# Rapid flood impact assessment on **water management infrastructure and agriculture in eastern Libya** in 2023

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# Abbreviations

| | |
|---|---|
| AfDB | African Development Bank |
| AICS | Italian Agency for Cooperation Development |
| AOI | area of interest |
| EMS | Emergency Management Services |
| EVI | Enhanced Vegetation Index |
| FAO | Food and Agriculture Organization of the United Nations |
| GAUL | Global Administrative Unit Layers |
| HDX | Humanitarian Data Exchange |
| IagWat | Evaluation of irrigation infrastructure, crop mapping and estimation of agricultural water use in Libya |
| KC | kappa coefficient |
| MerWat | Monitoring, evaluation and rationalization of water use for agriculture sector in Libya |
| NDVI | Normalized Difference Vegetation Index |
| NDWI | Normalized Difference Water Index |
| NICFI | Norway's International Climate and Forests Initiative |
| OA | overall accuracy |
| SAR | synthetic aperture radar |
| SEPAL | System for Earth Observation Data Access, Processing and Analysis for Land Monitoring |
| SHP | shapefile |
| TIFF | Tagged Image File Format |

# Executive summary

Between 6-15 September 2023, Libya faced a catastrophic flooding event, created by relentless storms and heavy rainfall. This crisis was further compounded by the collapse of two major dams, resulting in widespread devastation and a tragic loss of life. Preliminary assessments indicate that an estimated 2 000 individuals have lost their lives, while 10 000 people remain missing (ReliefWeb, 2023). The most affected area is the city of Derna, with the districts of Benghazi, Al-Jabal Al-Akhder, Al-Marj, Batah, Bayada, Albayda, Shahat, and Sousse also affected. These districts have suffered substantial damage to buildings, infrastructure, and the agricultural sector, underlining the urgent need for relief efforts and post-disaster management.

In October 2023, as laid out in this report, the Food and Agriculture Organization of the United Nations (FAO) carried out a rapid geospatial flood impact assessment in eastern Libya on infrastructure and farming community during September 2023, employing state-of-the-art technology and satellite data. It focused on six critical indicators:

1. the extent of annual water in dams and reservoirs;
2. the extent of flooding;
3. the land cover affected;
4. an assessment of population exposure to flood risks;
5. the extent of irrigated cropland; and
6. the exposure of farmers to flooded irrigated cropland.

This report provides results for the following:

- the flood extent;
- the exposed population;
- the exposure of farmers to flood;
- the land cover affected;
- the impacted agriculture infrastructure; and
- the sampling design for field data collection.

The results are provided as maps by administrative units (including a flood extent map using Sentinel-1 data at 10 m resolution (European Space Agency, 2023) and a land cover map using Sentinel-2 data for the year 2023 (European Space Agency, 2023), the national land cover reference system (Nwer *et al.*, 2023), and a tabular presentation with descriptive statistics for the various indicators mentioned previously. Recent advances in geospatial and information technologies will pave the way for updated land cover and crop-specific information adapted to the national conditions, with tailored field campaigns and the potential for better support response programmes and agricultural development in the future.

The results show that:

- Benghazi was the most affected district by flood (36 245 hectares [ha], or 2.7 percent of the total land area of Benghazi district);

- Derna was the most impacted district based on population exposure to the flooded area (9 789 people, or 6 percent of the total population in the district);

- Benghazi was the most affected area, based on farmer exposure to the flooded irrigated land (using hexagonal analysis);

- Benghazi district had the highest cultivated area (136 771 ha, or 9 percent of the total land area in the district);

- Two agricultural infrastructures were affected in Derna district (Wadi Abu Mansour Dam and Wadi Darna Dam); and

- The overall accuracy of the flood extent (83 percent) indicates a good agreement between the satellite-based flood map and ground-based observations.

The findings point towards the necessity of region-specific flood mitigation strategies that address both human and agricultural vulnerabilities, with a view to preserving food security and community livelihoods post-disaster.

# Background

The recent catastrophic flood in eastern Libya between 6-15 September 2023, caused by storm Daniel and further intensified by a tropical cyclone, has dealt a devastating blow to the region's agriculture. The inundation of fields with water has resulted in widespread crop losses, particularly affecting staples like cereals and vegetables. The force of the floodwaters has led to soil erosion, compromising the structural integrity of agricultural lands and reducing their fertility. Moreover, critical agricultural infrastructure – including irrigation systems and storage facilities – has been severely damaged, crippling the ability of farmers to resume normal operations. Livestock losses have also been significant, further exacerbating the economic strain on local farming communities. The disruption of planting schedules and limited access to fields due to damaged roads and bridges will likely have enduring repercussions on the agricultural sector. As a result, the affected areas are facing a profound challenge in rebuilding their agricultural capacity, with long-term implications for food security and the livelihoods of local farmers.

Initial reports indicate that roughly 25 percent of Derna city has been destroyed. Among the most severely affected districts are Al-Akhder, Al-Marj, Albayda, Batah, Bayada, Benghazi, Shahat, and Sousse (ReliefWeb, 2023). The extensive flooding, exacerbated by the failing dams, inundated vast regions of cropland, rendering them temporarily or permanently unusable. This agricultural damage poses a severe threat to food security and sustainable agricultural practices in these regions. Immediate relief and recovery efforts are crucial to mitigating the long-term impacts on the livelihoods of those dependent on agriculture.

The Food and Agriculture Organization of the United Nations (FAO) is providing continued support to the countries to deal with disaster management and mitigation. Various impact assessments have already been conducted by FAO in several countries, including Madagascar, Malawi, Mozambique, Pakistan, Zambia, Zimbabwe, and others (**Mushtaq**, **F**. *et.al.,* 2022a, 2022b, 2022c). A rapid geospatial assessment was conducted by FAO in close collaboration with national counterparts to deliver a comprehensive and spatially-explicit geospatial analysis delineating the extensive ramifications of the flood in eastern Libya. The analysis encompasses various key indicators including the impact on dams and reservoirs, flood extent,[1] exposed population to floods,[2] exposure of irrigated cropland due to flooding,[3] and affected land cover.

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[1] The total land area which is inundated by water.

[2] The number of persons exposed or living close to the flooded areas by district.

[3] Any submerged crop area that has been inundated by water.

Figure 1. Methodological diagram for the flood impact assessment in Libya
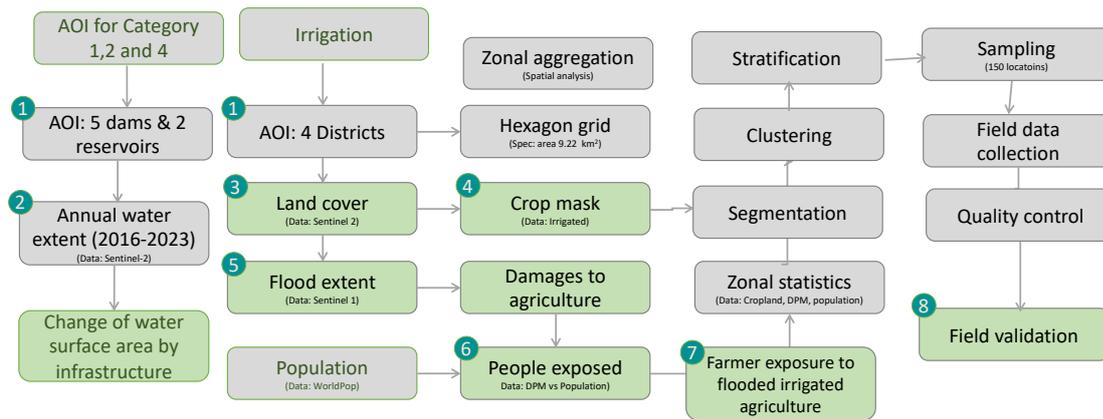
Source: Authors' own elaboration.

## Methodological approach

The presented schema in Figure 1 outlines a methodological approach for the rapid geospatial impact assessment of flooding for eastern Libya. The approach is systematic and relies on geospatial techniques to assess the impact of flooding on agricultural areas and local communities. The details for each of the eight steps in the methodological diagram are explained in the following sections.

### Step 1: Selection of area of interest (AOI)

The selection of the area of interest (AOI) was based on the flood extent map derived from the Copernicus EMS Rapid Mapping platform (Copernicus EMS, 2023) For the administrative boundary layer, different sources were compared, including the dataset from the Global Administrative Areas (GADM) database (GADM, 2023) and the Humanitarian Data Exchange (HDX) (HDX, 2023). The Humanitarian Data Exchange administrative boundary layer was selected as the data source for the assessment, providing updated and better detailed administrative information (HDX, 2023). Table 1 shows the selected districts for this assessment.

