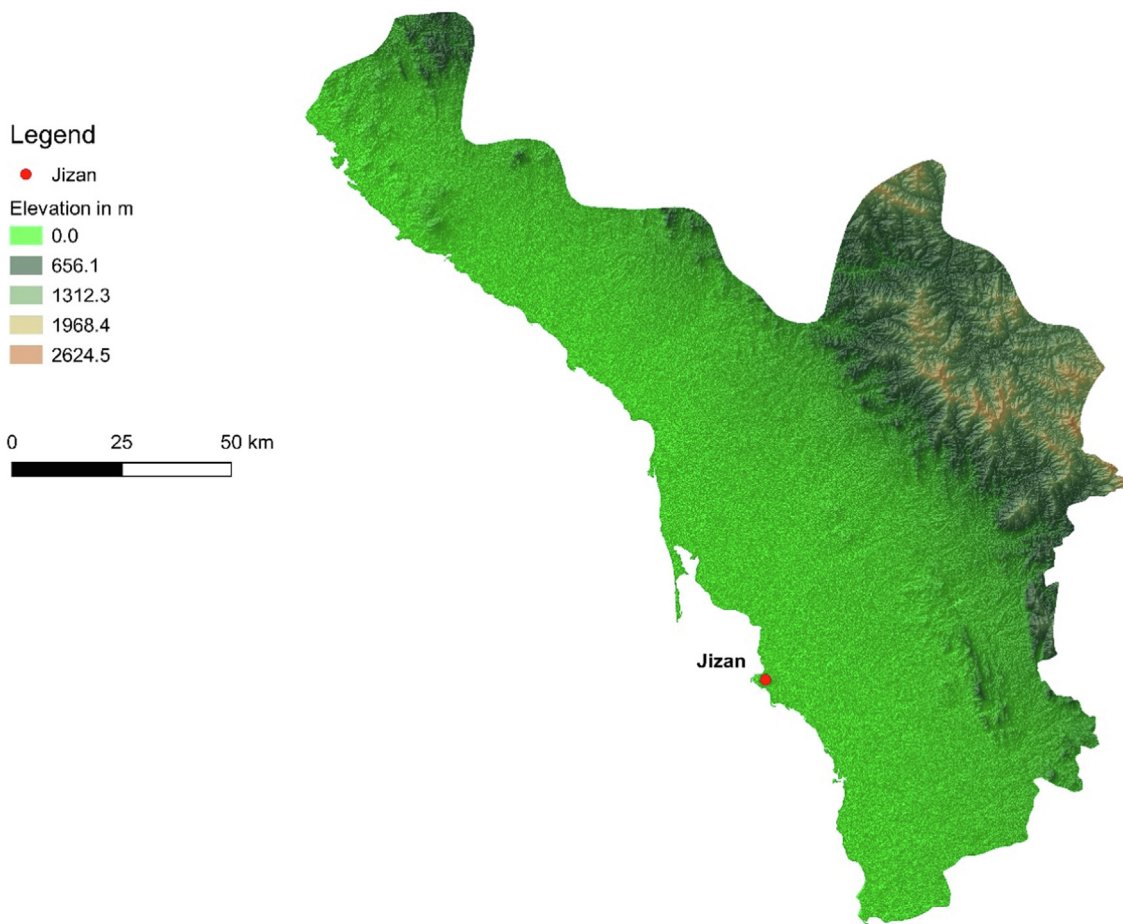


Fig. 4. Relief properties of Jizan region.

autumn, the belt of (16–20) days with fog is distributed on 941.8 km² or 8.1 %. It covers the coastal zone of Jizan, mountain areas and one belt close to the city Sabya. In this belt 90 % of all crops belong to palms and 10 % to wheats.

The belt with 24 and more days with fog covers the area of 1061.7 km² or 9.1 %. The area of this belt is identical to the belt with (16–20) days. The highest potential for fog harvesting in Jizan region is during winter. The belt with (16–20) days has the area of 1043 km² or 8.9 %. The belt > 24 days has the area of 1186.8 km² or 10.2 %. This belt is distributed in the coastal areas, south of the city of Jizan, mountain areas, and in some parts bordered with the Asir region. In this region 85 % of areas belong to olives, 15 % to wheats (see Table 2; Fig. 7).

