Food and Agriculture Organization of the United Nations

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Abbreviations

AfDB	African Development Bank
AICS	Italian Agency for Development Cooperation
DIP	drip irrigation
FAO	Food and Agriculture Organization of United Nations
GCWW	General Company for Water and Wastewater
GDC	General Desalination Company
GDP	gross domestic product
GECOL	General Electricity Company of Libya
GMR	Great Man-Made River
IagWat	Evaluation of irrigation infrastructure, crop mapping and estimation of agricultural water use in Libya
IPI	irrigation pipes
LAR	large agricultural reservoirs
MC	main canals
MerWat	Monitoring, evaluation and rationalization of water use for agriculture sector in Libya
MIX	mixed irrigation system
PIP	pipes
PIV	pivot irrigation equipment
PS	pumping stations
SPR	sprinkler irrigation
TAN	agricultural reservoirs
WEL	local wells
WFM	water flow monitoring points
WFP	World Food Programme

Executive summary

This report presents a thorough evaluation of two key initiatives, OSRO/LIB/100/AFB and OSRO/LIB/002/ITA, which utilize advanced remote sensing technologies alongside field data collection to enhance water management systems. The primary aim is to assess the infrastructure related to water management, focusing specifically on irrigation systems, crop production, and water productivity across Libya, with particular attention to the Fezzan (south), west, and east regions of Libya.

The overarching goal of these projects is to improve sustainable water resource management practices. By leveraging the insights gained from these initiatives, there is potential to apply the knowledge and techniques developed here on a national scale. The expected outcomes include the identification of areas requiring rehabilitation and development, as well as the creation of deep insights into innovative practices and cutting-edge technologies that can significantly enhance water productivity at the microfarm level.

This assessment of water management infrastructure in Libya utilized a methodological approach that combined remote sensing technology and ground-based surveys. The selected area of interest (AOI) was Libya as a whole, with the administrative boundaries sourced from the United Nations Office for the Coordination of Humanitarian Affairs (UNOCHA) (HDX, 2023).[1] Sampling locations were chosen using geolocation data for extraction and collection, and storage, drone monitoring for transportation (proposed but not implemented), and remote sensing data for irrigation effectiveness, using the Normalized Difference Vegetation Index (NDVI) and the Food and Agriculture Organization of the United Nations (FAO)’s portal to monitor WAter Productivity through Open-access of Remotely sensed derived data (WaPOR) evapotranspiration data (FAO, 2023).[2] This stratified and clustered approach ensured a representative data collection. Field visits were conducted in the southern (Fezzan), western, and eastern regions, collecting 750 samples using the Kobo Toolbox (Kobo Toolbox, 2023).[3] The data was thoroughly analysed to provide insights into the current state of water management infrastructure and identify areas for improvement. This integrated methodology offers a robust framework for ongoing monitoring and enhancement of water management systems, to improve the efficiency and sustainability of Libya’s agricultural water use.

The results of the water management infrastructure assessment in Libya reveal a detailed categorization and status evaluation of various facilities critical to the country's agricultural water management. The infrastructure was categorized into four main areas:

Category 1: Extraction/collection includes well fields, dams, and desalination plants. Monitoring in this category included both field surveys and remote sensing-based Normalized Difference Water Index (NDWI) analysis. Technicians physically inspected wells, dams, and desalination plants, while NDWI data provided insights into the changing size of water bodies, allowing the identification of reductions

[1] **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.

[2] **FAO**. 2023. WaPOR: a portal of AQUASTAT. [Accessed on 14 October 2022]. https://data.apps.fao.org/wapor/?lang=en. Licence: CC-BY-4.0.

[3] **Kobo Toolbox.** 2023. High Quality Data Collection for Everyone. In: *Kobo Toolbox*. Cambridge, USA. [Cited 10 September 2024]. https://www.kobotoolbox.org

due to droughts, overuse, or poor maintenance. Key findings show that Libya has 21 desalination plants with a total capacity of 525.68 m^3 daily, but many face issues such as a lack of maintenance and operational inefficiencies. The major dams surveyed – such as Wadi Al-Magineen and Wadi Kaam – exhibit severe structural damage, electrical and mechanical failures, and in a significant need for rehabilitation. Out of 1 300 wells in the major well fields, nearly 50 percent are non-functional due to technical faults, lack of maintenance, and vandalism.

Category 2: Storage includes large agricultural reservoirs and smaller agricultural tanks. Field teams inspected the physical conditions of both large and small water storage facilities. These surveys provided real-time insights into the operational status, efficiency, and capacity of storage infrastructure. Key reservoirs like the Grand Omar Mukhtar Reservoir have substantial storage capacities but face issues such as sedimentation and reduced efficiency during peak water demand periods. The storage capacity of large reservoirs ranges from 4 to 24 million (M) m^3, with significant declines observed during summer months due to increased demand and pipeline supply issues.

Category 3: Transportation includes pumping stations and canals, including the Great Man-Made River (GMR) Project. The transportation infrastructure, which plays a critical role in moving water from extraction points to storage and agricultural fields, was monitored through field inspections and infrastructure assessments. This network includes main canals, pumping stations, and water flow monitoring points. The main canals are essential for transporting water to storage facilities, but face challenges such as leakage and sedimentation. Pumping stations are crucial for maintaining water flow but suffer from mechanical and electrical issues. Water flow monitoring points provide vital data for managing distribution but require regular maintenance to ensure accuracy.

Category 4: Distribution/irrigation includes pipes, pivot irrigation equipment, local wells, irrigation pipes, drip irrigation, mixed irrigation, and sprinkler systems. These were evaluated using remote sensing and field data. Remote sensing, particularly NDVI, was used to assess crop health and water productivity by using actual evapotranspiration data, while field data provided ground truth and detailed insights into infrastructure conditions. The combined approach allowed for the accurate identification of crop types and evaluation of irrigation efficiency. The analysis indicates that the condition and maintenance of these systems significantly impact water distribution and agricultural productivity. Addressing these issues of maintenance and upgrading is essential to enhance water distribution efficiency, support sustainable agriculture, and improve the overall productivity in Libya.

Recommendations include prioritizing the maintenance and repair of pipes, pivot irrigation equipment, and sprinkler systems to prevent water loss and ensure efficient irrigation. Technological upgrades and regular maintenance of drip and mixed irrigation systems are also essential for improved water conservation and distribution. Enhanced monitoring using remote sensing and field data should be regularly conducted to assess crop health and water productivity, allowing for timely interventions. Implementing security measures will also protect local wells and irrigation infrastructure from vandalism and theft. Additionally, training local technicians and farmers on effective maintenance and operation of irrigation systems is crucial for sustained agricultural productivity.

Background

While crop and livestock production contributed less than 3 percent of Libya's gross domestic product (GDP) in 2012, 22 percent of Libyans are engaged in some form of agricultural production (WFP, 2020) and crop and livestock production are a significant source of food security for many Libyan households, which tend to be small producers (FAO, 2014). However, the agricultural sector faces various challenges, with difficult environmental conditions, mostly dominated by limited access to water resources (only 4 percent of Libya lies outside the desert and the arid agroecological zone [Fischer *et al.,* 2021], and approximately only 7 percent of the country receives a total precipitation exceeding 100 mm annually [World Bank, 2022]), together with conflict, political instability, and insecurity impacting individuals and families as well as the entire sector's economy and institutions (FAO, 2014).

Previous assessments (FAO, 2018, 2020; WFP, 2020) have shown that the crisis has exacerbated pre-existing challenges associated with agricultural production in Libya, including water scarcity, animal and plant diseases, desertification, and labour shortages. In addition to these longer-term challenges, the crisis has ruptured market linkages and disrupted access to water, electricity, inputs, and transportation. Problems are exacerbated due to the limited availability of arable land for agriculture (less than 2 percent).

While cereals, fodder crops and some fruits are grown in the small, coastal, rainfed area, the larger irrigated area is devoted to the cultivation of vegetables (such as potatoes, onion, and tomatoes), fruits (such as watermelons, oranges, dates, grapes, and olives), and cereals (wheat and barley). Most of the farms are small, ranging from 5 to 20 hectares (ha) (FAO, 2020). To respond to the issue of lack of freshwater, the Government of Libya developed the Great Man-Made River (GMR) Project implemented in three main phases over the course of more than two decades, aiming at extracting fossil water from the south of the country (mainly the Nubian Sandstone Aquifer System). An underground network of pipes covering 1 600 km distributes freshwater over the coastal areas where most of the population live. Other projects were aimed at finalizing phase three and developing phase four and five of the GMR Project, to increase the areas served with water (Aqeil, Tindall and Moran, 2012), as well as additional support given to the Agricultural Ministry to expand irrigation projects for cereal production in the southern region of Fezzan under this project.

Along with recent progress in bringing political stability, the government has a strong interest in accelerating agricultural development and improving agricultural production. In parallel, there is also an interest in maximizing water and crop productivity, considering that water and arable land are the most limiting constraints to agriculture, equipment and labour. Accordingly, there is a need to evaluate the status of water management infrastructure that contributes to the agricultural sector.

Considering that most of the information on irrigation is either no longer available or outdated, sparse or fragmented, the OSRO/LIB/002/ITA project, "Monitoring, evaluation and rationalization of water use for agriculture sector in Libya" (MerWat), funded by the Italian Agency for Development Cooperation (AICS) and the OSRO/LIB/100/AFB project, "Evaluation of irrigation infrastructure, crop mapping and estimation of agricultural water use in Libya" (IagWat), funded by the African Development Bank (AfDB), aim to improve knowledge on the irrigation infrastructure damages, and the impact on water efficiency and crop and water productivity, supported by remote sensing (RS) and GIS technologies. The overall objective is to improve food security in the country by more performant and efficient use of agricultural water. This document aims to describe the methodological approach to support these two ongoing projects in Libya.

Objectives

The overall objective of this assessment is to characterize the state of water management infrastructures, with a particular focus on irrigation, crop and water productivity, using remote sensing and field data information to improve sustainable water resources management and crop productivity in Libya, starting in eastern Libya (Fezzan) and western Libya.

The characterization of water management infrastructures provides quantitative information to prioritize their rehabilitation, development and consequently boost agricultural development. In parallel, the outcomes of these projects support the development of approaches for scaling up the project at the national level and the identification of good practices and affordable technologies to increase water productivity at the farm level (through identifying low productive land by crop type and answering questions such as where water use efficiency, and agricultural productivity can be improved and how).

The first section of this assessment provides an account of the methodological framework, starting with an overview of water management conditions for agriculture at the national level, with the aim of supporting a methodological framework to be piloted in Fezzan and northwest Libya. The subsequent subsections provide the results of the assessment for water management infrastructures for water extraction and collection, the results on water storage facilities, and the results for the water distribution and irrigated areas, respectively. The second section provides the methodological steps for a sampling design for the irrigation infrastructure.

Methodological approach

This methodological approach has been designed to assess the water management infrastructure in Libya, and encompasses various steps, integrating both remote sensing technology and ground-based surveys to provide a holistic evaluation of Libya's water resources and management systems. The goal is to improve the efficiency of water management in Libya, so that water use for agriculture is rationalized sustainably. The integrated use of field data and remote sensing data in this methodology provides a robust framework for the continuous monitoring and improvement of water management infrastructure. The following sections lay out the key steps of methodology that were adopted.

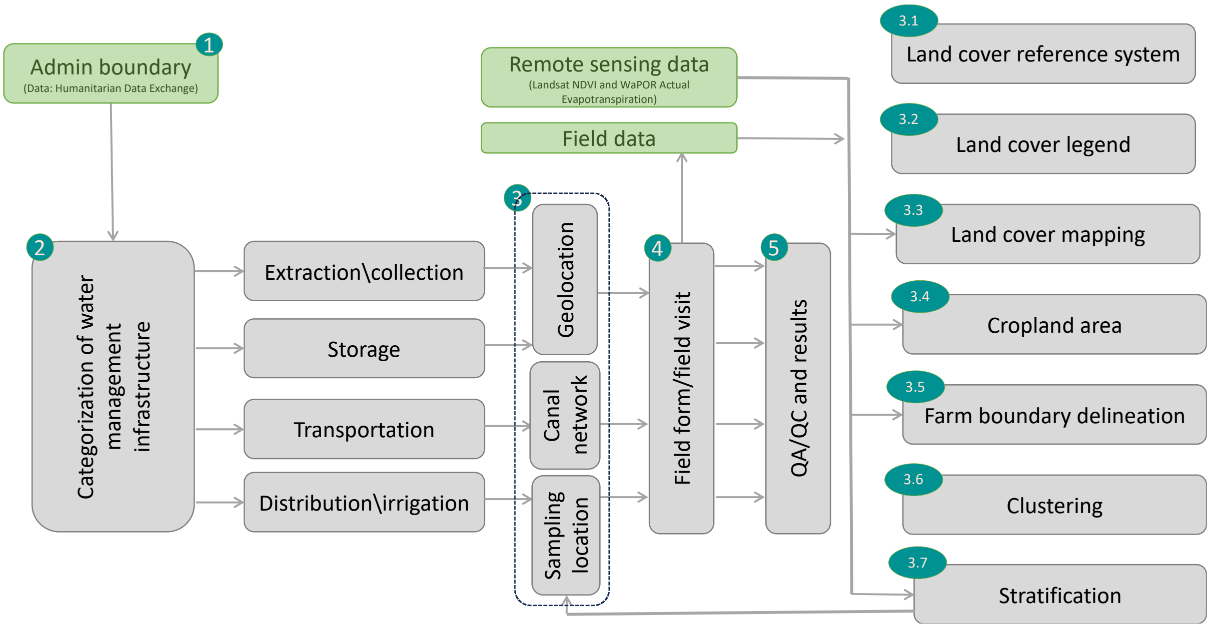
Step 1. Selection of the area of interest (AOI)

The entire country was chosen for this study. The administrative boundaries were obtained through the Food and Agriculture Organization of the United Nations (FAO)'s country office in Libya, and from the United Nations Office for the Coordination of Humanitarian Affairs (UNOCHA)'s Humanitarian Data Exchange (HDX) (HDX, 2023).

Step 2. Categorization of the water management infrastructure

The characterization of water management infrastructure in Libya involved a detailed assessment of various systems crucial for the agricultural water management. Those infrastructures were characterized through detailed field surveys and assessments, helping to identify critical areas needing intervention, and facilitate targeted improvements to enhance the efficiency and reliability of water management in Libya.

Figure 1. Schematic methodological approach for assessing water management infrastructure categories in Libya



Source: Authors' own elaboration.

This methodology ensured comprehensive data acquisition which was crucial for evaluating the current state of infrastructures and identifying necessary interventions across the following four infrastructure categories:

1. Extraction/collection (E)
2. Storage (S)
3. Transportation (T)
4. Distribution/irrigation (D)

Step 3. Selection of sampling locations

Different strategies were implemented across the various categories of water management infrastructure, dictated by the infrastructure characteristics and the data collection requirements.