### Step 2: Mapping annual surface water extent (2016–2023) to assess the impact on dams and reservoirs

The annual assessment of surface water extent was conducted on five dams and two water reservoirs from 2016 to 2023. The Normalized Difference Water Index (NDWI) was computed utilizing Sentinel-2 multispectral imagery (Gao, 1996). By applying a threshold of 0, a binary water mask was generated. and then superimposed onto corresponding Sentinel-2 imagery, facilitating the extraction of surface water extent for each year within the specified timeframe. Validation procedures included the utilization of ground truth data and visual inspection to ensure the accuracy and reliability of the results.

### Step 3: Preparation of land cover map

The land cover legend was derived from the Libyan Land Cover Reference System (Nwer *et al.*, 2023). A land cover map was prepared at the subnational level using Sentinel-2 (10 m resolution) data, with training data from a high-resolution base map. A Normalized Difference Vegetation Index (NDVI) mask

for the entirety of 2022 was used to delineate the cultivated area. Around 300 training data were used to train the random forest model in SEPAL to generate the land cover dataset. The land cover map defined seven different classes: Water (W), Tree-dominated areas (Tt), Herbaceous-dominated areas (Har), Cultivated/managed vegetation (Vc), Artificial surfaces (Ast), Bare soil (Bs) and Shrub-dominated areas (St).

**Step 4: Preparation of cropland map**

The cropland map was prepared using Landsat 5-8 (30 m resolution) and Sentinel-2 satellite data from 2010 to 2022. The mean annual composite of NDVI and the Enhanced Vegetation Index (EVI) was considered for this process.

**Step 5: Derivation of flood extent map**

The flood extent was calculated utilizing a change detection algorithm applied to Sentinel-1 synthetic aperture radar (SAR) data at 10 m resolution. The dates chosen for image acquisition before and after the event were 13 June 2023 to 29 July 2023 (dry period), and 6-13 September 2023 (wet period). Preprocessing steps such as radiometric calibration, terrain correction, speckle filtering, multi-looking, and geocoding enhance data quality were used. A change detection approach was used to identify the inundated areas. The SAR image acquired during the wet season was subtracted from the image captured during the dry season to produce the change map and a flood mask was extracted from the change image.

**Step 6: Assessment of population exposure**

Population exposure was estimated using the flood extent map and Worldpop population data (Worldpop, 2020). The flood mask layer was overlaid on the population layer to estimate the exposure as an amount of per capita on flood-affected areas. The district boundary was further divided into hexagons with an area of 10 km$^2$ to assess the impact at high granularity. The percentage of the population exposed to flood for each hexagon was calculated using the total population of the area being assessed.

It is important to note that these estimations all depend on the quality and the accuracy of the open datasets used. The actual number of people affected by the flood may vary depending on various factors, including the accuracy of the data, the intensity of the flood, and the specific characteristics of the affected population.

*Table 1. Selected districts for the flood impact assessment in Libya, 2023*

| ID | District | Total land area (ha) |
|---|---|---|
| 1 | Benghazi | 1 533 382 |
| 2 | Al Marj | 1 006 639 |
| 3 | Al Jabal Al Akhdar | 853 384 |
| 4 | Derna | 1 850 177 |
| Total land area (ha) | | 5 243 583 |

Note: Refer to the disclaimer on page ii for the names and boundaries used in this map.
Sources: Administrative boundaries from **HDX (Humanitarian Data Exchange).** 2023. Libya Data Grid. Libya – Subnational Administrative Boundaries. [Accessed on 23 April 2023]. https://data.humdata.org/dataset/cod-ab-lby. License: CC-BY-IGO.

**Step 7: Exposure of farmers to flooded irrigated cropland**

Irrigated cropland classes were extracted from the developed land cover map. Pixels of irrigated cropland classes were aggregated by hexagons using mean reduction. Each input pixel was converted to a "hex coordinate" and a unique ID was then computed. The irrigated cropland mask and damage proxy map was then overlaid to map the farmers' exposure to flood, and Humanitarian Data Exchange boundaries (HDX, 2023) were used to extract the statistics at the district levels.

**Step 8: Field validation for flood mapping**

A total of 150 sample points were collected from a field survey in December 2023, gathering from both flooded and non-flooded areas across eastern Libya. Based on the comparison between the flood map predictions and the ground truth, an error matrix was then constructed. This matrix included metrics such as true positive (TP), false negative (FN), false positive (FP), and true negative (TN), which then formed the basis for subsequent accuracy assessments. Overall accuracy (OA) and the kappa coefficient (KC) were calculated using the error matrix. Overall accuracy provided a general assessment of the flood map's correctness, while KC accounted for chance agreement, offering a more nuanced evaluation of classification performance.

# Results

## Result 1: Area of interest (AOI)

As mentioned in the methodology section, the AOI was identified using the Copernicus EMS Rapid Mapping platform (Copernicus EMS, 2023). The four districts selected for the assessment had a total land area of 5 243 583 ha (3 percent of the total land area in Libya), as well as five dams and two agricultural reservoirs (Figure 2). The details of the identified agricultural infrastructure with their locations can be found in Table 2. For the analysis, HDX administrative boundaries were used (HDX, 2023). To validate the identification of correct districts, the mean rainfall for all four districts was calculated using gridded data from CHIRPS (Climate Hazards Center, 2024). The results showed that the mean rainfall in September 2023 was two to three times higher than the historical average (Figure 3).

*Figure 2. Area of interest at district level in eastern Libya*
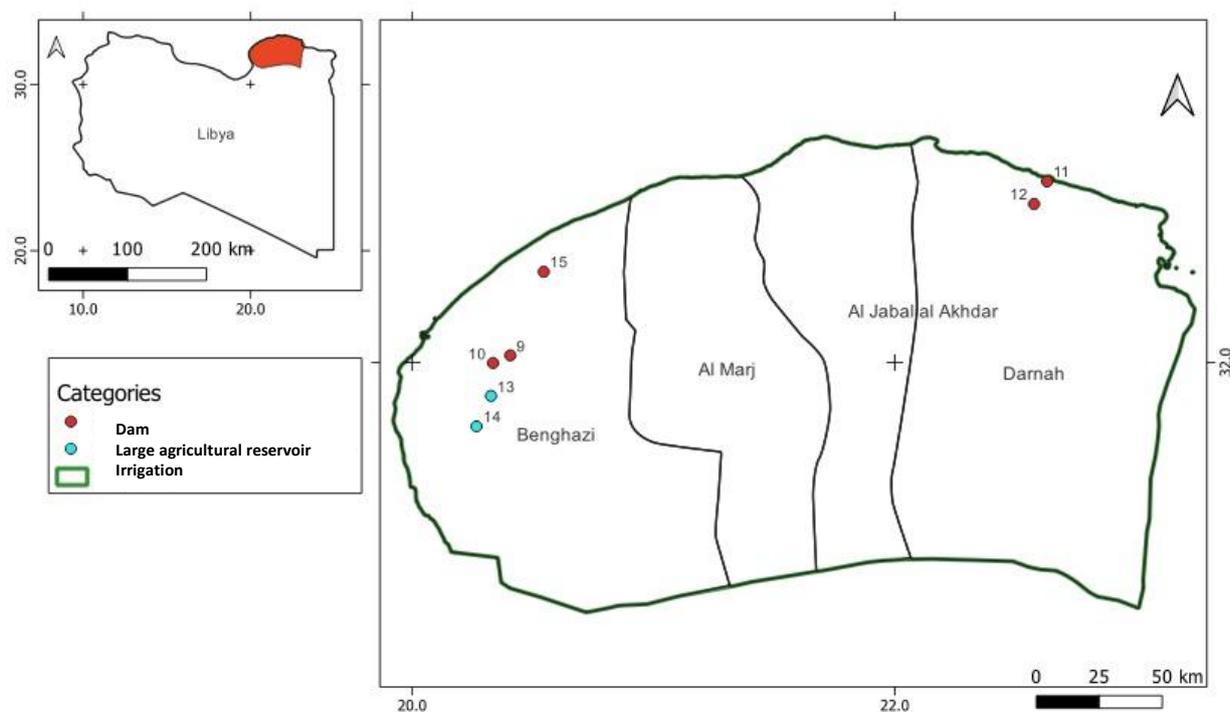


Note: Refer to the disclaimer on page ii for the names and boundaries used in this map.
Source: Administrative boundaries from **HDX**. 2023. Libya Data Grid. Libya – Subnational Administrative Boundaries. [Accessed on 23 April 2023]. https://data.humdata.org/dataset/cod-ab-lby. License: CC-BY-IGO.