This belt is also highly concentrated in the mountain areas. The elevation of fog occurrences in the last thirty years is divided into three belts. The first belt occupies the territory from the Red Sea area (coastal zone) to 2.5 km inland areas up to the northeast with the average elevation of 0 m. This belt is useful for watering of palms. The second belt is between settlements Sabya, Al Hanayah, and Fayfa in the hilly and mountainous areas with the elevation of 600 m. This belt is useful for watering of palms and partly wheats. The third belt is on Jabal Sawda's mountain with the average elevation of 1600 m. This belt is very suitable for watering olives and partly wheat. According to the analysis and data from the satellite recordings and period (1991–2021), the most applicable months for fog harvesting are August in summer and December in winter. These months are slightly different for fog use. In December, the fog was highly concentrated in the coastal area of Jizan in the xeric scrub zone. This type of fog belongs to the Arabian Peninsula

coastal fog desert. GIS analysis of the fog belt showed that the fog belt has an average inland diameter of 7.1 km. The densest fog in December has a width between 1.7 km and 3.5 inland from the coastal line of the Red Sea. Another belt is distributed on Sawart mountain and has width of 50.1 km. In the summer season, the highest concentration of fog is in August. The average distance of fog from coastal zone, during the summer, was 7.7 km. The densest fog belt in August has width of 4.3 km. Another area was in mountain areas with the width of 77.9 km. This belt is very close to the Sabya settlement, which gives an increasing possibility for fog harvesting in urban areas. Fog occurrence in the Red Sea zones near the Jizan region were estimated for the first time, within the period between (1991–2021). The average width of the fog belt was calculated for spring, summer, autumn, and winter season. The average distance of fog belts from the coastal zones and open sea in spring was 3.8 km. In summer this distance was 3.4 km, and in autumn 4.1 km. The difference between summer and autumn is 0.7 km or 700 m. The highest concentration of fog was in the region of Jizan between coastal areas of the settlement Al Araq and the city of Jizan. The estimation showed that crops with palms (*Phoenix dactylifera*) can be watered in growing season with 60 % of yearly water from fog. The wheat (*Triticum durum*) with 20 % and olive (*Olea europaea*) with 80 %.

4.5. Elevation and belts properties of fog occurrence in Jizan region

The new findings from this research preliminary suggest that the water from fog can be used in some parts and during the same period in the Jizan region. The semi-arid and arid areas of the King-