3.1 Extraction/collection and storage categories

Geolocation was primarily used to identify and select specific sites for detailed assessment. This process involved mapping out the locations of wells, dams and reservoirs using geographic coordinates. The selection focused on key sites known for their strategic importance or where previous data had suggested prevalent issues.

3.2 Transportation category

For the canal network, the approach included a combination of geolocation data and direct observation via drone monitoring. It was proposed to use drones to assess the condition of canal infrastructure, allowing for the identification of areas prone to leaks or damage, and areas where vegetation might obstruct the canals. However, it was not implemented on the ground.

3.3 Distribution/irrigation category

Remote sensing data was utilized to determine the effectiveness of irrigation practices in the study area. Landsat NDVI (USGS, n.d.) and FAO's Water Productivity Open-access portal (WaPOR) (FAO, 2023), actual evapotranspiration data were employed to identify suitable sampling locations by analysing crop productivity and water usage efficiency across agricultural lands. This data helped in identifying areas where irrigation was either underperforming or exceeding expectations and guided the selection of sampling locations that would provide the most impactful insights into irrigation efficiency.

The sampling design for irrigation infrastructure assessment integrated remote sensing and field data to analyse the effectiveness and condition of irrigation systems. The following substeps were used for the stratification for sampling design:

- **Establishment of a land representation system:** Initially, a detailed land representation system was established to accurately classify and depict land features (Nwer *et al*., 2023). This system served as the backbone for subsequent mapping and analysis processes, ensuring that all land types were properly categorized and represented.
- **Development of a land cover legend:** Alongside the representation system, a land cover legend was created, acting as a vital reference for categorizing various land cover types. This

legend was crucial for consistent classification and helped in aligning remote sensing data with recognizable land features.

- **Creation of land cover maps:** Detailed land cover maps were generated through utilizing remote sensing data. These maps illustrate the distribution and extent of different land cover types across the area of interest, providing a visual foundation for identifying the areas specifically used for agriculture.
- **Application of a proxy crop mask:** To focus specifically on agricultural zones, a proxy crop mask was applied. This mask isolated areas dedicated to crop cultivation from other land cover types, facilitating targeted analysis of agricultural practices and irrigation efficiency.
- **Segmentation:** Segmentation was used to delineate field boundaries for assessing the irrigation infrastructure. This was achieved by using object-based image analysis (OBIA) to segment images by grouping pixels to generate objects with different geometries. In the analysis, eCognition Developer image processing software (Trimble, 2023) was used to perform a segmentation of the NDVI composite of years 2010, 2015 and 2021 using Landsat Thematic Mapper (TM) satellite imagery. A multiresolution segmentation algorithm was applied, with the following settings:
    - scale parameter = 10;
    - shape = 0.1; and
    - compactness = 0.9.
- **Clustering:** Clustering is the task of dividing the data points into several groups such that data points in the same groups are more like other data points in the same group than those in other groups (segregating groups with similar traits and assigning them into clusters). To determine natural groupings in the collected data, the k-nearest neighbour (KNN) algorithm – an unsupervised clustering algorithm – was used.
- **Stratification:** The clusters were reclassified into five classes: gain; high, no change; medium, no change; low, no change; and loss, and were based on NDVI and water productivity dynamics between the years 2010 and 2021. Crop productivity was analysed using NDVI derived from Landsat 7 (2010) and Landsat 8 (2021) data (USGS, n.d.), whereas water productivity was analysed using actual evapotranspiration and interception (ETIa) data from the years 2010 and 2021, sourced from WaPOR data (FAO, 2023). Both the crop and water productivity of land parcels were considered to identify diverse locations for field data collection and to identify the linkage between crop and water productivity. The differences between historical and the most recent annual NDVI (2021) were calculated to identify areas of gain and loss in terms of mean annual vegetation for the stratification. A gain was defined with a NDVI increase of greater than 0.3 and a loss with a NDVI decrease of less than 0.3. Google Earth Engine (GEE) was used to extract NDVI data from Landsat 5 and Landsat 8 satellite images (Earth Engine, 2017). The NDVI data was then processed and visualized using the correlation coefficient (R). Landsat's visible red band and near-infrared band were used to prepare NDVI maps. After comparison between the average historical data from 2010 and recent data from 2021, the NDVI was able to provide information on vegetation anomalies, such as where crop failure had been potentially due to damage of irrigation facilities. It also allowed for the characterization of areas by the possible risk of damage to infrastructure. The

overlapping of the district boundaries with the resulting classified clusters was identified, and the results were tabulated by district. To identify suitable sampling locations, the following steps were carried out for stratification:

- The NDVI was calculated for 2010 as historical and 2021 as recent.
- The NDVI differences between 2010 and 2021 were classified into three strata classes (gain, loss, and stable).
- The stable class was then masked to classify the stable class into three classes (low [no change], high [no change], and medium [no change]).
- The NDVI average was calculated for 2010 and 2021.
- The average NDVI was reclassified (reclassification is the process of reassigning average NDVI values in a raster dataset to new output values) after masking by a stable shapefile into three classes (low [no change], high [no change], and medium [no change]).

The zonal statistics was calculated for each zone defined by a zone dataset, based on values from another dataset (a value raster). A zone is all the cells in the NDVI that have the same value, whether or not they are contiguous, while the input zone layer defines the shape, values, and locations of the zones. A single output value was computed for every cluster in the input zone dataset. The Zonal Statistics as Table tool (Esri, 2022), calculated all subsets or single statistics that were valid for the specific input, returning the result as a table instead of an output NDVI. An integer field in the zone input was specified to define the zones, although a string field can also be used. Both raster and feature datasets can also be used as zone datasets. Within these stratified groups, specific locations were selected for detailed field data collection. This selection was guided by the stratification criteria, ensuring that the sampling covered a representative cross-section of irrigation practices and conditions.

Step 4. Field form/field visit: Structured data collection forms were designed to standardize the recording of information during field visits. Rigorous quality assurance and quality control measures were also implemented to maintain the accuracy and reliability of the data collected.

Field visits were conducted to collect ground truth data, which were then verified against the remote sensing findings. This dual approach of field and remote sensing data collection ensured a more complete understanding of the status and effectiveness of the water management infrastructure. Field campaigns were conducted in the Fezzan region during December 2022, in the west region during June 2023 and in the east region during December 2023. In total, 750 samples were collected across all regions. The field data collection was conducted using Kobo Toolbox (Kobo Toolbox, 2023).

Step 6. Data synthesis and result generation: The collected data was thoroughly analysed and synthesized to generate results able to provide valuable insights into the effectiveness of the water management infrastructure.

Categorization of water management infrastructure

The proposed methodological approach categorizes water management for agriculture in Libya into four categories and 15 subcategories (Figure 1), including the category and subcategory abbreviations used in the approach. The four categories and 15 subcategories are as follows:

Category 1: Extraction/collection (E)– this includes well fields (WF), dams (DAM), and sea water desalination plants (SWD). Desalination technologies have been used in Libya and 21 desalinization plants have been constructed along the coast with a total daily capacity of 525.68 m^3.

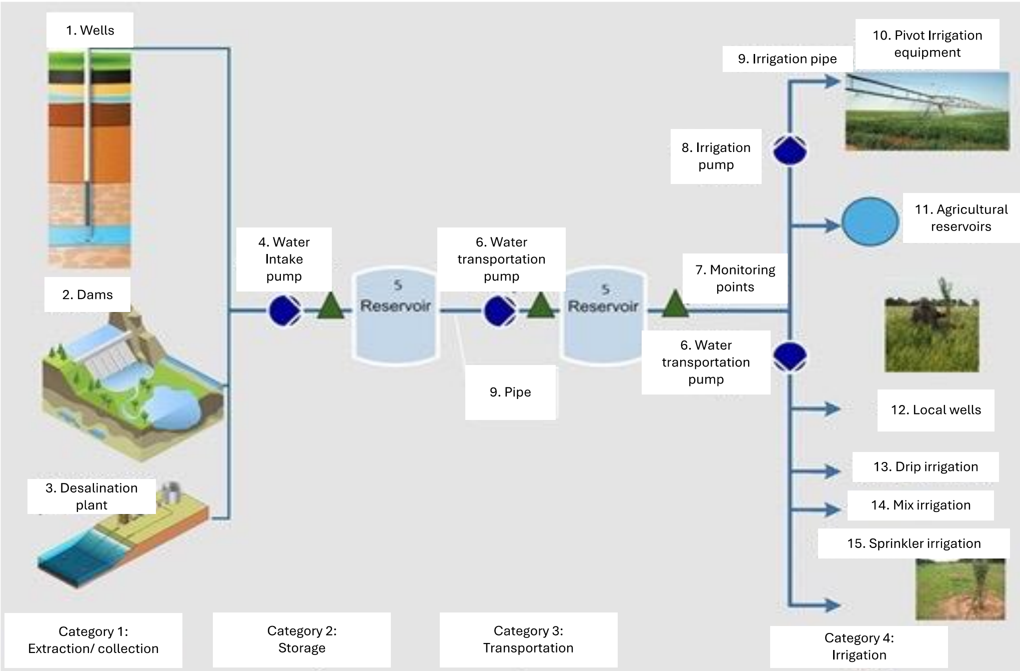
Category 2: Storage (S)– this includes large agricultural reservoirs (LAR), and agricultural reservoirs (TAN).

Category 3: Transportation (T)– this includes pumping stations (PS), main canals (MC), and water flow monitoring points (WFM). The pipe network (mostly underground) of the Great Man-Made River (GMR) project is considered as the main water infrastructure in the country. Its role consists of the transport of water from south to north for domestic and irrigation purposes.

Category 4: Distribution/irrigation (I)– this includes irrigation facilities used for agriculture like pipes (PIP), pivot irrigation equipment (PIV), local wells (WEL), irrigation pipe (IPI), drip irrigation (DIP), mixed irrigation system (MIX), and sprinkler irrigation (SPR).

A specific methodological approach was designed for each category using field and remote sensing analysis (Figure 2).

Figure 2. Schematic representation of water management infrastructure categories and subcategories in Libya



Source: Authors' own elaboration.
Photo credit: © FAO/ Bashir Nwer

Table 1. Schematic representation of water management infrastructure categories and subcategories in Libya

Name*	Description	Visual description
Category 1: Extraction/collection (E)		
1. Well fields (WF)	The five most important well fields are located in Tazrbo, Sarir, and three in Jebel Hasouna (one in east Jebel Hasouna and two in northeast Jebel Hasouna). There are around 1 300 production wells and monitoring wells distributed in the south of the country. (see questionnaire in Table A1.1).	 Sarir well fields
2. Dams (DAM)	The dams are constructed in the north of the country to control wadi floods, supply irrigation water and recharge underground aquifers. Dams such as Magnin are used to supply water for irrigation to nearby farms. These dams can be affected by cracks, leakage, maintenance problems, and other issues (see questionnaire in Table A1.2).	 Wadi Magineen Dam
3. Seawater desalination plant (SWD)	There are 21 desalination plants in Libya. Their contribution to water supply and irrigation is very limited, although still an important water resource. This subcategory can face many problems, including a lack of maintenance, productivity and stoppage (see questionnaire in Table A1.3).	 Tobruk desalination plant

Name*	Description	Visual description
Category 2: Storage (S)		
4. Large agricultural reservoirs (LAR)	There are five main reservoirs in Libya, designed to provide large amount of water for domestic and agricultural purposes. These reservoirs face problems due to leakage, pollution, and the reservoirs' reduced capacity due to sedimentation (see questionnaire in Table A1.4).	 The Grand Omar Mukhtar reservoir in GMR
5. Agricultural reservoirs (TAN)	The agricultural reservoirs and tanks represent a storage facility for agricultural projects (for example, Sidi Sayhe tank to the southeast of Tripoli). Among possible problems that can affect these infrastructures are the destruction of connected pipelines and pumping system (see questionnaire in Table A1.5).	 Sidi Sayhe tank
Category 3: Transportation (T)		
6. Pumping stations (PS)	Several pumping stations are constructed to stabilize the water flow in the system and to ensure the distribution of water for agricultural and domestic purposes. The functioning of pumping stations can be affected by the destruction or the disconnection from the pipeline, the damage or absence of pumping equipment and the damage of electrical equipment (see questionnaire in Table A1.6).	 Pumping station in GMR

Name*	Description	Visual description
7. Main canals (MC)	The main pipe network transports water from the south (well fields) to the northern cities and the agriculture areas. The pipework is buried underneath the surface, with leakage being the greatest issue (see questionnaire in Table A1.7).	 Main canals in GMR
8. Water flow monitoring points (WFM)	The water flow monitoring points are a construction facility built to monitor water flow in GMR systems. The destruction, damage and illegal water connections can damage these facilities (see questionnaire in Table A1.8).	 Waterflow monitoring point in GMR
Category 4: Distribution/irrigation (D)		
9. Pipes (PIP)	The pipes distribute water from reservoirs to farms and projects for irrigation. Their dysfunction can be caused by damage, missing elements, missing pipes, or leakage (see questionnaire in Table A1.9).	 Pipelines in GMR project

Name*	Description	Visual description
10. Pivot irrigation equipment (PIV)	Pivot irrigation, also known as centre-pivot or circle irrigators, describes a method of crop irrigation in which equipment rotates around a pivot and crops are watered with a sprinkler. This irrigation method is widespread in state projects in the south of Libya and some private farms. Some problems can affect the role of this pivot, including missing equipment, maintenance, connection to pipes and other issues (see questionnaire in Table A1.10).	 Pivot irrigation equipment
11. Local wells (WEL)	Within agricultural state projects and private local farms, local wells represent the main source of water for irrigation. The lack of equipment or missing equipment, and the wells' partial or full destruction could affect their role (see questionnaire in Table A1.11).	 Local water wells in farm
12. Irrigation pipes (IPI)	The objective of irrigation pipes is to transport water from wells to irrigation systems. This objective can be affected by the missing equipment, leakage, or their partial or full destruction (see questionnaire in Table A1.12).	 Pipes for irrigation systems

Name*	Description	Visual description
13. Drip irrigation (DIP)	Drip irrigation is mostly used within agricultural projects, especially in date development projects. Several problems could disrupt the role of drip irrigation, due to missing equipment, lack of maintenance, leakage, sedimentation, lack of connection to the pipes, and their partial or full destruction (see questionnaire in Table A1.13).	 Drip irrigation in the south
14. Mixed irrigation system (MIX)	Using a combination of drip and sprinkler irrigation is common in some projects, especially in date palm development projects. Missing equipment, lack of maintenance, leakage, lack of connection to the pipes, and their partial or full destruction could affect this infrastructure (see questionnaire in Table A1.14).	 Mixed irrigation system
15. Sprinkler irrigation (SPR)	The sprinkler irrigation systems used to irrigate crops are widespread in the Fezzan area in smallholdings and state farm projects. Possible problems that could disrupt the functioning of this system include a lack of maintenance, leakages, or destruction (see questionnaire in Table A1.15).	 Sprinkler irrigation in the south

*Note: This title indicates the subcategories that have been measured.