*Table 2. Location of identified dams and large agricultural reservoir at district level in eastern Libya*

| District | Infrastructure name | Type | Latitude | Longitude | Code |
|----------|--------------------|------|----------|-----------|------|
| Benghazi | Wadi Quattara Dam | Dam | 32.02 | 20.4 | 9 |
| Benghazi | Supplementary Wadi Quattara Dam | Dam | 32.02 | 20.4 | 10 |
| Derna | Wadi Abu Mansour Dam | Dam | 32.84 | 22.21 | 11 |
| Derna | Wadi Darna (Alblad) Dam | Dam | 32.75 | 22.63 | 12 |
| Benghazi | Omar Mukhtar Reservoir | Large agricultural reservoir | 31.73 | 20.26 | 13 |
| Benghazi | The Grand Omar Mukhtar Reservoir | Large agricultural reservoir | 31.85 | 20.32 | 14 |
| Benghazi | Wadi Zaza Dam | Dam | 32.37 | 20.54 | 15 |

*Figure 3. Comparison of September mean precipitation (1981–2023)*
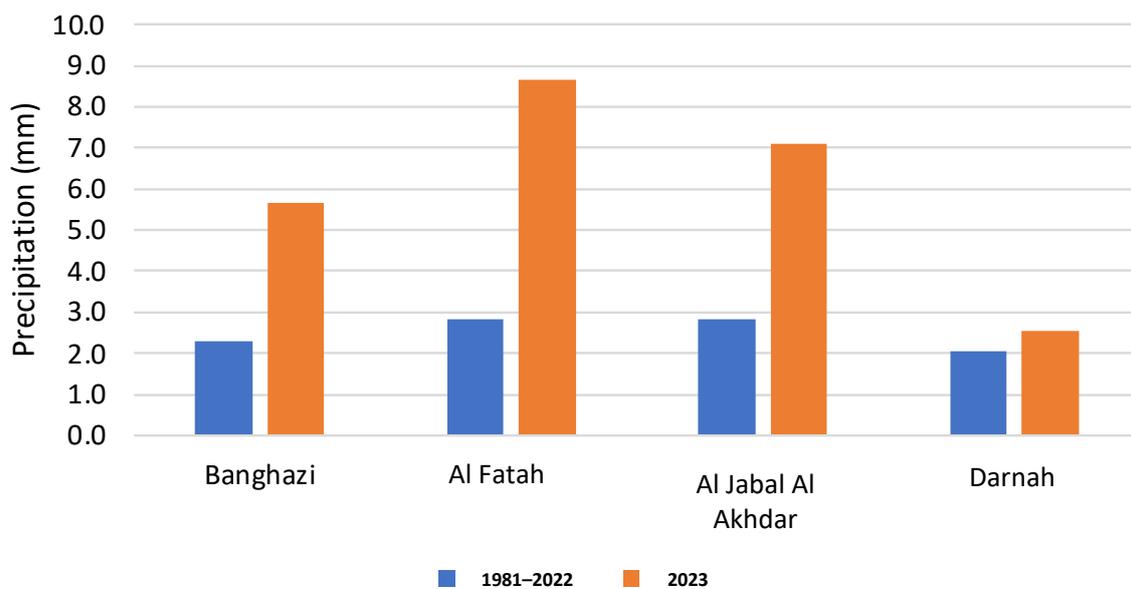


Source: **Climate Hazards Center.** 2023. Climate Hazards center InfraRed Precipitation with Station data (CHIRPS). [Accessed on 3 April 2024]. https://www.chc.ucsb.edu/data. License: CC-BY-4.0.

## Result 2: Impact on dams and reservoirs

The flooding significantly impacted the dams and reservoirs in the four districts. Figure 4 shows the images and locations of the five dams and two agriculture reservoirs. Results indicated that during the flooding event (September 2023), the surface water extent in the Wadi Abu Mansour and Wadi Darna dams in Derna district was much higher than usual, about two to four times greater than the historical mean of the last six years (Figure 5, Figure 6 and Figure 7). However, no major changes were observed in the surface water extent in the three dams and two agriculture reservoirs in the Benghazi district.

Figure 8 shows the annual surface water change in the two Benghazi reservoirs (Omar Mukhtar Reservoir and The Grand Omar Mukhtar Reservoir).

*Figure 4. Location of dams and reservoirs in the area of interest at district level in eastern Libya*
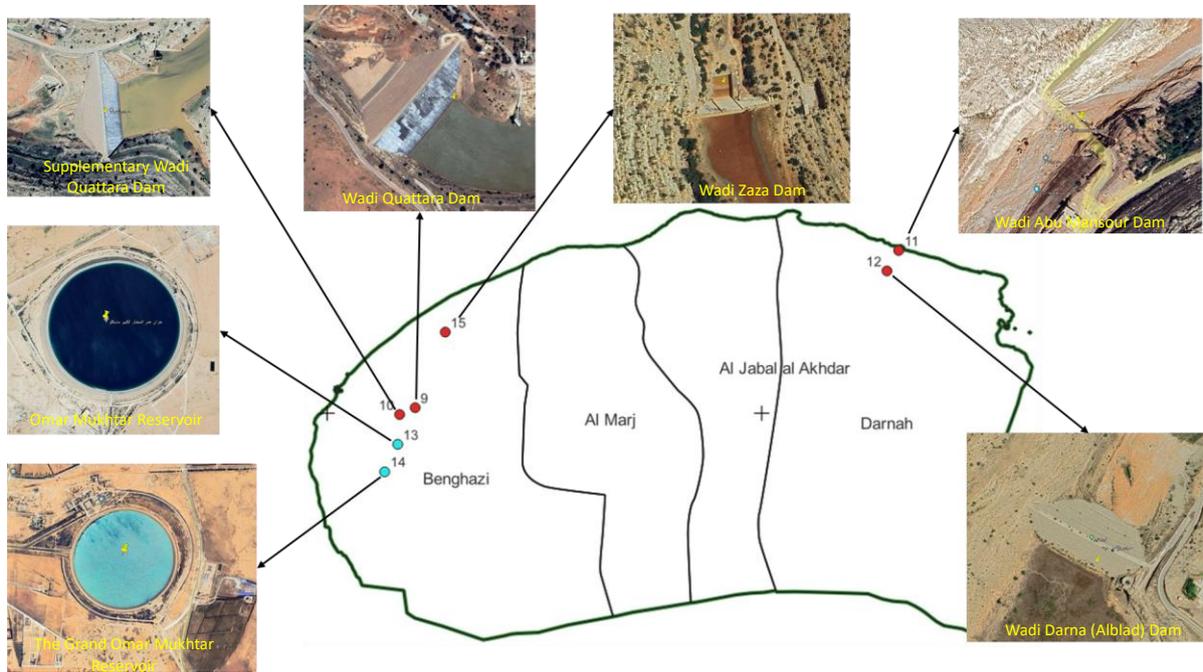


Note: Refer to the disclaimer on page ii for the names and boundaries used in this map.
Source: Administrative boundaries from **HDX**. 2023. Libya Data Grid. Libya – Subnational Administrative Boundaries. [Accessed on 23 April 2023]. https://data.humdata.org/dataset/cod-ab-lby. License: CC BY-IGO.

Images taken from **Google Earth**. 2024. Satellite imagery of Libya. In: *Google Earth*. Mountain View, USA. [Cited 24 September 2023]. https://earth.google.com.

*Figure 5. Annual surface water change in Wadi Ouattara Dam, Benghazi, eastern Libya*
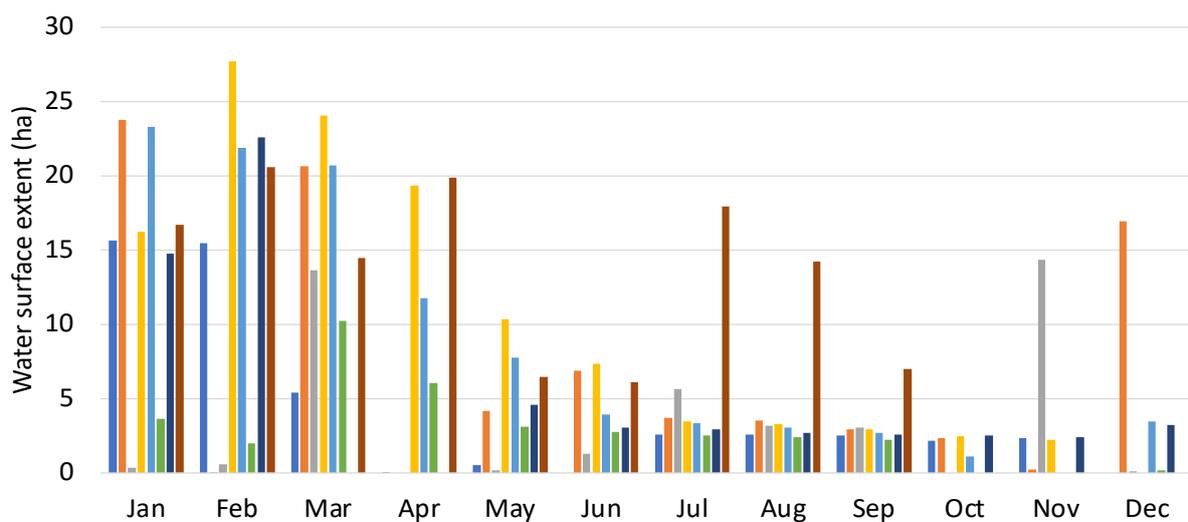


Source: Author's own elaboration.