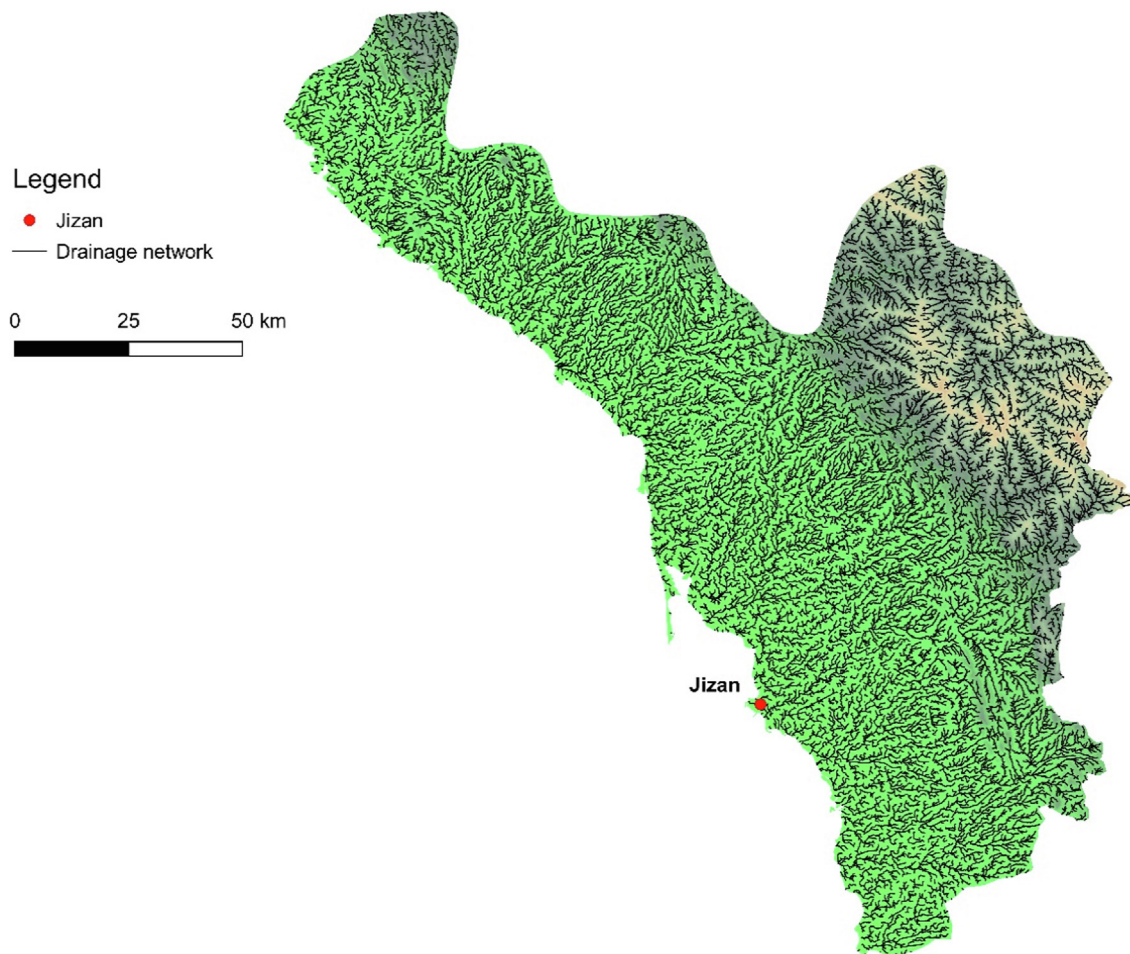


Fig. 5. Drainage network of Jizan region.

dom of Saudi Arabia are concentrated in the Jizan region too. Specific climate patterns and the phenomenon of seasonal coastal fog may be a good reason for installing new fog collectors. Future research should be oriented toward the experimental methods for fog harvesting and identifications of suitable places in urban and rural areas. The most useful fog collectors can be installed on Sawart mountain and the areas between Sabya, Al Hanayah and Fayfa settlements. The elevation of collectors must be between 800 m and 1600 m. Another belt for fog utilization is between Al Araq and Jizan and Muwassam in coastal xeric scrub zones. The budget of drinkable and potable water is constantly decreasing in the Arabian Peninsula. In this zone also is high percent of areas with palms and it is good possibility for efficiently watering.

GIS and Remote sensing analysis within this research could be very useful in future calculations and estimations of the potential of fog utilization in agricultural sector for another types of fruits and vegetables. This additional water can be used in the periods of big drought and deficiency of water in growing season in Jizan region. The south-east and south parts of Sawart mountain are good for fog harvesting and watering for crops. Very low possibility of fog occurrence according to GIS and Remote sensing analysis are placed in the north and north-east parts of Jizan region. This part of Jizan is a desert zone. The central and coastal parts of the Jizan region are densely populated. In these zones, it is possible to use water from fog in urban areas. In that case, it is valuable to install collectors on roofs and connected reservoirs with watering areas.

General screening of the landscape indicated very dominant potential of temperature inversion in winter season. In summer season north-west winds blowing in coastal region increase the potential for fog occurrence. The slopes with the highest values of fog potential are with the azimuth of 190° W. The topography of the highest mountain in Saudi Arabia, Sawarth, includes very high slopes in Jizan near Asir region. The average slope adequate for fog harvesting, according to GIS analysis is 9.65° . Apart from hilly and mountain areas, 30 % of coastal zones near the Red Seas have good potential too. The main problem for watering of crops is in sharp slopes especially for wheat in hilly and mountain areas. These three types of plants are essential for agricultural sector in the KSA. This sector growing every year for 3 % of production in total.