Photos: Great Man-Made River Project.

Category 1: Extraction/collection (E)

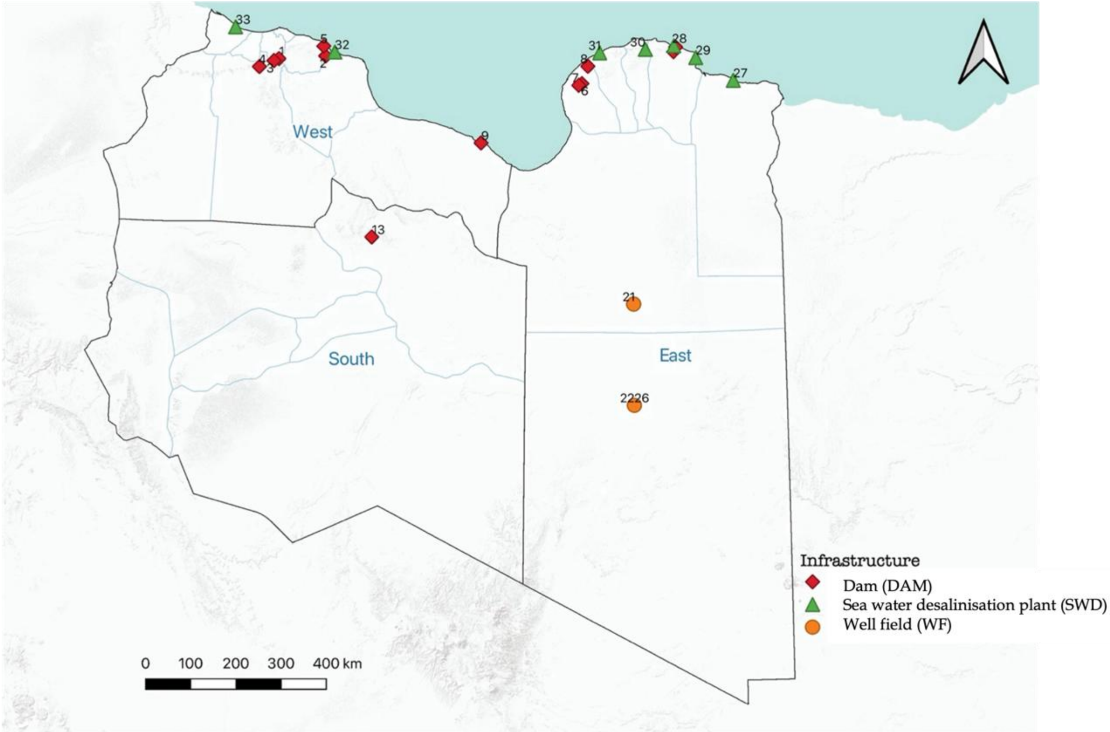
This category refers to all infrastructures which collect or extract water for irrigation infrastructure systems in Libya. Three main subcategories (typologies) were identified: dams (DAM), well fields (WF), and desalination plants (SWD). Table 2 and Figure 3 detail the geographic location for the main infrastructures for extraction/collection at the national level. Annex I provides the field forms prepared for the field data collection (Table A1.1, Table A1.2 and Table A1.3). The remote sensing analysis was conducted using very high-resolution imagery aggregating the results over time (by season) and over land extent (by district or smaller unit) to find land with irrigated crop failure as a proxy for damages to irrigation facilities.

In addition, more than 1 000 local wells and their coordinates were collected and stored in the database. Table 2 lists dams (DAM), well fields (WF) and desalination plants (SWD) regarding Category 1: Extraction/collection.

Table 2. Geolocation of infrastructures for extraction/collection in Libya

ID	District name	Infrastructure name	Subcategory	Latitude	Longitude
1	Tripoli	Wadi Al-Magineen Dam	Dam (DAM)	32.294	13.247
2	Alkums	Wadi Kaam Dam		32.409	14.343
3	Gharyan	Wadi Ghan Dam		32.244	13.136
4	Gharyan	Wadi Zaaret Dam		32.106	12.806
5	Alkums	Wadi Libda Dam		32.603	14.283
6	Bengahzi	Wadi Quattara Dam		32.027	20.406
7	Bengahzi	Supplementary Wadi Quattara		31.995	20.335
8	Darna	Wadi Mourkos Dam		32.869	22.237
9	Surt	Wadi ben Gawad Dam		30.802	18.068
10	Bengahzi	Wadi Zaza Dam		32.376	20.545
11	Darna	Wadi Abu Mansour Dam		32.659	22.5772
12	Darna	Wadi Darna (Alblad) Dam		32.753	22.631
13	Al Jufrah	Wadi Wishka Dam		28.836	15.631
22	Al Kufrah	Sarir well field	Well field (WF)	27.591	21.601
23	Al Kufrah	Tazerbo well field		25.553	21.606
24	Ash Shati	Northeast Jabal Hasouna		28.910	14.340
25	Ash Shati	East Jabal Hasouna		28.660	14.46
26	Tubruk	Tobruk desalination plant	Desalination plant (SWD)	32.061	23.979
27	Derna	Derna desalination plant		32.779	22.589
28	Al-Bombh	Al-Bombh desalination plant		32.536	23.104
39	Sousse	Sousse desalination plant		32.715	21.911
30	Benghazi	Abu Taraba desalination plant		32.649	20.824
31	Zeltin	Zeltin desalination plant		32.499	14.550
32	Zwara	Zwara desalination plant		32.858	12.172
33	Zawiyah	Zawiyah desalination plant		32.790	12.671

Figure 3. Distribution of water management infrastructures for water extraction (Category 1) in Libya



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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.

Status of dams (DAM)

Dams have been constructed in Libya to mobilize surface water resources (Wheida and Verhoeven, 2014). The main aim is to recharge underground water, protect major cities from irregular flood risk and collect water for use. Even if 50 percent of the water can be intercepted to form a resource, this 100 million m^3 annually would represent only 1 to 2 percent of the water resources (Pallas, 1980). In this project, 13 out of 18 dams were surveyed to assess the status of the dams. The other five dams were not accessible for surveying due to a combination of logistical and security challenges. Some of the dam sites were located in regions affected by ongoing conflict or instability, which restricted the safe access for field teams. In addition, poor infrastructure and limited transportation options made it difficult to reach certain remote areas. Furthermore, some dams were situated in regions where local authorities were unable to provide the necessary support or permits for on-site assessments.

The current state of various dams as shown in Table 3, presents a concerning scenario for agricultural practices in the region. Each dam exhibits distinct damage and requirements for restoration, which directly influence their effectiveness in supplying water for irrigation. For example:

- Wadi Al-Magineen Dam is in dire need of electrical and mechanical maintenance. The entire electrical network within the tower has been disrupted, rendering it non-functional. Furthermore, the lighting system is completely out of order. Notably, the dam's concrete barrier from the upstream side bears visible cracks, indicative of structural concerns. Additionally, Gate one is currently out of service, necessitating immediate attention. There is an urgent requirement to install 5.5 HP and 7.5 HP pumps to facilitate the drainage of filtered water.

- Wadi Kaam Dam has experienced severe damage, affecting its operational capacity. The main and electrical control rooms, along with the designated room, have been broken into, and doors have been stolen. The situation demands comprehensive rehabilitation efforts. Moreover, the intake tower, a pivotal component of the dam's infrastructure, is in ruins, with some parts completely destroyed and others stolen.
- The operational status of Wadi Ghan Dam has been compromised due to significant damage. The dam has suffered extensive structural and functional impairments, including disruptions to the electrical network and substantial damage to mechanical equipment, including the escalator. Additionally, the lighting poles above the bridge are in a state of disrepair, demanding immediate attention. Maintenance of the surveying measurement points across the dam's body is essential. This dam's mechanical equipment, including the escalator and stilling basin, require thorough cleaning to restore functionality.
- While it does not exhibit specific damage, Wadi Zaaret Dam does require attention. The entire electrical network inside the tower has been disrupted, and all mechanical equipment has been compromised. Furthermore, the lighting poles above the bridge are in a state of disrepair. The main gate has been severely damaged, necessitating repairs. Additionally, the piezometric network on the dam's body is obstructed with dust and stones, potentially hindering water management efforts.

The current conditions of these dams raise significant concerns for agricultural practices in the region as shown in Table 4. With disruptions to electrical and mechanical systems, compromised structural integrity, and a range of other issues, the provision of reliable water for irrigation becomes a pressing issue. Urgent attention and substantial investment are essential to restore the dams and ensure their continued effectiveness in supporting agriculture in Libya. The evolution of water capacity, considering remote sensing, is presented in Figure 4.

Table 3. Characterization of dams in Libya

ID	Infrastructure name	Dam type	Width of dam crest (m)	Catchment area (km^2)	Max foundation width (m)	Maximum water level elevation (m)	Max rate of spillway discharge (m^3/sec)	Max water level elevation (m)	Crest elevation (m)	Length of dam crest (m)
1	Wadi Al-Magineen Dam	Rock fill dam with upstream reinforced concrete screen	8	578.9	258.8	284	50	284	258.8	881
2	Wadi Kaam Dam		111	175	n/a	n/a	83	n/a	n/a	n/a
3	Wadi Ghan Dam	Rock fill dam with a loess core	10	650	352	343	1 640	343	352	316
4	Wadi Zaaret Dam	Rock fill dam with a clay core	10	175	350.5	344	1 050	344	350.5	2 700
5	Wadi Libda Dam	Earth fill dam with a clay core and clay cutoff extended downward 7–8 m	7	174	39	35	n/a	35	39	515
6	Wadi Quattara Dam	Limestone bedrock and alluvial deposits, clayey and silt	235	1224	n/a	160	n/a	160	33	305
7	Supplementary Wadi Quattara Dam	Limestone bedrock and alluvial deposits, clayey and silt	217	1285	n/a	n/a	n/a	n/a	28.6	217
8	Wadi Mourkos Dam	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
9	Wadi ben Gawad Dam	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
10	Wadi Zaza Dam	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
11	Wadi Abu Mansour Dam	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

ID	Infrastructure name	Dam type	Width of dam crest (m)	Catchment area (km^2)	Max foundation width (m)	Maximum water level elevation (m)	Max rate of spillway discharge (m^3/sec)	Max water level elevation (m)	Crest elevation (m)	Length of dam crest (m)
12	Wadi Darna (Alblad) Dam	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
13	Wadi Wishka Dam	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

Note: n/a = not available

Table 4. Damage status of dams in Libya

ID	Infrastructure name	Control room damage	Intake tower damage	Lighting damage	Structural damage of dam	Recommendations
1	Wadi Al-Magineen Dam	Electrical and mechanical maintenance needed.	Entire electrical network inside the tower disrupted.	Lighting completely out of order.	Presence of cracks on the concrete barrier from the upstream side. Gate one out of service.	Supply and installation of a 5.5 HP and 7.5 HP pump for draining filtered water urgently needed.
2	Wadi Kaam Dam	The main and electrical control rooms, along with the adjacent designated room on the dam's body, have been damaged, with even the doors having been stolen.	Need for rehabilitation.	Completely destroyed and some lights stolen.		
3	Wadi Ghan Dam	Damaged and out of service.	The electrical network was destroyed, mechanical equipment was damaged, including escalator.	Lighting poles above bridge completely out of order.	Maintenance of surveying measurement points needed on entire body of dam.	Stilling basin cleaning needed.

ID	Infrastructure name	Control room damage	Intake tower damage	Lighting damage	Structural damage of dam	Recommendations
4	Wadi Zaaret Dam	None.	The entire electrical network inside the tower was disrupted and all mechanical equipment damaged.	Lighting poles above bridge completely out of order.	Main gate destroyed.	Piezometric network on dam's body blocked with dust and stones.
5	Wadi Libda Dam	None.	The entire electrical network inside the tower was disrupted and all mechanical equipment damaged.		n/a	Entire cement cover on the crest of the dam destroyed by vandalism.
6	Wadi Quattarah Secondary Dam	Hydraulic oil is needed for the main dam control room.	None.	Lighting poles completely out of order, replacement needed.	Main fence around dam and inlet tower destroyed.	New weather station and electronic water level meter needed.
7	Supplementary Wadi Quattara Dam	None	Entire electrical system damaged.	Reinstallation of lighting needed.	Cracking due to differential settlement. The fence and tower were heavily damaged.	All equipment lost.
8	Wadi Mourkos Dam	n/a	n/a	n/a	n/a	n/a
9	Wadi ben Gawad Dam	n/a	n/a	n/a	n/a	n/a
10	Wadi Zaza Dam	n/a	n/a	n/a	n/a	n/a
11	Wadi Abu Mansour Dam	Destroyed by flood.	Destroyed by flood.	Destroyed by flood.	Destroyed by flood.	Destroyed by flood.
12	Wadi Darna (Alblad) Dam	Destroyed by flood.	Destroyed by flood.	Destroyed by flood.	Destroyed by flood.	Destroyed by flood.
13	Wadi Wishka Dam	n/a	n/a	n/a	n/a	n/a

Figure 4. Heatmap of average monthly water area (ha) for 13 dams in Libya (2016–2023)

Source: Authors' own elaboration.

Figure 4 represents the evolution of water extent around various dam sites in Libya (blue colour shed shows higher monthly water and red colour shed shows lower water area), assessed with the NDWI derived from Sentinel-2 satellite imagery. Noteworthy changes in water extent were observed in 2023 when compared to the mean values from 2016 to 2022. Only the Wadi Al-Magineen, Wadi Kaam, and Wadi Zaaret dams maintain relatively stable water areas, each covering more than 20 ha. In contrast, most of the other dams have an average water area of less than 10 ha throughout the year, which can pose challenges for providing sufficient water for irrigation and other supply needs.