*Figure 6. Annual surface water change in Supplementary Wadi Ouattara Dam in Benghazi, eastern Libya*
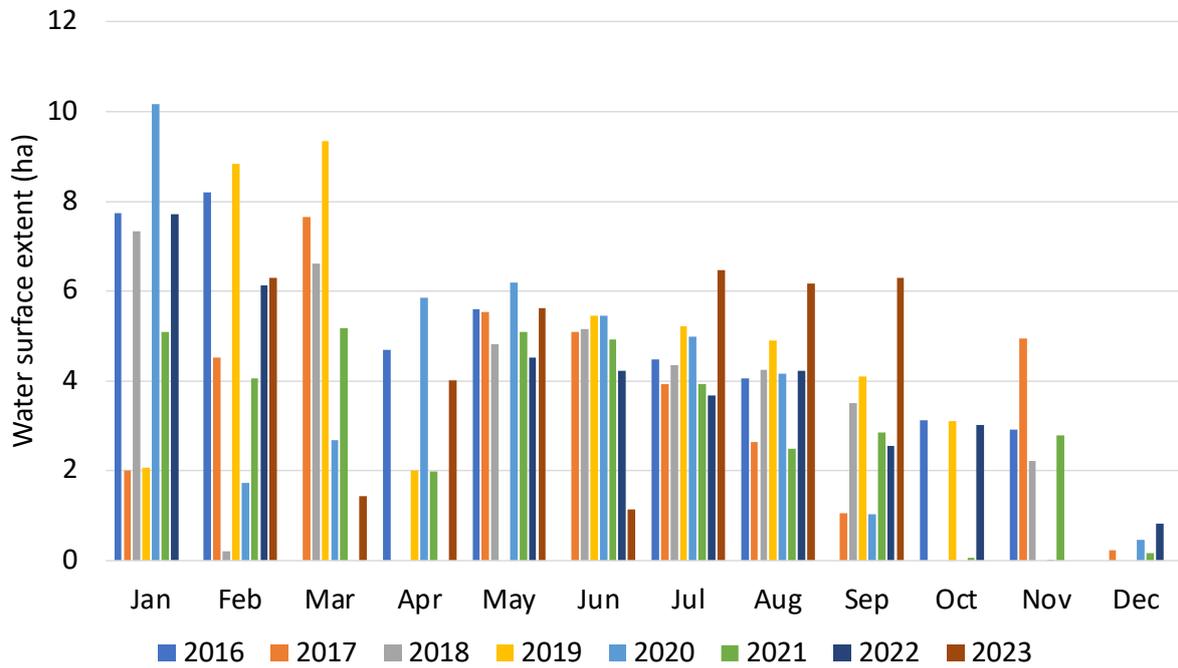


Source: Author's own elaboration.

*Figure 7. Annual surface water change in Wadi Zaza Dam, Benghazi, eastern Libya*
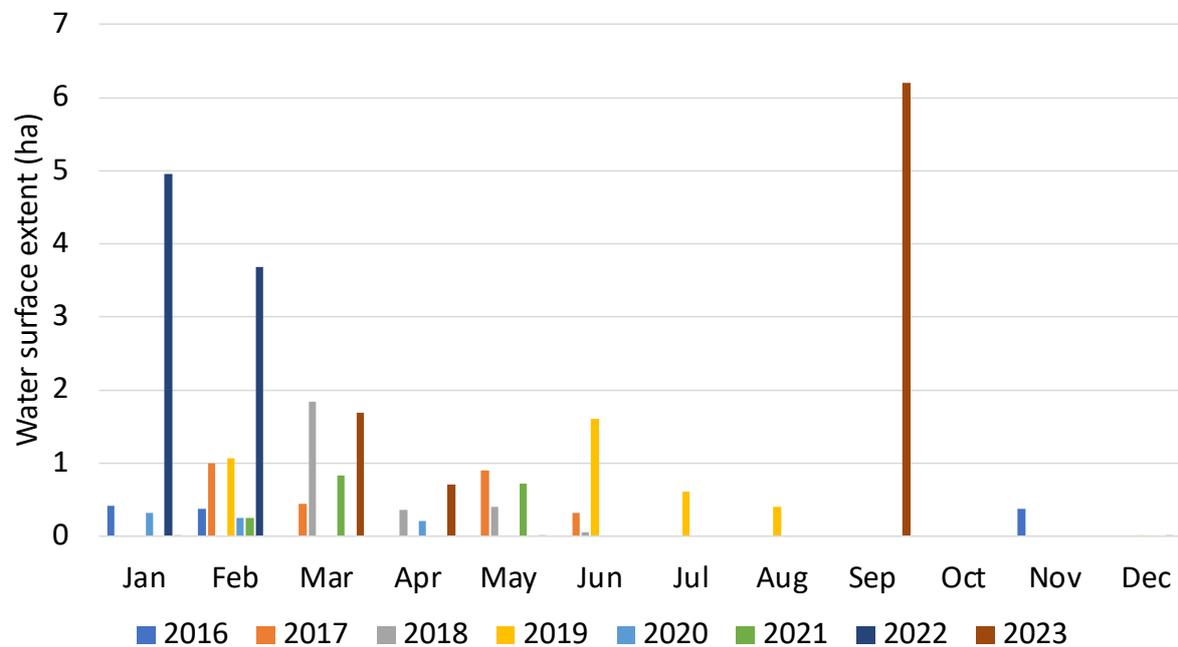


Source: Author's own elaboration.

*Figure 8. Annual surface water change in two reservoirs in the area of interest in eastern Libya*
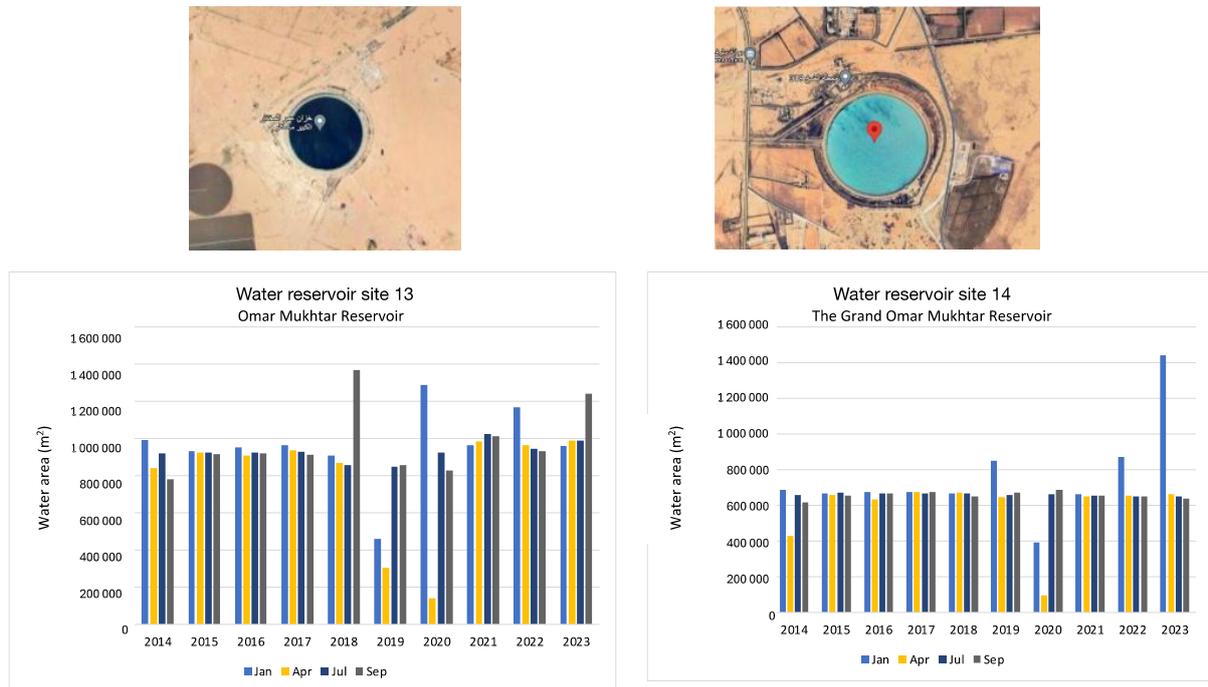


Note: Images taken from **Google Earth**. 2024. Satellite imagery of Libya. In: *Google Earth*. Mountain View, USA. [Cited 24 September 2023]. https://earth.google.com

## Result 3: Land cover map

The land cover mapping was carried out for the districts of Al Jabal Al Akhdar, Al Marj, Benghazi and Derna, with a total cover of 5 243 583 ha (Figure 9). Shrub-dominated areas, bare soil (Bs), and cultivated irrigated areas were the predominant classes (Table 3). Shrub-dominated areas extended across 4 133 407 ha, with Derna having the highest amount, at 1 534 413 ha (82.92 percent of total land area of Derna).