5. Conclusion

Many regions in the world are entirely dependent on water resources, especially new ones. Water from fog may be a significant source of water supplies in the arid areas of Jizan region. There is a high possibility for fog harvesting in the area near the border of Yemen and cities Al Zabbain, Al Sehi. Another area is in the southern and eastern parts of mountain Jabal Sawda. The third valuable area is in the north, between settlements Either, Sabkah and Dana Bay.

The average positions of fog collectors in the region of Jizan are between minimum 0° of slope and 47° . The best results of fog har-

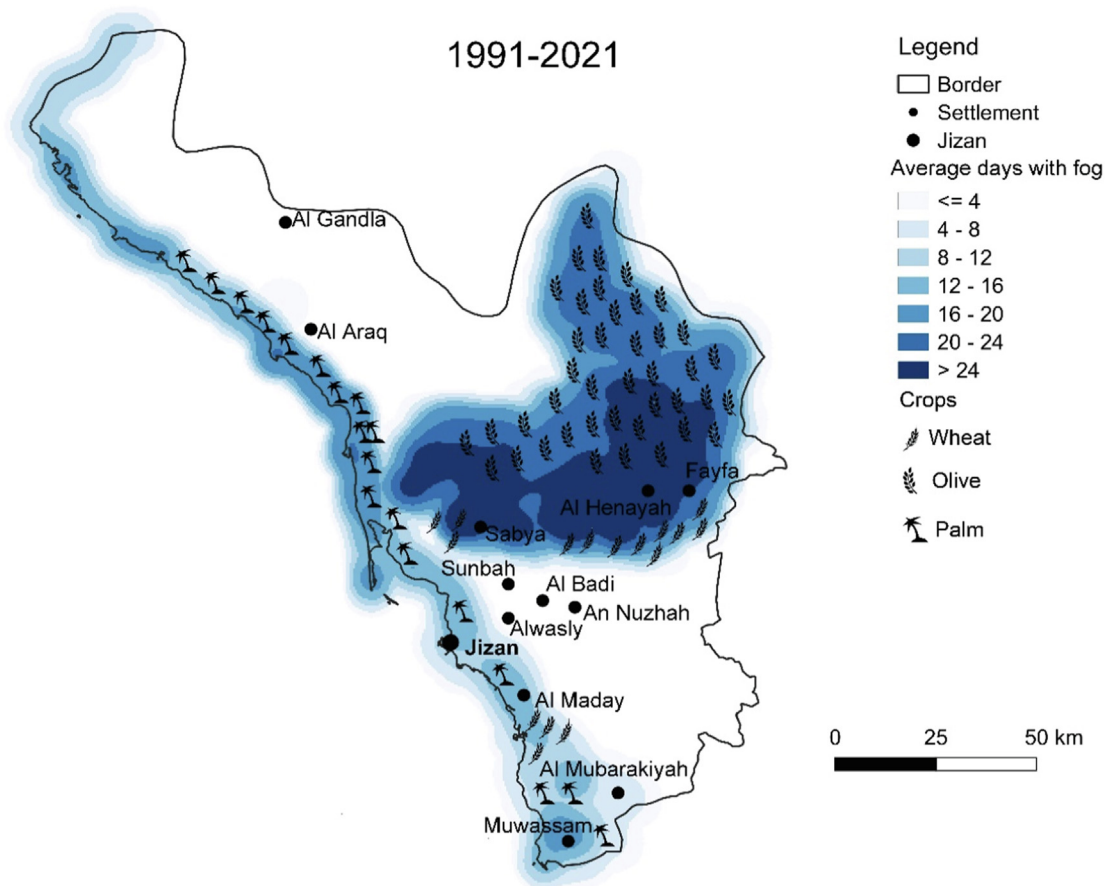


Fig. 6. Distribution of average days with fog in continental Jizan region within the period (1991–2021).

Table 1

The average seasonal areas of fog in the last thirty years in Jizan region.