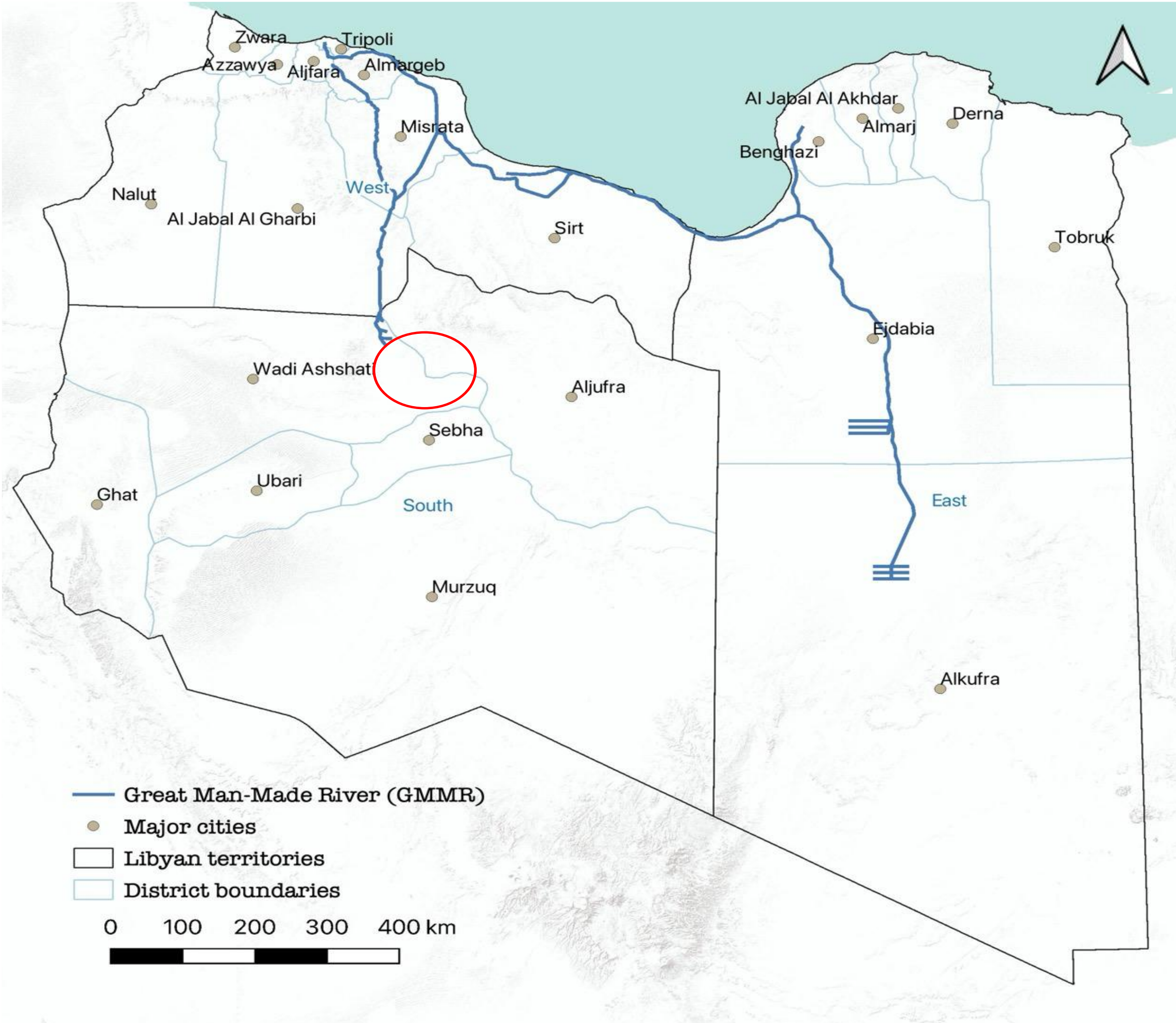
Status of well fields (WF)

The well fields (WF) are a crucial component of the nation's water infrastructure since they provide water to the system that transports it to the north. Table 5 displays the questionnaire's findings for well fields (WF). According to the assessment results, half of the wells were not operating. The assessment of the Jabal Hasouna well field (location in Figure 5) showed that 44.9 percent of the wells in the field were not functional. Consequently, there was a reduction of almost 50 percent of the targeted quantities to be collected to the water system (Table 5). The technical limitations, lack of maintenance and theft and vandalism were the main reasons behind this reduction.

The findings from the questionnaire showed that there are repeated cases of complete blackouts in the general electricity network in the western region. This situation created a major factor in the prevention of water pumping from the Jabal Hasouna system and caused some damage to the well field's electrical facilities. In addition, the well fields were subjected to repeated raids from armed groups.

The interruptions in water pumping at the Jabal Hasouna well field have highlighted the need for enhanced security measures, technological advancements, and efficient restoration processes. By addressing these aspects comprehensively, it can ensure a more reliable and sustainable water supply for the future.

Figure 5. Location of the Jebel Hasouna well field (in red circle)



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MMRPA (Man-Made River Project Authority). 2023. *Water Management Infrastructure and Reservoir Assessment Report*. Tripoli, Man-Made River Project Authority.

Status of seawater desalinization plants (SWD)

Desalination technologies have been used in Libya by oil companies in water shortage locations since the early 1960s (Abufayed and El-Ghuel, 2001). Since then, several seawater desalinization plants (SWD) have been constructed at various locations along the coast. There are about 21 desalination plants in operation currently, with a total daily capacity of 525.68 m^3. Thermal desalination facilities account for around 95 percent of operational desalination plants, while reverse osmosis membrane technology accounts for about 5 percent. In the year 2002, desalination contributed 1.4 percent to the whole local water supply (Ashour and Ghurbal, 2004). Table 6 shows the difference between the full operational capacities of some desalination plants and the existing capacities. According to the General Desalination Company of Libya (GDCOL), the existing desalination plant produced 70 Mm^3 in 2012 and has since reduced even further to 32 Mm^3 in 2023 (GDCOL, personal communication, 2023).

There have been major contracting, technical, operational, and maintenance problems associated with the desalination process (Abufayed and El-Ghuel, 2001). The technical contracting problems occurred due to limited local experience in the early 1960s and 1970s. Consequently, local constraints and factors were given little consideration in the design criteria, process technology, operation, and maintenance system. The operational and maintenance problems were caused by a lack of experienced personnel, spare parts, and materials. Water desalination technologies have faced many challenges. One of these challenges is that the actual capacities do not match the potential capacities, being only a small fraction of what might be anticipated (Kershman, 2001) The differences between the full operational capacities of some desalination plants and the existing capacities reached 95 percent, which raises an important question about the current technical and maintenance practices in place (Table 7).

Table 5. Status of water wells in the well fields subcategory (Category 1) (Jebel Hasouna well field)

ID	District name	Infrastructure name	Number of wells	Number of functional wells	Number of non-functional wells	Damage description
22	Ash Shati	Northeast Jabal Hasouna well field	167	80	87	Technical faults and lack of maintenance. Theft of cables and sabotage of power. transformers, the communications and control system. Destruction and burning of main and electrical substations.
23	Ash Shati	East of Jebal Hasouna well field	309	182	127	
24	Al Sarir	Al Sarir well field	126			
25	Tazrbo	Tazrbo well field	108			

Table 6. Seawater desalination plants (SWD) and their designed and current capacities in Libya

ID	District name	Infrastructure name	Designed daily capacity (m^3/day)	Current daily capacity* (m^3)	Latitude	Longitude
26	Tubruk	Tubruk desalination plant	40 000	13 135	32.0611	23.9786
27	Derna	Derna desalination plant	40 000	2 162	32.7794	22.5886
28	Al-Bombh	Al-Bombh desalination plant	30 000	0	32.5363	23.1036
29	Sousse	Sousse desalination plant	50 000	230	32.7147	21.9113
30	Benghazi	Abu Taraba desalination plant	40 000	41 450	32.6486	20.8238
31	Zeltin	Zeltin desalination plant	30 000	413	32.4995	14.5505
32	Zwara	Zwara desalination plant	80 000	0	32.8577	12.1719
33	Zawiyah	Zawiyah desalination plant	80 000	9 337	32.7902	12.6708
	Total		390 000	15 942.65		

*Daily rates calculated from six-month quantities for the first six months of 2023.

Source: **WRM (Water Resources Ministry**). 2023. *Water Infrastructure Status Report*. Tripoli, Water Resources Ministry.

Table 7. Comparison of total between designed capacities of seawater desalination plants (SWD) and their capacities in 2023

Year	Designed daily capacity (m^3)	Current daily capacity (m^3)	Reduction in capacity (%)
Total designed capacity	390 000	15 942	95.9

* Yearly rates estimated using the rates from the first six months.

Source: **WRM (Water Resources Ministry)**. 2023. *Water Infrastructure Status Report*. Tripoli, Water Resources Ministry.

There is a lack of accuracy with the available data and the information concerning the water from desalination plants and there is uncertainty about the number of plants in operation and their capacities. One of the main obstacles facing the gathering of data about desalination is that desalination plants belong to different authorities, even though they are all owned by the Government of Libya. The responsible authorities for the desalination plants are the General Electricity Company of Libya (GECOL), GDCOL and the General Company for Water and Wastewater (GCWW). Data obtained from GDCOL (GDCOL, personal communication, 2023) indicated that the total amount of desalinated water produced in 2010 from desalination plants belonging to the company was 71 Mm^3 whereas it was estimated to be reduced to 32 Mm^3.

Category 2: Storage (S)

This category provides comprehensive insights into the current condition and any incurred damages pertaining to substantial water storage infrastructures, specifically large agricultural reservoirs (LAR) as well as agricultural reservoirs and tanks (TAN). Table 8 shows geolocation of infrastructures for storage. These infrastructures play a pivotal role in water resource management within agricultural contexts, serving as crucial components for storing and regulating water supply for irrigation and other agricultural activities. By evaluating the status and potential damages of these reservoirs and tanks, it becomes possible to assess the effectiveness of water storage systems and plan for necessary maintenance or rehabilitation efforts to ensure sustained and efficient water supply for agricultural practices. This information is of paramount importance for safeguarding the productivity and resilience of the agricultural sector, especially in regions where reliable water access is necessary for successful crop cultivation and overall agricultural sustainability.

Figure 6. Distribution of water management infrastructures for water storage (Category 2) in Libya

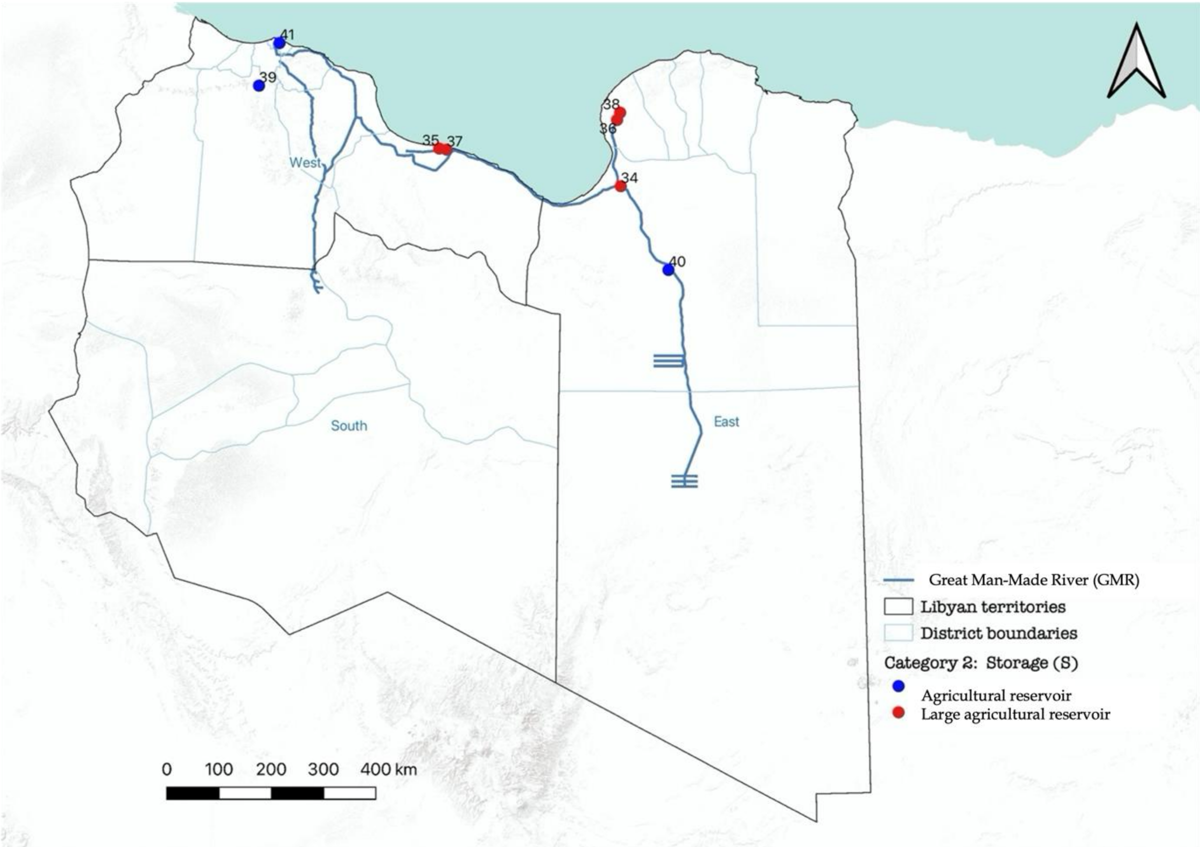

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Table 8. Geolocation of infrastructures for storage

ID	District name	Infrastructure name	Typology code	Typology	Latitude	Longitude
34	Ajdabiya	Ajdabiya Holding Reservoir	LAR	Large agricultural reservoir	30.5794	20.3491
35	Surt	Al Gardabiya Reservoir		Large agricultural reservoir	31.1622	16.6800
36	Bengahzi	Omar Mukhtar Reservoir		Large agricultural reservoir	31.7300	20.2652
37	Surt	The Gran Al Gardabiya Reservoir		Large agricultural reservoir	31.1477	16.8297
38	Bengahzi	The Grand Omar Mukhtar Reservoir		Large agricultural reservoir	31.8572	20.3266
39	Gharyan	Abu Zeyan Tank	TAN	Agricultural reservoir	32.0705	12.9700
40	Ajdabiya	Awjilah Tank		Agricultural reservoir	29.1269	21.3008
41	Tripoli	Tajura Tank		Agricultural reservoir	32.8308	13.3230

Status of large agricultural reservoirs (LAR)

Table 9 shows the storage capacity for large agricultural reservoirs. The five major reservoirs in Libya collectively provide a total storage capacity of 54 900 000 m^3), with the largest being the Grand Omar Mukhtar Reservoir in Benghazi (24 000 000 m^3) and the smallest being the Ajdabiya Holding Reservoir (4 000 000 m^3). The Gran Al Gardabiya Reservoir in Surt (15 400 000 m^3) also contributes significantly to the region’s water supply. These reservoirs are critical for supporting agricultural and domestic water needs, but issues like sedimentation and seasonal demand fluctuations may impact their efficiency.

Table 9. Storage capacity for large agricultural reservoirs

ID	District name	Infrastructure name	Category	Storage capacity (m^3)
34	Ajdabiya	Ajdabiya Holding Reservoir	S	4 000 000
35	Surt	Al Gardabiya Reservoir	S	6 800 000
36	Bengahzi	Omar Mukhtar Reservoir	S	4 700 000
37	Surt	Gran Al Gardabiya Reservoir	S	15 400 000
38	Bengahzi	Grand Omar Mukhtar Reservoir	S	24 000 000
Total storage capacity				54 900 000

Status of agricultural reservoirs and tanks (TAN)

The status of agricultural reservoirs and tanks (TAN) is a critical aspect of water resource management within the agricultural sector. Table 10 shows storage capacity for agricultural reservoirs and tanks (TAN). These infrastructures play a pivotal role in storing and regulating water supply for irrigation and other agricultural activities. Their condition directly impacts the efficiency and effectiveness of water storage systems, which in turn, has significant implications for crop cultivation and overall agricultural sustainability. Regular assessments are essential to ensure their structural integrity and functionality, including evaluating factors such as physical condition, leakage rates, sedimentation levels, and any signs of degradation or damage. Additionally, water quality parameters should be monitored to guarantee that stored water meets the required standards for agricultural use. Maintenance and rehabilitation efforts are crucial to address any identified issues and ensure their optimal performance. This may involve tasks such as desilting, repairing leaks or structural damage, and implementing erosion control measures. Moreover, routine inspections and preventive maintenance measures should be implemented to proactively identify and rectify potential issues before they escalate.