*Table 3. Land cover class area (ha) in the area of interest at district level in eastern Libya*

| Land cover class (ha) | Benghazi | Al Marj | Al Jabal Al Akhdar | Derna | Total area of class |
|---|---|---|---|---|---|
| Water | 2 956 | 199 | 501 | 1 129 | 4 785 |
| Tree-dominated areas | 17 626 | 21 054 | 38 304 | 8 248 | 85 233 |
| Herbaceous-dominated areas | 2 | 0 | 11 | 41 | 54 |
| Cultivated/managed vegetation areas | 136 771 | 53 588 | 22 023 | 9 886 | 222 267 |
| Artificial surfaces | 56 850 | 3 794 | 17 015 | 7 926 | 85 585 |
| Bare soil | 152 402 | 1 47 007 | 124 309 | 288 534 | 712 252 |
| Shrub-dominated areas | 1 166 776 | 7 80 997 | 651 221 | 1 534 413 | 4 133 407 |
| **Total area of district (ha)** | **1 533 382** | **1 006 639** | **853 384** | **1 850 177** | **5 243 583** |

*Figure 9. Land cover map of eastern Libya (2022)*
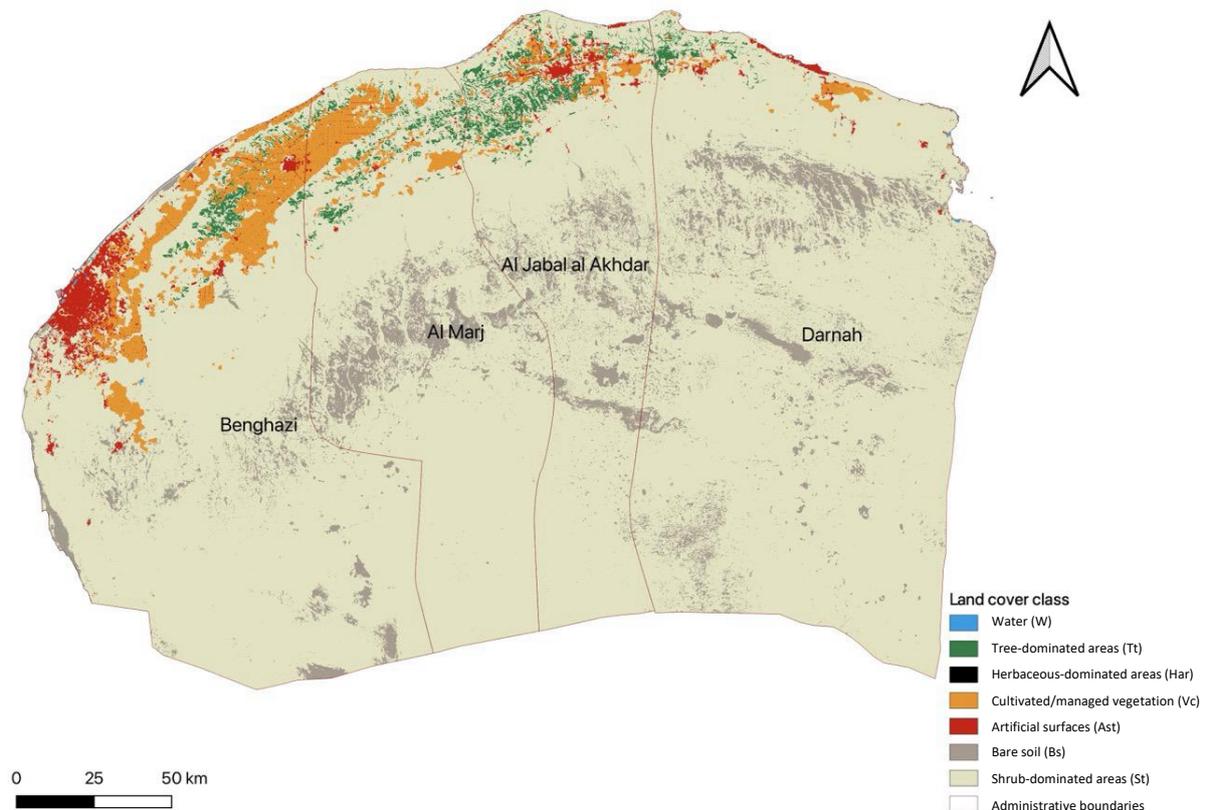


Note: Refer to the disclaimer on page ii for the names and boundaries used in this map.
Source: Administrative boundaries from **HDX**. 2023. Libya Data Grid. Libya − Subnational Administrative Boundaries. [Accessed on 23 April 2023]. https://data.humdata.org/dataset/cod-ab-lby. License: CC-BY-IGO.

Bare soil was the second most extensive land cover class, covering 712 252 ha, with Derna again having the highest amount, at 288 534 ha (15.59 percent of total land area of Derna). Cultivated irrigated areas were also prominent, covering 222 267 ha, with the largest proportion in Benghazi at 136 771 ha (8.92 percent of the total land area in the Benghazi district).

## Result 4: Flood extent map

The assessment of flooded areas (masked by permanent water bodies) in eastern Libya revealed significant inundation, as shown in Figure 10a. The hexagonal area was classified into three flood categories to delineate the flood extent (Figure 10b). The categories are as follows:

1. **High flooded area** (>2 km²): Hexagons falling under this class represent regions with a substantial extent of flooded areas, indicating a significant risk of flooding events impacting a large land area.

2. **Medium flooded area** (0.5–2 km²): This class encompasses hexagons where the flooded area is moderate, suggesting a mid-level risk of flooding that could affect a moderately sized region.

3. **Low flooded area** (<0.5 km²): Hexagons in this class denote areas with a relatively small extent of flooded land, indicating a lower risk of flooding events affecting a small land area.

*Figure 10. Flood extent map (a) and map showing flood extent aggregated in hexagons (b) in eastern Libya, 7 September 2023*

Note: Refer to the disclaimer on page ii for the names and boundaries used in this map.
Source: Administrative boundaries from **HDX.** 2023. Libya Data Grid. Libya – Subnational Administrative Boundaries. [Accessed on 23 April 2023]. https://data.humdata.org/dataset/cod-ab-lby. License: CC-BY-IGO.

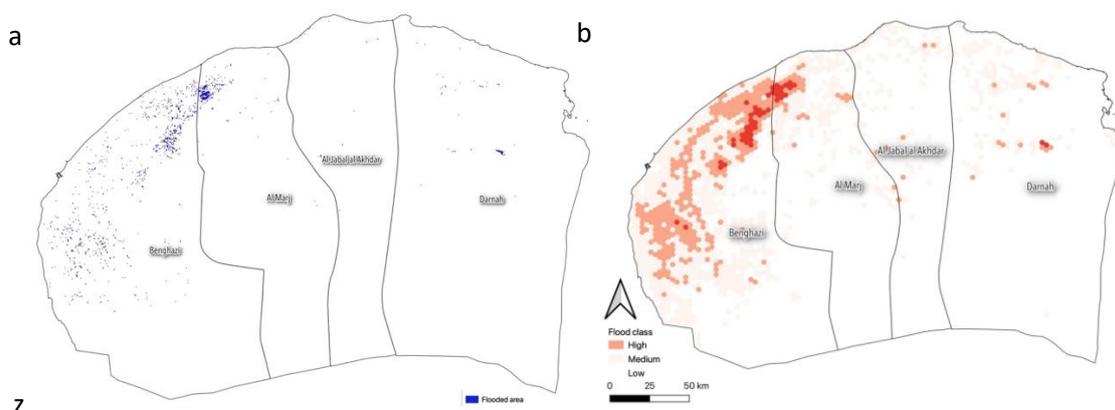The results showed that the total flooded area in the four districts was 79 400 ha (1.5 percent of the total land area of 5 243 582 ha in the four districts). Among the identified flood-prone areas, Benghazi emerged as the most severely-affected district (2.7 percent of the district area was inundated). Table 4 shows the total flooded areas and flooded area percentage in the four districts.

*Table 4. Flooded areas (ha) distribution in the area of interest in eastern Libya*

| District | Total land area (ha) | Total flooded area (ha) | Flooded area (%) |
|---|---|---|---|
| Benghazi | 1 533 382 | 36 245 | 2.7 |
| Derna | 1 850 177 | 23 664 | 1.3 |
| Al Marj | 1 006 639 | 12 046 | 1.2 |
| Al Jabal al Akhdar | 853 384 | 7 445 | 0.6 |
| **Total** | **5 243 582** | **79 400** | **1.5** |

## Result 5: Exposure of people

In this assessment, it was assumed that the more people were surrounded by flood-impacted areas, the greater their vulnerability. The results showed that a total of 48 079 people had been exposed to floods (4 percent of the total population in the four districts). Benghazi was the most impacted district based on the exposure of people to floods (23 255 people), compared to the other districts (Al Marj [11 015 people], Derna [9 789 people], and Al Jabal Al Akhdar [4 020 people]).