Average fog year in days	1991–2021 in km ²	Spring	Summer	Autumn	Winter
No fog	6815	9001.6	6856.7	7001	6799.8
<=4	461.5	505.6	945.5	678.8	657.6
4–8	139.2	234.5	435.9	459.2	500.5
8–12	555.2	456.8	779.5	812.3	783.8
12–16	202.1	103.4	556.7	668.2	700.2
16–20	1764.8	533.7	1049	989.8	1042.3
>24	1733.2	835.4	1047.7	1061.7	1186.8
Total	11,671	11,671	11,671	11,671	11,671

Table 2

The average seasonal areas in hectares of palms, olives and wheats can be watered according to fog occurrences in Jizan region.

Average fog year in days	Area with crops in ha	Spring	Summer	Autumn	Winter
> 24	Palms	1,300	3,900	2,200	2,500
16–20	Olives	2,500	5100	2,900	4,900
12–16	Wheats	1,000	1,100	1,600	1,000
Total	30,000	4,800	10,100	6,700	8,400

vesting would be on 5° of slope. The purpose of the methods presented in this paper is to provide better theoretical estimation of fog potential in Jizan (KSA), as well as its detailed geospatial analysis for agricultural purposes due to Arabian Peninsula water scarcity problems and negative future climate projections regarding the climate change impact on arid environments. Two key factors for building an environmentally sustainable surrounding in the country include climate change and water scarcity issues.

Groundwater, rainfalls, and desalination are significant sources of water supplies in arid areas like the Kingdom of Saudi Arabia. Unfortunately, these kinds of water are not enough and not drinkable in all regions of Saudi Arabia. The method of desalination is very expensive and not always acceptable. According to climate change effects on Saudi Arabia, the budget of rainfall is not equal and it decreases every year. Groundwater sources have problems with a high concentration of nitrate and in some wells with high