Table 10. Storage capacity for agricultural reservoirs and tanks (TAN)

ID	**District name**	**Infrastructure name**	**Category**	**Storage capacity (m^3)**
37	Gharyan	Abu Zeyan tank	S	300 000
38	Ajdabiya	Awjilah tank	S	
39	Tripoli	Tajura tank	S	

Category 3: Transportation (T)

The construction of the Great Man-made River (GMR) was initiated to address the severe shortage of fresh water along the Libyan coast, impacting urban, agricultural, and industrial needs. This involved the transportation of large quantities of water from underground reservoirs in the Jebal Hasouna, Tazerbo and Sarir basins through prestressed concrete pipes (canals). These pipes, with a diameter of up to 4 m, can initially transport 4 Mm^3 of fresh water per day. In this assessment, the transportation category consists of three main subcategories:

1. the main canal (MC);
2. the pumping station (PS); and
3. water flow monitoring points (WFM).

Status of the main canal (MC)

The main canal (MC) holds paramount importance in the water transportation system of the Great Man-Made Reservoir Project (GMMRP). Its primary function is to facilitate the transfer of water from the southern aquifers, sourced from well fields to the northern regions of the country. This water is subsequently stored in large agricultural reservoirs and agricultural tanks, serving as crucial repositories for the distribution of water resources to support agricultural production. As such, the main canal forms the backbone of the entire transportation network within the GMMRP, playing a pivotal role in ensuring a reliable and efficient supply of water to agricultural areas. Table 9 shows canal length for various water transportation systems. Figure 7 shows spatial distribution of water management infrastructures for water transportation (Category 3) in Libya

The operational status of the main canal is of critical significance in maintaining the overall functionality of the GMR. Routine assessments and inspections are imperative to ascertain its structural integrity, hydraulic efficiency, and overall operational performance. Factors such as water flow rates, sedimentation levels, and any signs of wear and tear are meticulously monitored to identify any potential issues that may hinder its optimal functioning. Furthermore, regular maintenance and timely repairs are essential to address any anomalies detected promptly. This may encompass activities such as desilting, clearing obstructions, reinforcing canal banks, and repairing any structural damage. The incorporation of advanced monitoring technologies, such as flow sensors and telemetry systems, can provide real-time data on water flow rates and alert operators to any deviations from normal operating conditions.

Table 11. Canal length for various water transportation systems.

ID	Water transportation system	Canal length (km)
1	Sarir/Sirt to Tazerbo/Benghazi	1 586
2	Hasouna to Jeffara Plain	983
3	Al-Gardabiya to Assdada	189
4	Ghadames via Zwara to Zawia	821
5	Al-Kufra to Tazerbo	385
6	Ajdabiya to Tobruk	Not complete

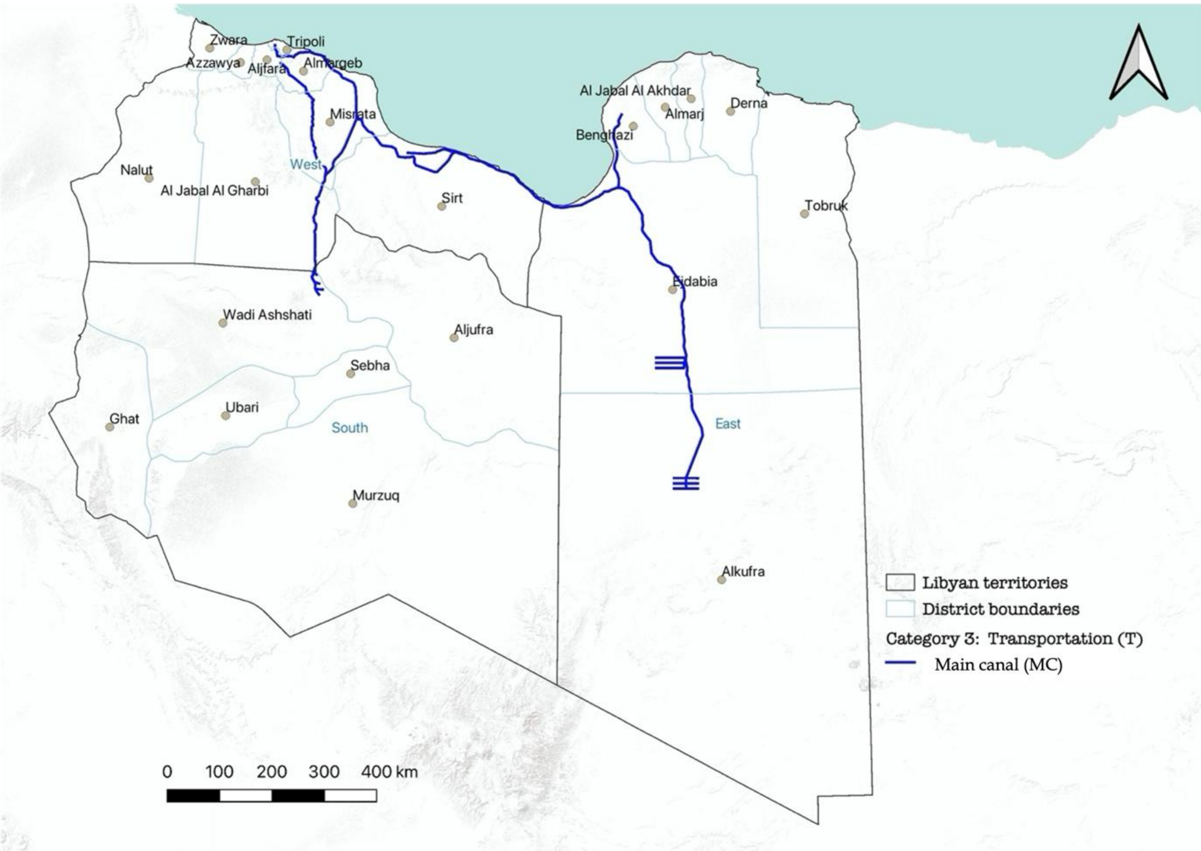
Status of pumping stations (PS)

The pumping station (PS) holds a crucial role in the GMMRP by managing the extraction and distribution of water resources from the well fields to the main canal and ultimately to the agricultural reservoirs and tanks. The operational status of the pumping station is of paramount importance to ensure a reliable and efficient water supply that supports agricultural production. Regular assessments are conducted to evaluate its mechanical integrity, electrical systems, and hydraulic performance. This includes monitoring the functionality of pumps, motors, valves, and associated control systems. Any signs of wear, inefficiencies, or malfunctions are promptly addressed to prevent disruptions in the water supply. Maintenance activities such as lubrication, alignment checks, and replacement of worn-out components are undertaken on a scheduled basis. Additionally, emergency response protocols are established to swiftly address unexpected failures or breakdowns, minimizing downtime, and ensuring an uninterrupted water supply.

Status of water flow monitoring points (WFMP)

Water flow monitoring points (WFMP) serve as critical instruments for tracking the movement and distribution of water within the GMMRP. These monitoring points are strategically located along the main canal and other key channels to provide real-time data on water flow rates, which is vital for optimizing water distribution and managing the overall system. The operational status of water flow monitoring points is regularly assessed to ensure accurate and reliable data collection. Calibration checks and sensor maintenance are conducted to verify the accuracy of flow measurements. Any discrepancies or anomalies are investigated and rectified to maintain the integrity of the monitoring system. Moreover, water flow monitoring points are equipped with telemetry and communication systems to facilitate seamless data transmission to the central monitoring station. This allows for an immediate response to any deviations from expected flow patterns and enables timely adjustments to water distribution strategies.

Figure 7. Spatial distribution of water management infrastructures for water transportation (Category 3) in Libya



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Drone-based canal monitoring

To enhance the efficiency and effectiveness of canal maintenance and management, the GMMRP utilizes a cutting-edge drone-based canal monitoring system. This innovative approach employs drones equipped with specialized infrared cameras to detect potential damage and leaks within the canal network.

One of the primary functions of this system is to identify potential leaks that may be hidden beneath the surface of the canal bed. Infrared cameras are employed to capture thermal imagery, allowing for the detection of "hot spots" where leaks may be occurring. This is achieved by observing the change in temperature of the surrounding sand, which occurs when water from a leak evaporates from the surface.

The use of infrared technology provides a unique advantage in leak detection. Traditional visual inspections may not always reveal hidden or subsurface leaks, making them challenging to identify. Infrared cameras, however, are capable of detecting temperature variations, highlighting areas where water is evaporating due to leakage. This allows for the precise pinpointing of potential trouble spots.

The utilization of drones offers several key benefits in canal monitoring. Drones provide a bird's-eye view of the entire canal network, enabling comprehensive coverage and reducing the need for manual inspections that can be time-consuming and resource intensive. Additionally, the high-resolution imagery captured by the infrared cameras allows for the accurate identification of potential issues, ensuring timely intervention and maintenance.

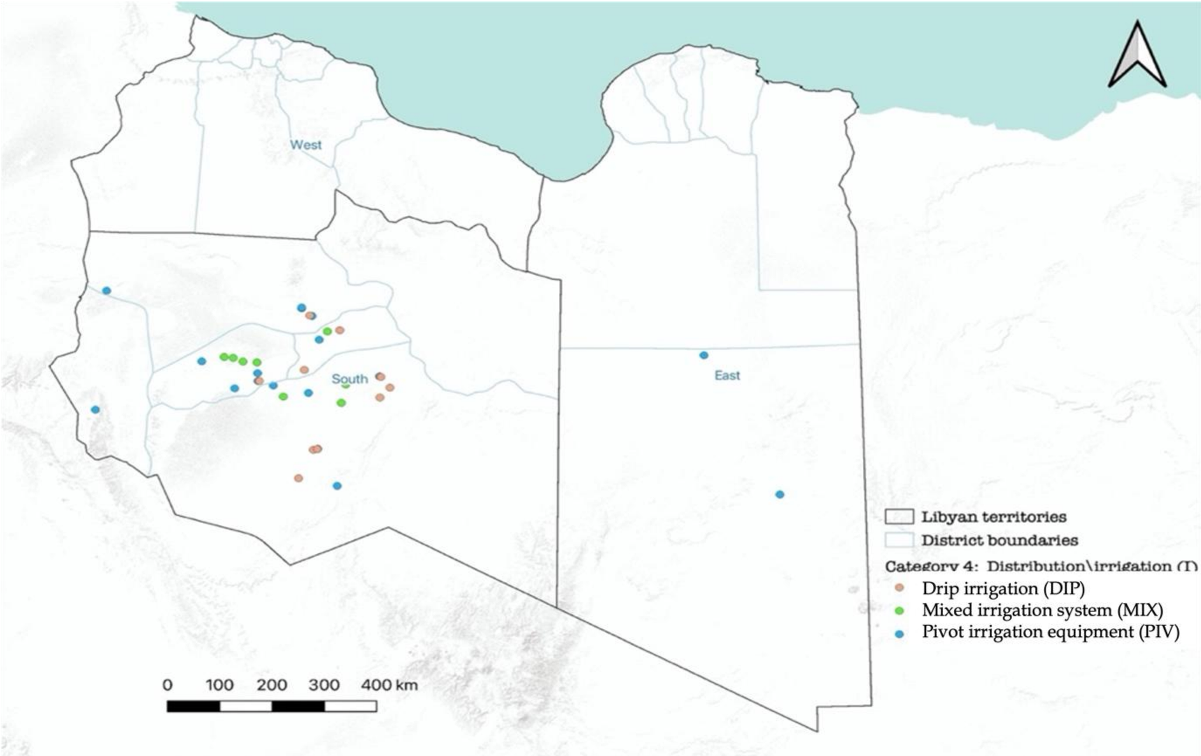
The data collected from the drone-based canal monitoring system is integrated into the central monitoring station of the GMMRP. This ensures that any identified damages or leaks are promptly addressed, minimizing the risk of further deterioration or disruption to the water supply.

Category 4: Distribution\irrigation (I)

Efficient water distribution and irrigation are crucial components of the GMMRP to ensure optimal agricultural productivity. To assess the effectiveness of irrigation infrastructure, a comprehensive monitoring system integrated both remote sensing data with ground-based field observations. Crop productivity, a key indicator of agricultural efficiency, was evaluated using the NDVI derived from remote sensing imagery. The NDVI provided insights into the health and vigour of vegetation, enabling the identification of areas with varying levels of crop growth and health. Water productivity, another vital metric, was assessed through the measurement of actual evapotranspiration using remote sensing techniques. This parameter reflected the efficiency of water use in relation to crop yield, offering valuable insights into the effectiveness of irrigation practices. Figure 8 shows geolocation of irrigation infrastructures (Category 4) in Libya.

This category encompasses an evaluation of various distribution and irrigation infrastructures, each playing a critical role in the efficient conveyance of water to agricultural fields. These infrastructures include pipes (PIP), pivot irrigation (PIV), local wells (WEL), irrigation pipes (IPI), drip irrigation systems (DIP), mixed irrigation systems (MIX), and sprinkler irrigation systems (SPR). The monitoring process adopts a combined approach, utilizing both on-the-ground field data collection and remote sensing technology. This approach ensured a comprehensive assessment of the irrigation infrastructure. The assumption is that remote sensing data captures changes in vegetation, which in turn reflect variations in crop productivity.

Figure 8. Geolocation of irrigation infrastructures (Category 4) in Libya



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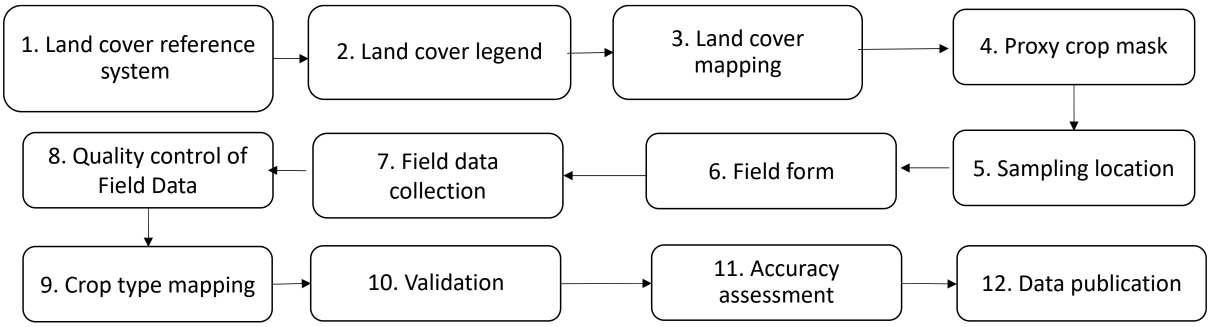
The NDVI served as a proxy for changes in water productivity. By integrating field observations with remote sensing data, the monitoring programme provided actionable insights for optimizing irrigation practices. By identifying infrastructure damage and inefficiencies, this will allow for timely repairs and improvements to be made, ultimately enhancing the overall efficiency of water distribution and irrigation systems.