Figure 11 presents a flood risk assessment for northeastern Libya, focusing on regions such as Benghazi, Al Marj, Al Jabal Al Akhdar, and Darnah. The level of flood risk in each area is determined by a combination of two factors: population density and the extent of flooded areas. The colour gradient on the map, ranging from green to red, represents different levels of risk. Green areas indicate a lower flood risk, generally found in zones with low population density and limited flooding. In contrast, red areas signify a higher flood risk, typically where both population density and flooding are substantial.

In the bottom-left corner, a matrix legend provides more detail on the risk levels. The vertical y axis represents the extent of flooded area (low to high), while the horizontal x axis represents population density (low to high). This matrix helps clarify that high-risk zones (indicated by dark red) are areas where both population density and flooded area are high, whereas low-risk zones (shown in green) have lower values for both factors. Geographically, the map shows that Benghazi and parts of Al Jabal Al Akhdar are among the highest-risk areas, with dark red areas indicating dense populations exposed to significant flooding. On the other hand, Darnah and Al Marj mostly display lower risk levels, with greener and lighter-coloured hexagons, suggesting these areas are less affected by flooding or have lower population densities. Table 5 represents the percentage of the population exposed to flood at the district level, (calculated using the total population of the area being assessed). The map in Figure 11 illustrates the percentage of the population exposed to floods. Different levels of exposure are indicated by differences in colour. Figure 12 illustrates hexagons with nine different classes delineating the exposure of the population to flooding in eastern Libya by combining criteria related to the extent of flooded areas and population density.

*Figure 11. Exposure of people during flood in eastern Libya, 2023*
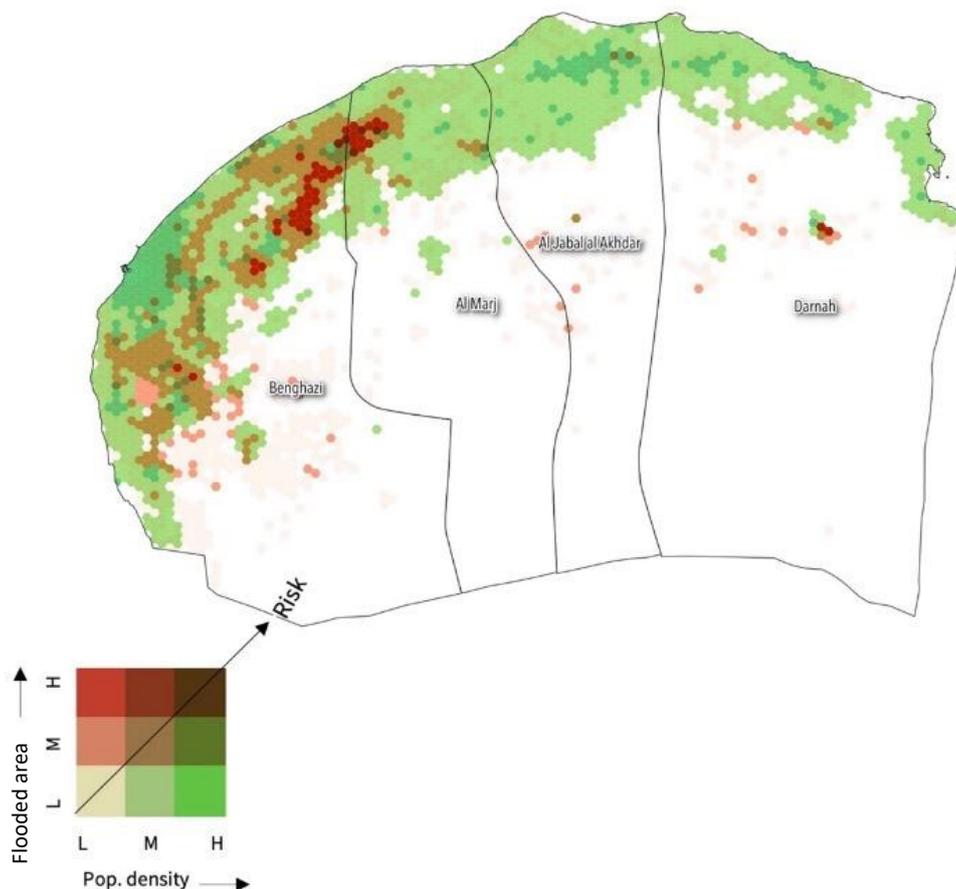


Note: Refer to the disclaimer on page ii for the names and boundaries used in this map. In the matrix legend, the x-axis represents population density (from low to high), and the y-axis represents the extent of flooded areas (also from low to high). High-risk zones, shown in dark shades, reflect areas where both factors are high, indicating regions with both high population density and significant flood exposure. Conversely, low-risk zones, in light green, indicate areas with low values for both factors, where population density and flood exposure are minimal.
Source: Administrative boundaries from **HDX.** 2023. Libya Data Grid. Libya – Subnational Administrative Boundaries. [Accessed on 23 April 2023]. https://data.humdata.org/dataset/cod-ab-lby. License: CC-BY-IGO.

*Table 5. Exposure of people to floods by districts in eastern Libya*

| District | Total area (ha) | Population (2020) | Affected population | Affected population (%) |
|---|---|---|---|---|
| Benghazi | 1 533 382 | 670 797 | 23 255 | 6 |
| Al Marj | 1 006 639 | 185 848 | 11 015 | 4 |
| Derna | 1 850 177 | 163 351 | 9 789 | 6 |
| Al Jabal Al Akhdar | 853 384 | 203 156 | 4 020 | 2 |
| Total | 5 243 582 | 1 223 152 | 48 079 | 4 |

The nine classes were derived from different combinations of the three classes, using the extent of flooded area and population density. These nine classes are as follows:

1. **High flooded area and high population density**: Hexagons in this class represent regions with a substantial extent of flooded areas (>2 km²) and a high population density (>500 people per km²). These areas face a significant risk of flooding, impacting a large land area and a densely-populated community.

2. **High flooded area and medium population density**: Hexagons in this class denote regions with a substantial extent of flooded areas (>2 km²) and moderate population density (200–500 people per km²). These areas face a significant risk of flooding, but with a relatively lower population density compared to the first class.

3. **High flooded area and low population density**: This class includes hexagons with a substantial extent of flooded areas (>2 km²) and a low population density (<200 people per km²). While these areas have a significant risk of flooding, the impact on the population is less severe due to lower population density.

4. **Medium flooded area and high population density**: Hexagons falling into this class represent regions with a moderate extent of flooded areas (0.5–2 km²) and a high population density (>500 people per km²). These areas face a mid-level risk of flooding, but due to densely populated communities, the impact is still considerable.

5. **Medium flooded area and medium population density**: Hexagons in this class denote regions with a moderate extent of flooded areas (0.5–2 km²) and a moderate population density (200–500 people per km²). These areas face a mid-level risk of flooding with a moderate impact on the population.

6. **Medium flooded area and low population density**: This class includes hexagons with a moderate extent of flooded areas (0.5–2 km²) and a low population density (<200 people per km²). The risk of flooding is moderate, and the impact on the population is lower due to the sparse population.

7. **Low flooded area and high population density**: Hexagons falling into this class represent regions with a small extent of flooded areas (<0.5 km²) and a high population density (>500 people per km²). While the risk of flooding is lower, the impact on the densely populated community is still noteworthy.

8. **Low flooded area and medium population density**: Hexagons in this class denote regions with a small extent of flooded areas (<0.5 km²) and a moderate population density (200–500 people per km²). These areas face a lower risk of flooding, with a moderate impact on the population.

9. **Low flooded area and low population density**: This class includes hexagons with a small extent of flooded areas (<0.5 km²) and a low population density (<200 people per km²). These areas have a lower risk of flooding, and the impact on the population is minimal due to the sparse population.

## Result 6: Extent of irrigated cropland

The extent of irrigated cropland plays an important role when assessing the impact of flooding in agriculture. The results showed that the total irrigated area of the AOI was 222 267 ha (4.2 percent of the total land area of the four districts). The spatial distribution of irrigated cropland is shown in Figure 12. Benghazi had the highest irrigated cropland (1 368 ha) followed by Al Marj, with 536 ha of irrigated cropland. Figure 13 shows that Derna and Al Jabal Al Akhdar had minimal areas under irrigation, which could suggest a lower potential impact of floods on agricultural lands.