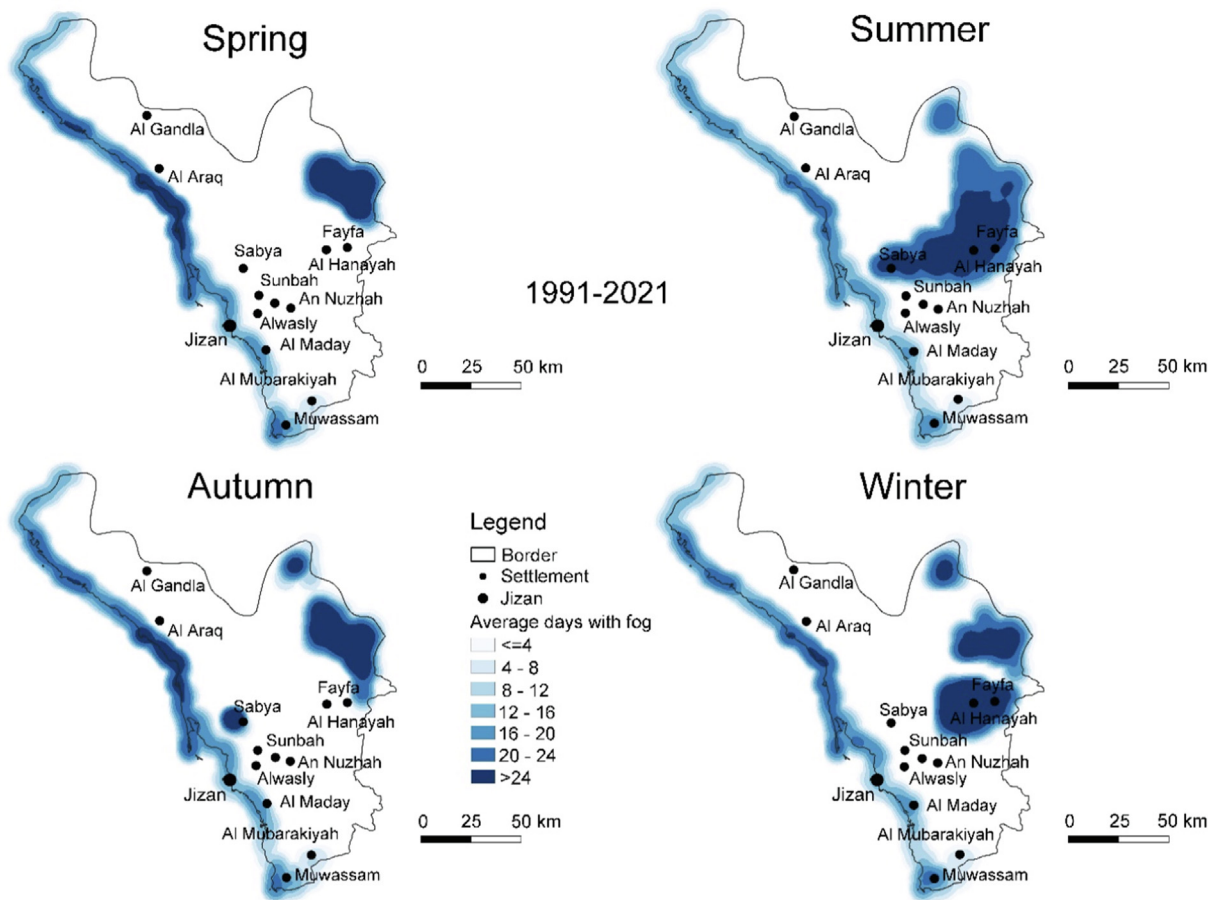


Fig. 7. Seasonal distribution of fog in Jizan region and potential for crops watering by palms, wheats and olives in the period between (1991–2021). In Spring season 4,800 ha and in Autumn 6,700 ha.

levels of heavy metals. Furthermore, new groundwater wells are very difficult to find.

The estimation of water from fog in the last twenty years showed that 8×10^{13} L from the Jizan region can be used. This water can be crucial in the watering of fruit and vegetables in drought periods. The yields of Barley, Millet, and Wheat can be watered with 55 mm of water produced from a fog throughout a year. The necessary minimum of water for these plants is 200 mm per year or 200 L. The plants such as apples, bananas, grapes, mangoes, papayas, plums, and citrus varieties must have a minimum of 600 m of water for growth throughout the year. 55 mm or 55 L can be crucial in the growing season, especially for the palms and grapes. The minimum of water collected from fog trough year according to the 20 years' analysis is 20 mm. The belts close to shorelines and hilly areas give satisfying results. The maximum is 110 mm. This kind of water with other water resources could be very important in the watering of plants or like drinkable water. Although the region of Jizan presents a small territory of Saudi Arabia, only 0.057 % of the fog occurrence is significant. The simulations in this research showed that when temperatures in Jizan rise above 35° and relative humidity is higher than 85 %, reaching its maximum to 100 %, hot fog can be expected during the day and a warm fog at night. The Jizan region also belongs to the part of the Arabian Peninsula coastal fog desert area. This belt has another name, it being Arabian coastal xeric scrub belt. This belt is with xeric scrub vegetation and the analysis included various species of vegetation. Vegetation progressively decreases away from the coast to the mainland. Even for Palm

(*Phoenix dactylifera*) it is necessary minimum of 700 mm of water, for olive (*Olea europaea*) is 200 mm and for wheat (*Triticum durum*) is 400 mm the additional water from fog is most useful for olives and palms in the growing period. The cutting of trees may reduce the possibility for dew collecting. Better agricultural management may be approved with future analysis of fog. The climate change effects may also be better monitored by the implementation of new terrestrial meteorological stations. This region has the potential for fog harvesting and can present one of the most important regions in the Kingdom of Saudi Arabia for fog analysis and crops watering. We are aware of the shortcomings and spatial errors of the satellite data from the period of thirty years ago, but the advantage is the display of historical movement of fog in this region. Thus, it demonstrates the economic justification of fog utilization in the region and potential of watering of presented crops. Agricultural sector in the KSA in future using the alternative water may survive and extend the food production. Ecological balance with rational use of water from the fog can't be broken. The utilization of water from fog in hilly areas may extend the growing period of plants and preserve plants in arid seasons.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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