Sampling design for irrigation infrastructure

The assessment of irrigation infrastructure through the integration of remote sensing and field data involved a structured approach, comprising of several key steps. Initially, a land representation system was established to accurately classify and represent land features. A land cover legend was then developed, serving as a reference guide for categorizing different types of land cover. Using remote sensing data, detailed land cover maps were created to depict the distribution and extent of various land cover types. A proxy crop mask was then applied to isolate areas dedicated to crop cultivation. The mapped area was further segmented into distinct regions based on similarities in spectral characteristics, followed by clustering to group segments with similar characteristics. Stratification was employed to create subgroups based on defined criteria, allowing for a more focused analysis. Sampling locations within these strata were selected for field data collection, ensuring representative samples. A structured data collection form was designed for recording information during field visits, which involved onsite assessments to gather ground truth data and verify remote sensing findings.

Figure 9. Methodological approach for sampling design for irrigation infrastructure (Category 4)



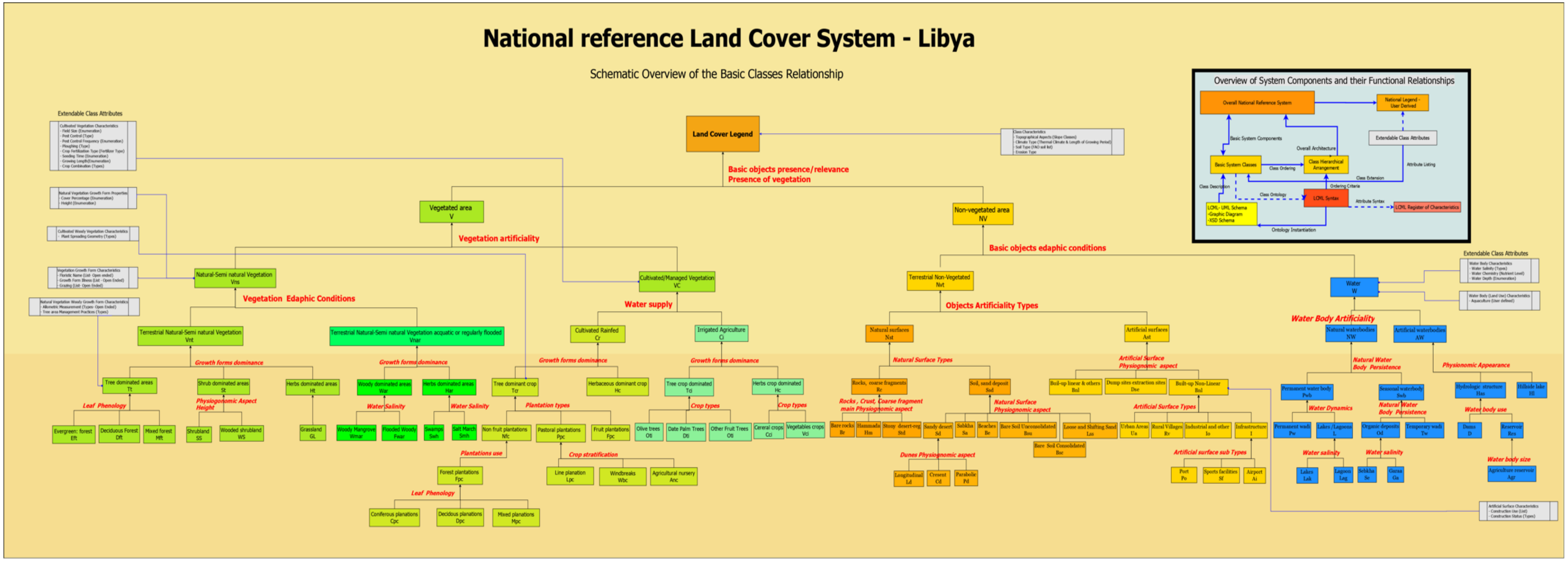
Source: Authors' own elaboration.

Rigorous quality assurance and quality control measures were implemented to ensure data accuracy and reliability. Finally, the collected data was analysed and synthesized to generate comprehensive results, providing valuable insights into the status and condition of irrigation infrastructure. This methodological framework combines advanced remote sensing technology with meticulous field data collection, ensuring a thorough and accurate assessment process. It enables informed decision-making and contributes to the optimization of water resource management in agricultural practices.

National land cover reference system (NLCRS)

The national land cover reference system (NLCRS) of Libya (Nwer *et al.*, 2023) is divided into four distinct levels for the complete understanding of all the land features in Libya (Figure 10). It provides the overall land representation system for mapping land cover and crop types, as well as further characterizing crop production considering biomass yields and water productivity. The NLCRS levels were generated with the help of the Land Cover Classification System (LCCS) v3 (De Gregorio, 2016). Each level is derived from one master category and are further granulated for identifying more distinct land cover categories, thus developing a land hierarchy.

Figure 10. The major structure of the national land representation system of Libya



Source: Nwer, B., Dadhich, G., Di Gregorio, A., Alkasih, A., Aboelsoud, H., Chenini, F., Mak, A. & Henry, M. 2023. *Libyan Land Cover Reference System*. Rome, FAO. https://doi.org/10.4060/cc7411en

Figure 11. Proposed land cover classes for Libya

Vegetated classes

Tree dominated area (Tt)
Evergreen forest (Eft)
Decidous forest (Dft)
Mixed forest (Mft)
Shrubland dominated area (St)
Shrubland (SS)
Wooded shrubland (WS)
Copse (CS)
Herbs dominated area (Ht)
Woody dominated area (War)
Woody mangrove (Wmar)
Tree mangrove (Tmar)
Herbaceous dominated area (Har)
Swamps (Swh)
Salt marsh (Smh)
Tree dominant crop (Tcr)
Non fruit plantation (Nfc)
Forest plantation (Fpc)

Coniferous plantation (Cpc)
Deciduous plantation (Dpc)
Mixed plantation (Mpc)
Pastoral plantation (Ppc)
other small size forest plantation (Opc)
Line plantation (Lpc)
Wind breaks (Wbc)
Agricultural nursery (Anc)
Fruit plantation (Fpc)
Herbaceous dominant crop (Hc)
Tree crop dominated (Tci)
Olive trees (Oti)
Date palm trees (Dti)
Other fruit trees (Ofti)
Herbaceous crop dominated (Hci)
Cereal crops (Cci)
Vegetable crops (Vci)

Vegetables
Onion
cucumber
tomatoes
Broccoli
Cabbage
Lettuce
Radish
peppers
Cabbage
Green chilli
Eggplant
melon
Celery

Crop
Wheat
Barley
Corn
Millet and Sorghum
Potato
Broad beans
Beans
Peas
Lentils
Peanuts

Non - vegetated classes

Rocks, coarse fragments (Rc)
Bare rocks (Br)
Hammada (Hm)
Stony desert – reg (Sd)
Soil, sand deposit (Ss)
Sandy desert (Sd)
Longitudinal (Ld)
Cresent (Cd)
Parabolic (Pd)
Sabkha (Sa)
Beaches (Be)
Bare soil unconsolidated (Bsu)
Bare soil consolidated (Bsc)
Loose and shifting sand (Lss
Builtup - non-linear (Bnl)
Urban areas (Ua)
Rural villages (Rv)
Industrial and other (Io)
Infrastructure (I)

Note: Crop type classes in red.

Source: Authors' own elaboration.

Creating a land cover legend of Libya

To ensure an accurate and consistent land cover classification across various regions and projects, the implementation of a standardized land cover reference system is imperative. Such a system provides a common framework and set of criteria for categorizing and mapping land cover types. This ensures that data collection and analysis methodologies are uniform, allowing for meaningful comparisons and reliable assessments of land cover changes over time. Additionally, a standardized reference system facilitates collaboration among different stakeholders, as it establishes a shared language and methodology for land cover classification. This ultimately enhances the effectiveness of land management and conservation efforts on both local and global scales.

The identification of the land cover classes was achieved through the analysis of the LCRS diagram (Figure 10). Figure 11 shows proposed land cover classes for Libya. For each ramification of the diagram, a group discussion with all the organizations involved, facilitated the understanding of which level of the system the land cover classes could be detected within the criteria considered. This allowed for the whole of Libya to be considered without gaps in the detected features.

Land cover map for Libya

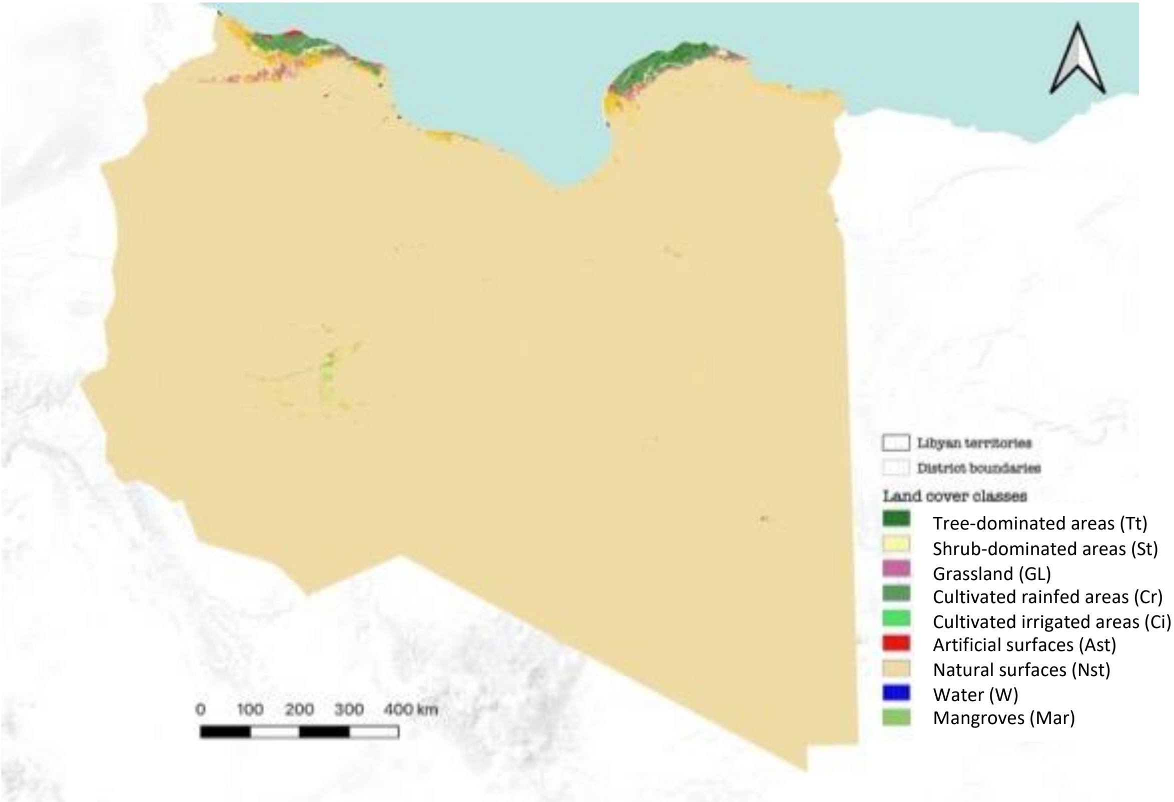
The land cover map of Libya as shown in Figure 12 and Table 13 provides land cover information across various districts in Libya and delineates the extent of different land cover classes. There are a total of nine classes in the national land cover map for Libya including shrubland, grassland, cultivated rainfed area, cultivated irrigated area, artificial surfaces, natural surfaces, water, aquatic vegetation, and tree-dominated areas. The result shows that the largest land cover classes in Libya (ha) are natural surfaces (Nst) at 158 360 ha (98 percent of the total land cover area), cultivated irrigated land at 1 087 540 ha (0.67 percent of the total land cover area), and cultivated rainfed land at 1 049 540 ha (0.64 percent of the total land cover area). Table 12 shows land area statistics in 2022 by land categories at district level in Libya.

In the east region, the total land area is 75 124 750 ha, in which natural surfaces cover approximately 98 percent of the total land cover area (73 626 420 ha), with cultivated land comprising around 1.13 percent of the total land cover area (848 900 ha). Tree-dominated areas account for roughly 0.3 percent of the total land cover area, while grasslands, shrublands, and artificial surfaces represent approximately 0.29 percent, 0.24 percent and 0.02 percent of the total land cover area, respectively.

In the west region, the total land area is 27 549 770 ha, in which natural surfaces cover approximately 93 percent of the total land cover area (25 849 390 ha), followed by cultivated land, comprising around 4 percent of the total land cover area (1 128 810 ha) and grasslands, comprising around 1.1 percent of the total land cover area (319 180 ha).

In the Fezzan region, the total land area is 59 565 510 ha, of which natural surfaces cover approximately 99 percent of the total land cover area (59 380 530 ha), followed by cultivated irrigated land comprising around 0.27 percent of the total land cover area (159 410 ha), and tree-dominated areas covering around 0.02 percent of the total land cover area (10 750 ha).