*Figure 12. Irrigated land area extent (a) and proportion (b) in eastern Libya*
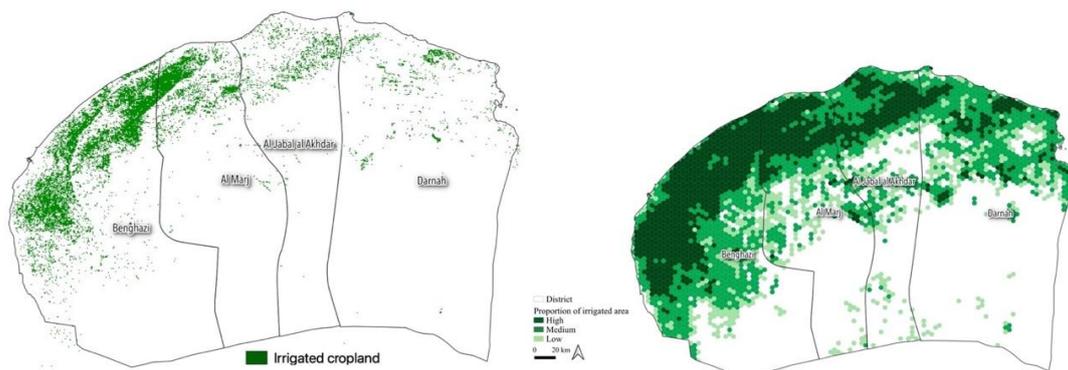


Note: Refer to the disclaimer on page ii for the names and boundaries used in this map.
Source: Administrative boundaries from **HDX**. 2023. Libya Data Grid. Libya – Subnational Administrative Boundaries. [Accessed on 23 April 2023]. https://data.humdata.org/dataset/cod-ab-lby. License: CC-BY-IGO.

*Figure 13. Irrigated land area in eastern Libya*
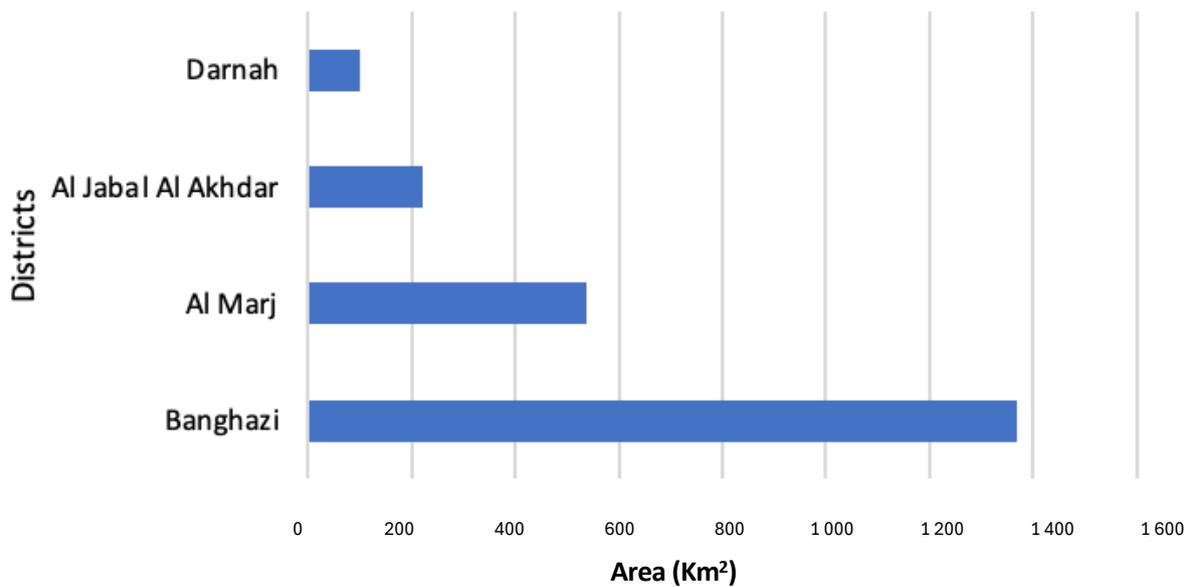
## Result 7: Exposure of irrigated cropland

In this assessment, the potentially impacted irrigated cropland areas were identified by overlaying the flood extent map over the irrigated cropland map. The findings suggest that Benghazi and Al Marj districts had a higher overall exposure of irrigated cropland compared to Al Jabal Al Akhdar and Derna. Figure 14 shows the hexagons with varying levels of exposure of irrigated cropland. In this analysis, the four districts were further subdivided into 10 km$^2$ hexagons. These hexagons are classified into nine distinct categories based on the extent of flooded areas and irrigated cropland. These classes were derived from the combination of two key criteria provided in Table 6. The damage classes and the irrigated cropland classes both included low, medium, and high. Table 6 illustrates the different degrees of affected area, based on the cropland area (km$^2$) and the population density (km$^2$). The colour scheme, which ranges from light green to darker shades, represents different levels of flood risk based on these two factors. The lighter green areas indicate a lower risk, typically where there is either limited irrigated cropland or lower population density, while darker shades signify higher flood risk, often found in areas with both extensive cropland and higher population density. Geographically, the map highlights Benghazi and the western part of Al Jabal Al Akhdar as regions with higher flood risk, likely due to the concentration of irrigated cropland in densely populated areas.

*Table 6. Classification degree of irrigated land area*

| Classification degree | High | Medium | Low |
|---|---|---|---|
| Cropland area (km$^2$) | >2 | 0.5–2 | <0.5 |
| Population density (number of people/km$^2$) | >500 | 200–500 | <200 |

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*Figure 14. Exposure of irrigated cropland*
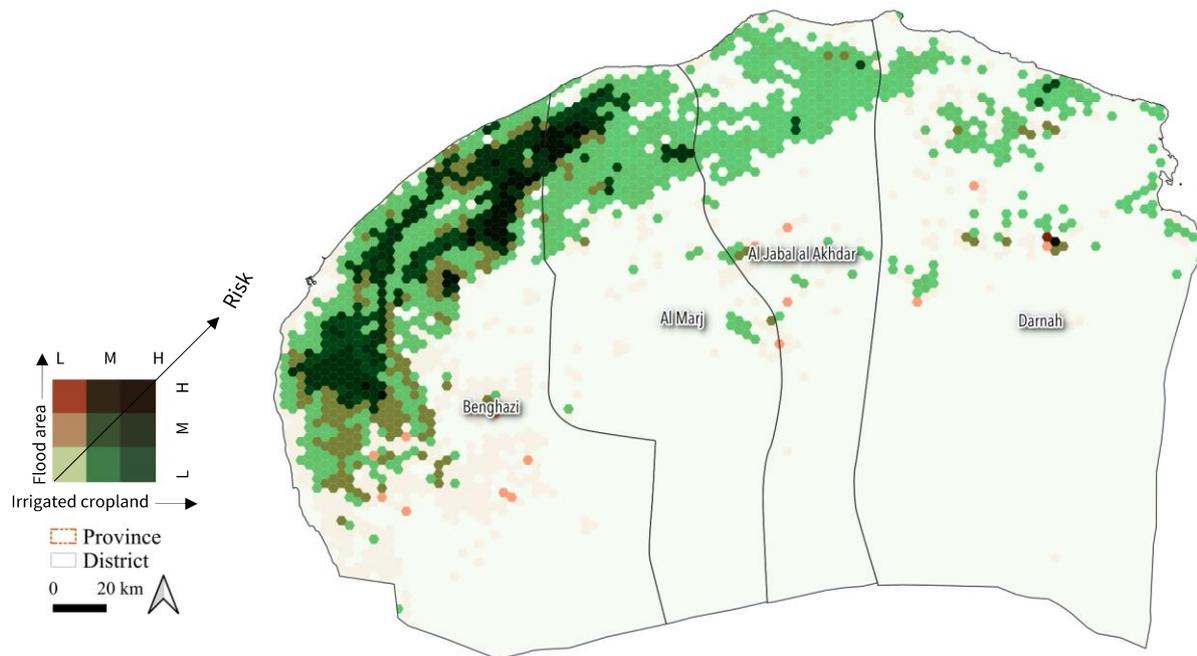


Note: Refer to the disclaimer on page ii for the names and boundaries used in this map. In the matrix legend, the x-axis represents the extent of exposure to irrigated cropland (from low to high), and the y-axis represents flood-prone areas (also from low to high). High-risk zones, shown in dark shades, indicate areas where both flood exposure and proximity to irrigated cropland are high. In contrast, low-risk zones, depicted in light green, reflect low values for both factors.
Source: Administrative boundaries from **HDX**. 2023. Libya Data Grid. Libya – Subnational Administrative Boundaries. [Accessed on 23 April 2023]. https://data.humdata.org/dataset/cod-ab-lby. License: CC-BY-IGO.

The nine classes (Table 7) are as follows:

1. **High cropland area and high population density:** Hexagons falling into this class indicate areas with extensive irrigated cropland (greater than 2 km$^2$) and a high population density (exceeding 500 people per km$^2$). These regions are particularly vulnerable to flooding, posing challenges for both agricultural assets and densely populated communities.

2. **High cropland area and medium population density:** This class represents hexagons with large cropland areas (>2 km$^2$) but with a moderate population density (200–500 people per km$^2$). While the risk of flood impact on agriculture is high, the population density is somewhat less, potentially easing the burden on emergency response and evacuation efforts.

3. **High cropland area and low population density:** Hexagons falling into this category have extensive irrigated cropland (greater than 2 km$^2$) but low population density (less than 200 people per km$^2$). These areas might experience significant agricultural damage during flooding, but the impact on human settlements may be relatively lower.

4. **Medium cropland area and high population density:** This class includes hexagons with moderate cropland areas (0.5–2 km$^2$) and high population density (>500 people per km$^2$). The combination suggests areas where flooding can affect both agricultural activities and densely populated communities, demanding a coordinated response.

Table 7. Number of hexagons combining the extent of irrigated areas and damage classes at district level

| ID | Damage class | Low | Low | Low | Medium | Medium | Medium | High | High | High |
|---|---|---|---|---|---|---|---|---|---|---|
|  | Irrigated cropland class | Low | Medium | High | Low | Medium | High | Low | Medium | High |
|  | District | Number of hexagons | | | | | | | | |
| 1 | Benghazi | 12 | 13 | 19 | 24 | 21 | 11 | 5 | 26 | 5 |
| 2 | Al Marj | 3 | 4 | 8 | 11 | 8 | 5 | 2 | 11 | 2 |
| 3 | Al Jabal Al Akhdar | 6 | 0 | 3 | 5 | 3 | 2 | 0 | 4 | 0 |
| 4 | Derna | 1 | 1 | | 3 | | | 1 | | 4 |

5. **Medium cropland area and medium population density:** Hexagons falling into this class feature moderate cropland areas (0.5–2 km$^2$) and a moderate population density (200 to 500 people per km$^2$). The risk is somewhat balanced, requiring a nuanced approach to address both agricultural and human related challenges during flooding.

6. **Medium cropland area and low population density:** This category represents hexagons with moderate cropland areas (0.5–2 km$^2$) and low population density (less than 200 people per km$^2$). While agricultural impacts may be significant, the lower population density can facilitate a more targeted response to safeguard crops.

7. **Low cropland area and high population density:** Hexagons in this class have small cropland areas (<0.5 km$^2$) but a high population density (>500 people per km$^2$). Flooding in these areas may have less impact on agriculture but poses a higher risk to densely populated regions, necessitating measures to protect communities.

8. **Low cropland area and medium population density:** This class includes hexagons with small cropland areas (<0.5 km$^2$) and a moderate population density (200–500 people per km$^2$). The focus in these areas would likely be on minimizing damage to agriculture while addressing the needs of moderately populated areas.

9. **Low cropland area and low population density:** Hexagons falling into this category have small cropland areas (<0.5 km$^2$) and low population density (less than 200 people per km$^2$). While the overall impact might be limited, a localized approach is still required to protect both agriculture and sparsely populated regions.

## Result 8: Sampling design

Sampling design was carried out using a stratified sampling technique. 150 sampling points were identified across AOI, based on the extent of flooding and irrigated cropland (Figure 15). The objective of the sampling design was to validate the results of the rapid flood impact assessment using remote sensing data. In this assessment, samples were stratified into three distinct classes based on flood damage levels and were defined as follows:

1. High: 26 samples

2. Medium: 97 samples
3. Low: 27 samples

## Result 9: Field validation

In December 2023, a field campaign was conducted over both flooded and non-flooded areas in the AOI. The results indicated a strong agreement between the remote sensing flood map and on-ground observations. Table 8 shows the confusion matrix of all field validation points. The overall accuracy of the flood extent map is 83 percent. The results showed the following:

- True positive (TP): 120 samples were correctly predicted as flooded.
- False negative (FN): 15 samples were incorrectly predicted as non-flooded when they were flooded.
- False positive (FP): 10 samples were incorrectly predicted as flooded when they were non-flooded.
- True negative (TN): 5 samples were correctly predicted as non-flooded.

*Table 8. Error matrix for accuracy assessment using reference field data*

|  | Predicted flooded | Predicted non-flooded |
|---|---|---|
| Actual flooded | TP: 120 | FN: 15 |
| Actual non-flooded | FP: 10 | TN: 5 |

*Figure 15. Sampling design in eastern Libya*
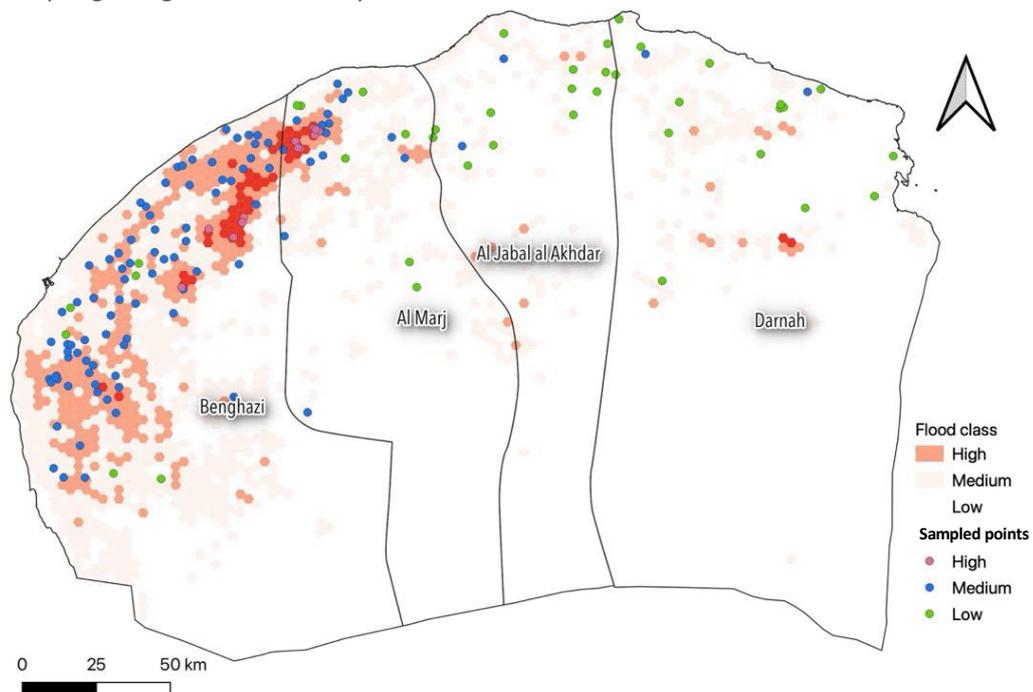


Note: Refer to the disclaimer on page ii for the names and boundaries used in this map.
Source: Administrative boundaries from **HDX**. 2023. Libya Data Grid. Libya – Subnational Administrative Boundaries. [Accessed on 23 April 2023]. https://data.humdata.org/dataset/cod-ab-lby. License: CC-BY-IGO.

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# Conclusion and recommendations

The assessment provided results on various key parameters, including the impact on dams and reservoirs, flood extent mapping, the exposed population, the exposure of irrigated cropland, and a detailed land cover map at a 10 m resolution. A methodological approach was developed to consider these parameters by using various datasets such as the administrative boundaries from HDX (HDX, 2023) and population data from Worldpop (Worldpop, 2020). The evaluation of the impact on dams and reservoirs was produced by utilizing the NDWI derived from Sentinel-2 imagery over the extensive time span of 2016 to 2023. The results from this analysis showed that the surface areas of water surpassed the designed capacity of the dams in Derna.

To assess the flood impact across eastern Libya, an updated land cover map was prepared. The flood extent mapping was conducted utilizing a change detection algorithm applied to Sentinel-1 data. Among the identified flood-prone areas, Benghazi emerged as the most severely affected. Population exposure was estimated using the flood extent map and Worldpop population data. Derna and Benghazi districts had the highest rate of the population affected by the flood. The irrigated crop land classes were extracted from the land cover map. The result was represented and visualized by a grid of 10 km[2] hexagons within three categories (high, medium, and low) for flood damage and inundated irrigated cropland. For validation, an accuracy assessment was conducted based on 150 sampling points. Field validation showed good agreement between the remote sensing-based flood map and on-ground observation. The recommendations are as follows:

- **Emergency response and relief efforts***:* Immediate humanitarian assistance should be prioritized, with a focus on providing emergency shelter, food aid, and hygiene kits to the affected population. Coordination with local authorities and relief organizations is crucial for the efficient delivery of aid.

- **Infrastructure rehabilitation:** Urgent measures are needed to repair and reinforce damaged dams and reservoirs. This will ensure the restoration of critical water management infrastructure and safeguard against future flood events.

- **Agricultural recovery and resilience building:** Targeted support should be extended to farmers and agricultural communities affected by flooded cropland. This includes the provision of seeds, tools, and training in flood-resistant agricultural practices.

- **Long-term planning and preparedness***:* Implementing robust flood mitigation strategies – including early warning systems and improved urban planning – is imperative to enhance resilience in the face of future flood events.

- **Ecosystem restoration:** Efforts should be made to rehabilitate affected natural habitats and promote sustainable land use practices to mitigate future environmental impacts.

- **Data monitoring and analysis:** Continual monitoring of water management infrastructure, land cover changes, and population exposure is essential for timely response and adaptive planning in future disasters.

By considering these recommendations, eastern Libya can bolster its resilience and capacity to mitigate the impacts of future flood events, ultimately ensuring the safety and well-being of its communities and the sustainable development of the region.

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