Figure 12. Land cover map of Libya



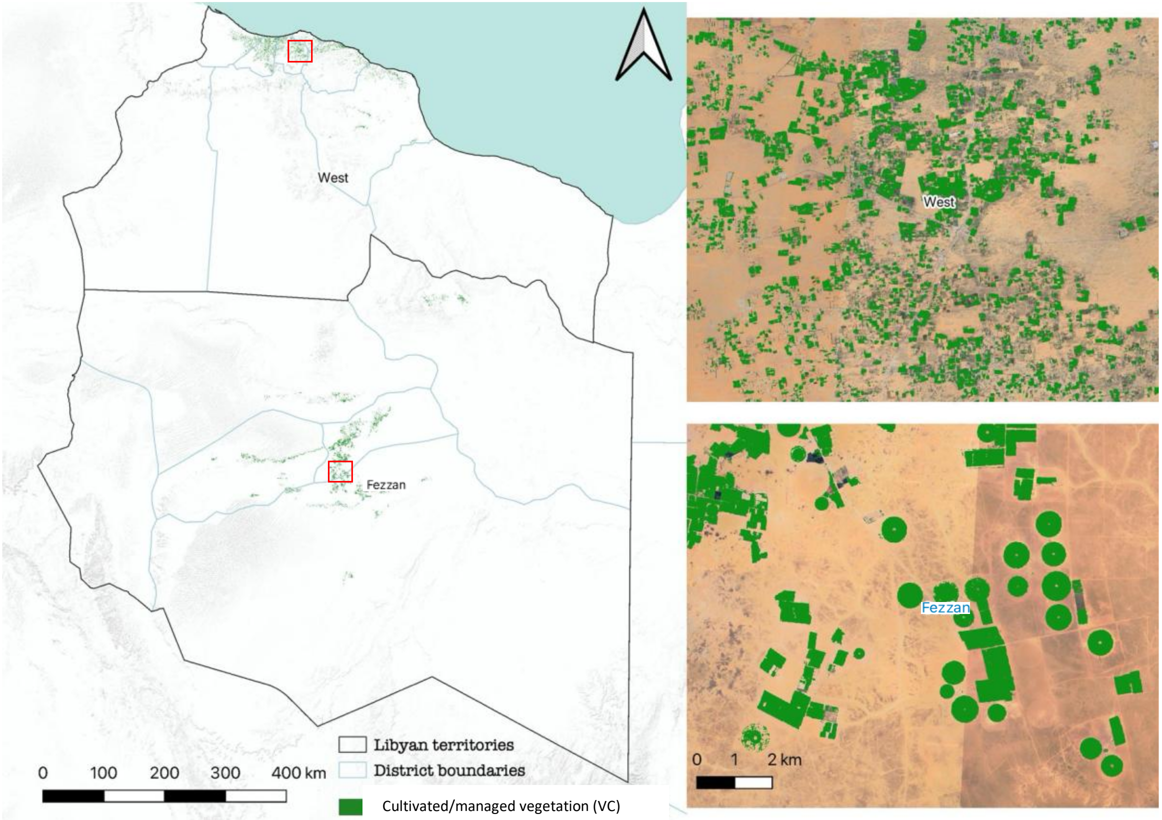
Note: Refer to the disclaimer on page ii for the names and boundaries used in this map.
Sources: Administrative boundaries from **HDX**. 2023. Libya Data Grid. Libya – Subnational Administrative Boundaries. [Accessed on 23 April 2023]. https://data.humdata.org/dataset/cod-ab-lby. License: CC-BY-IGO.

Table 12. Land area statistics in 2022 by land categories at district level in Libya

Region	District	Shrubland-dominated areas (St)	Grassland (GL)	Cultivated rainfed areas (Cr)	Cultivated irrigated areas (Ci)	Artificial surfaces (Ast)	Natural surfaces (Nst)	Water (W)	Aquatic vegetation (Vnar)	Tree-dominated areas (Tt)	Total land area (ha)
East	Al Jabal Al Akhdar	39 990	33 310	100 700	10 850	1 950	627 750	10	30	93 670	908 260
	Alkufra	140	130	n/a	7 940	860	41 096 270	80	10	3 100	41 108 520
	Almarj	62 140	34 980	197 130	13 240	1 520	731 220	n/a	20	71 740	1 111 990
	Benghazi	24 780	72 170	176 530	156 940	7 250	963 180	4 390	40	15 700	1 420 960
	Derna	50 470	68 360	66 420	23 160	3 180	1 977 320	90	40	36 540	2 225 590
	Ejdabia	560	1 470	20	25 640	1 380	20 078 710	1 890	n/a	3 030	20 112 700
	Tobruk	1 570	9 380	1 010	69 320	1 980	8 151 970	1 100	n/a	380	8 236 700
Fezzan (south)	Aljufra	250	660	n/a	9 710	480	11 702 580	n/a	n/a	850	11 714 530
	Ghat	540	280	n/a	1 150	200	5 030 310	n/a	n/a	290	5 032 770
	Murzuq	400	800	n/a	42 530	540	27 540 990	n/a	n/a	2 920	27 588 170
	Sebha	480	1 550	n/a	75 230	1 810	1 646 930	10	n/a	1 700	1 727 720
	Ubari	570	1 000	n/a	23 320	530	3 202 090	10	n/a	2 720	3 230 230
	Wadi Ashshati	3 030	930	n/a	7 470	750	10 257 630	n/a	10	2 270	10 272 090
West	Al Jabal Al Gharbi	17 170	116 540	3 300	89 530	4 430	7 707 400	20	n/a	140	7 938 530
	Aljfara	13 010	27 260	144 980	65 210	10 500	20 990	20	n/a	160	282 130
	Almargeb	76 430	83 160	141 520	120 440	3 890	291 410	90	n/a	1 310	718 230
	Azzawya	32 940	10 450	69 920	72 220	10 250	96 230	n/a	n/a	140	292 140
	Misrata	9 200	34 730	65 830	64 400	8 330	2 864 960	4 880	40	5 770	3 058 150
	Nalut	2 200	12 180	30	4 600	150	6 710 170	n/a	n/a	120	6 729 460
	Sirt	4 040	7 430	9 670	78 740	600	7 695 300	2 970	n/a	190	7 798 950
	Tripoli	980	8 970	45 860	3 730	23 830	5 110	40	n/a	740	89 250
	Zwara	9 890	18 460	26 640	122 190	4 860	457 820	2 950	n/a	110	642 930
	Total class area (ha)	**350 760**	**544 210**	**1 049 540**	**1 087 540**	**89 280**	**158 856 360**	**18 530**	**180**	**243 590**	**162 240 000**

Note: n/a = not available.

Figure 13. Extent of cropland areas in 2022 in Fezzan and west Libya



Note: Refer to the disclaimer on page ii for the names and boundaries used in this map.
Sources: 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.

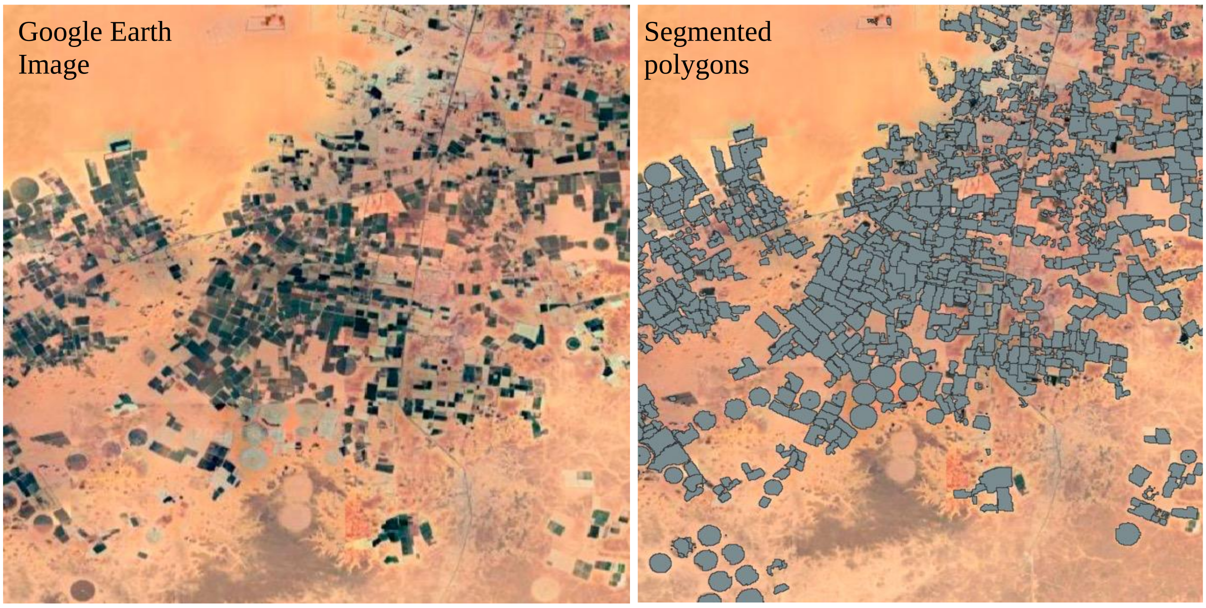
Proxy crop mask

The cropland area extent for the year 2022 was derived by merging two land cover classes: cultivated rainfed areas (Cr) and cultivated irrigated areas (Ci) using land cover data. The cultivated rainfed areas (Cr) class encompasses areas where agricultural activities rely solely on rainfall for crop growth. This class is pivotal for understanding the extent of agriculture that is subject to the vagaries of climate variability, and which plays a fundamental role in rainfed farming systems. On the other hand, the cultivated irrigated areas (Ci) class includes lands where agricultural production is enhanced through the application of irrigation, indicating regions with infrastructure capable of supplementing water, regardless of seasonal changes. Figure 13 shows extent of cropland areas in 2022 in Fezzan and west Libya.

Field boundary delineation using segmentation

The segmentation of the Landsat-8 data to delineate field boundaries appears to be quite effective, as shown in Figure 14 In the original Google Earth image, individual fields and plots are visually distinguishable by their colour variations and shapes but lack clear boundaries. In the segmented image, each field or plot is outlined, creating distinct, polygon-shaped areas that represent different parcels of land. Key observations from the segmentation results are as follows:

Figure 14. Parcel segmentation to extract farm boundaries



Note: Refer to the disclaimer on page ii for the names and boundaries used in this map.
Sources: Authors' own elaboration and **Earth Engine**. 2023. A planetary scale platform for Earth science data & analysis. [Accessed on 22 September 2023]. https://earthengine.google.com/. Licence: CC-BY-4.0.

- **Increased clarity and precision**: The segmentation process was able to transform the somewhat blended areas of the original image into clearly demarcated plots. This is crucial for precision agriculture practices where specific management actions are applied to individual plots based on their unique characteristics.
- **Area calculation and analysis**: With clearly outlined fields, it was then possible to calculate the area of each plot more accurately. This data is essential for various agricultural needs, including seeding rates, fertilization, and irrigation planning.
- **Improved monitoring and management**: The delineated boundaries make it easier to monitor changes over time within specific fields, assess the effectiveness of different agricultural interventions, and manage resources more efficiently.
- **Data integration and accessibility**: The structured format of the segmented polygons allows for the easier integration with other geospatial data layers (such as soil types, crop types, or historical yield data), facilitating complex analyses and decision-making processes.

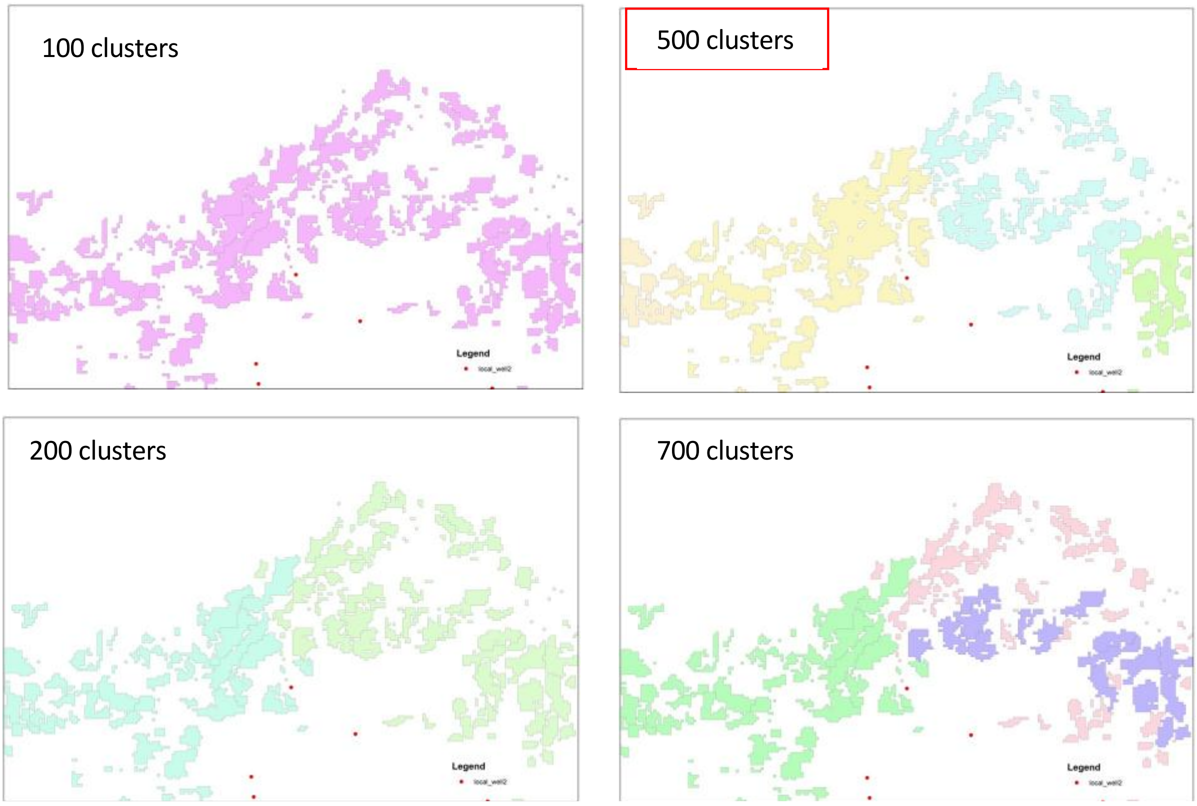
Cluster analysis

The cluster analysis depicted in Figure 15 effectively illustrates how data segmentation can be optimized to better understand and categorize the size of a land parcel. It shows clustering at four different intensities: 100 clusters, 200 clusters, 500 clusters, and 700 clusters. This approach, leveraging the KNN algorithm, aims to group data points with similar characteristics into clusters, thus enabling more precise agricultural and land management strategies.

The increase in the number of clusters from 100 to 700 shows a transition from broad to more detailed segmentation. Fewer clusters (100 and 200) present a more generalized view of the region, useful for large-scale management and planning. In contrast, higher numbers (500 and 700) provide detailed insights, which are critical for fine-tuning specific interventions in precision agriculture or detailed environmental monitoring.

Selecting the optimal number of clusters is crucial for balancing between oversimplification and excessive granularity. While 500 clusters might provide a good middle ground for detailed analysis without becoming too complex, the choice ultimately depends on the specific needs of the project, such as the scale of agricultural activities or the precision required for environmental monitoring. Figure 16 shows selection of number of clusters based on cluster area and number of parcels.

Figure 15. Testing cluster intensity for selection



Source: ESRI (Environmental Systems Research Institute). 2024. ArcGIS Desktop: Release 10.9. In: *ESRI*. Redlands, USA. [Cited 20 August 2023].

Figure 16. Selection of number of clusters based on cluster area and number of parcels

Source: Authors' own elaboration.

Stratification

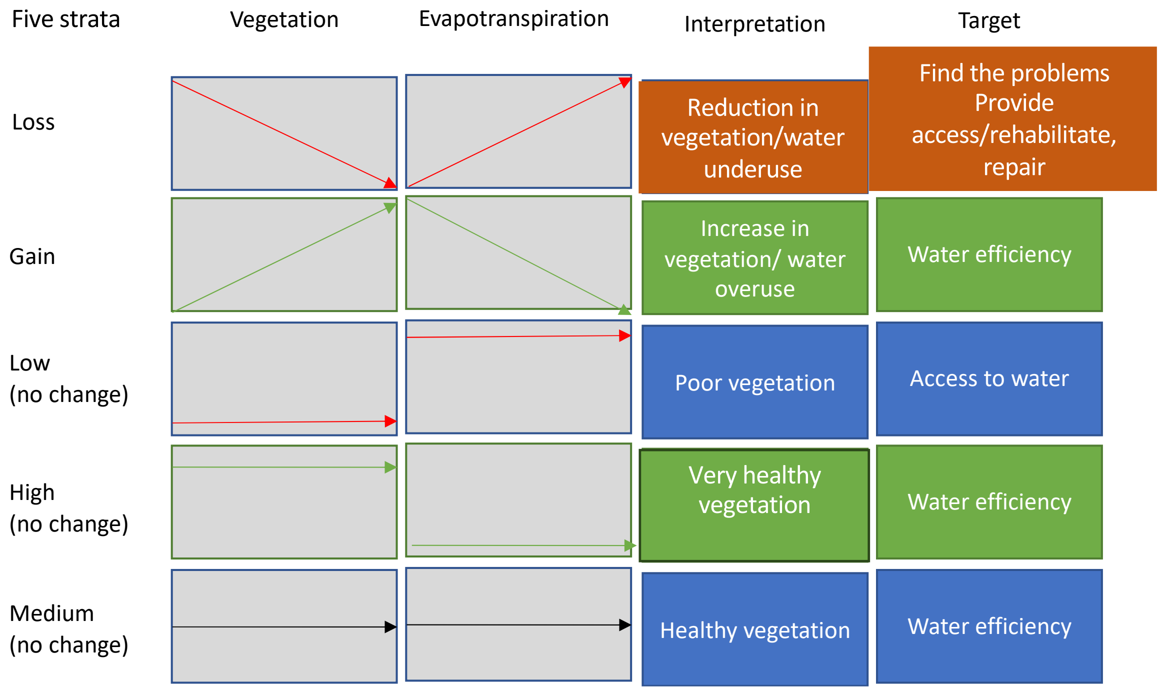
The stratification results in Figure 17 and 18, shows an analysis of vegetation health over an 11-year period, leveraging NDVI and actual evapotranspiration data. This data was processed to classify land into five categories: gain; high (no change); medium (no change); low (no change); and loss. This classification was critical for identifying areas where agricultural productivity was improving, stable, or declining, which could significantly inform targeted agricultural management and intervention strategies.

The gain class denotes areas with significant increases in vegetation health (with an NDVI increase greater than 0.3), suggesting successful agricultural or ecological management, or favourable climatic conditions. Conversely, the loss class indicates areas where vegetation health has substantially declined (NDVI decrease less than −0.3), which might be due to factors like water stress, land degradation, or overutilization of the land.

Areas classified as high (no change), medium (no change), and low (no change), have shown stability in vegetation health, which is crucial for sustainable agricultural practices. These categories help in understanding different levels of biomass stability, with high (no change) likely representing well-managed, fertile, and productive lands.

This detailed stratification allows for targeted interventions in areas classified under the loss category, while areas under gain can be studied for successful practices that can be replicated in other regions. The three no change categories also help in monitoring stability or detecting subtle changes over a longer period, essential for long-term environmental and agricultural planning.

Figure 17. Categories of stratification



Source: Authors' own elaboration.

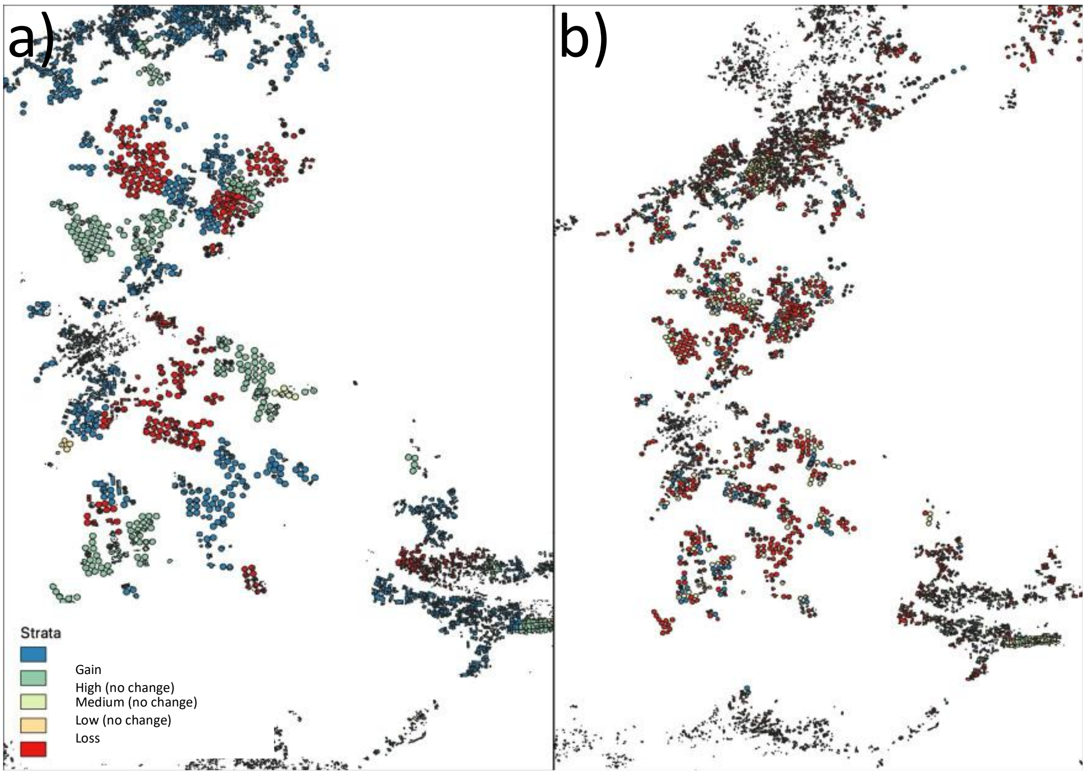
Allocation of sampling locations

To ensure a representative sample for the study, a stratified sampling approach was employed. This involved selecting an equal number of clusters from different strata, so that a comprehensive overview of the target population could be captured. Out of the total of 90 clusters identified, 18 clusters were allocated to each of the following categories: gain, high (no change), medium (no change), low (no change), and loss. The selection process was carried out through a random sampling technique, further enhancing the robustness and generalizability of the findings. This methodological approach minimized bias and allowed for the inclusion of a diverse range of clusters, each contributing unique insights to the analysis.

In total, 90 clusters were randomly selected, comprising a total of 450 parcels from each stratum. Within each selected cluster, we further refined our sample by selecting five parcels for detailed investigation. To facilitate efficient data collection, we identified the centroid for each of the selected parcels. These centroids served as precise geographic references, ensuring that field data collection was conducted accurately and consistently across all sampled parcels.

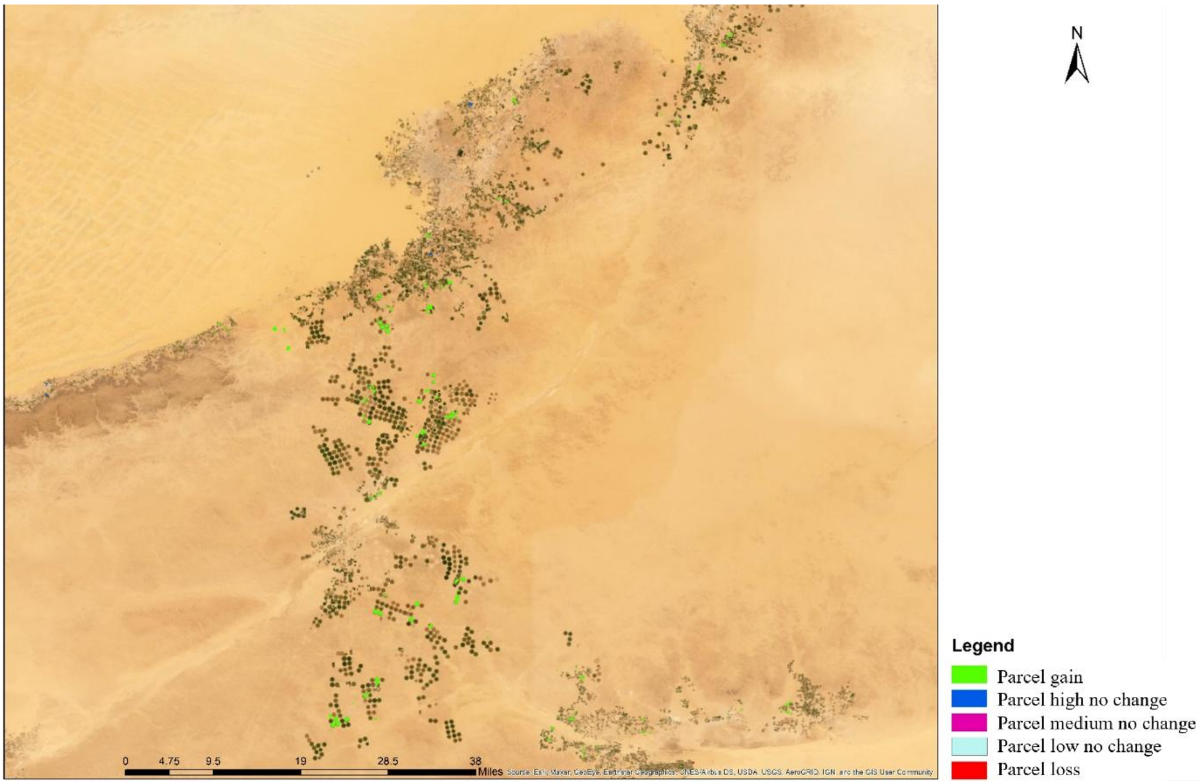
By systematically distributing the samples across the strata, the aim was to obtain a comprehensive understanding of the dynamics and characteristics within each category. This comprehensive approach meant that it was possible to draw meaningful conclusions and make informed recommendations based on the nuanced variations observed across different strata. It also ensured that the findings could be applied more broadly, providing valuable insights for a wide range of stakeholders in relevant fields. The allocation and geolocation of selected land parcels within the six districts of Fezzan, Libya. Figure 19 provides a spatial representation of the selected land parcels, illustrating their geographic distribution across the study area. Additionally, Figure 20 presents the geolocation of the centroid of these selected parcels, offering a centralized reference for spatial analysis. To further elaborate on the clustering of land parcels, Table 13 summarizes the number of clusters allocated in the six districts, highlighting variations in cluster density across different locations. Table 14 details the total area occupied by these clusters, providing insight into the spatial extent of land allocation in each district. Moreover, Table 15 presents the number of selected parcels within these clusters, demonstrating the distribution of individual parcels across the study region.

Figure 18. Classification of clusters based on the a) Landsat Normalized Difference Vegetation Index (NDVI) and b) actual evapotranspiration



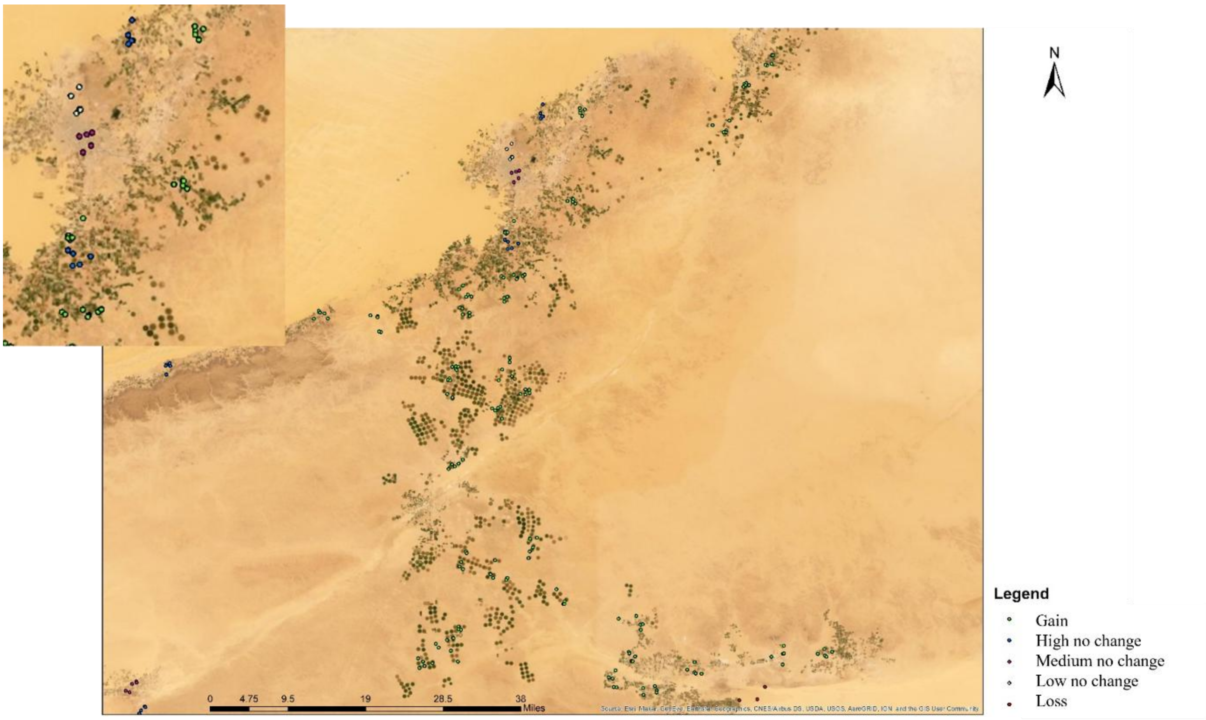
Source: Authors' own elaboration and **USGS (United States Geological Survey).** n.d. Landsat Data Access. In: *USGS*. Washington, DC. [Cited 20 August 2022]. https://www.usgs.gov/landsat-missions/landsat-data-access

Figure 19. Geolocation of selected land parcels



Source: Authors' own elaboration and **USGS (United States Geological Survey).** n.d. Landsat Data Access. In: *USGS*. Washington, DC. [Cited 20 August 2022]. https://www.usgs.gov/landsat-missions/landsat-data-access

Figure 20. Geolocation of centroid of selected parcels



Source: Authors' own elaboration and **USGS (United States Geological Survey).** n.d. Landsat Data Access. In: *USGS*. Washington, DC. [Cited 20 August 2022]. https://www.usgs.gov/landsat-missions/landsat-data-access

Table 13. Number of clusters allocated in six districts of Fezzan, Libya

Districts	District area (ha)	Number of parcels	Number of clusters						
			Total area of parcels (ha)	Total	Strata				
					Gain	High (no change)	Medium (no change)	Low (no change)	Loss
Aljufra	1 160 1364	6 149	9 950	73	9	23	22	16	3
Wadi Ashshati	10 176 191	5 263	10 652	73	9	23	23	14	4
Sebha	1 721 922	10 055	64 097	126	62	24	4	10	26
Ubari	3 242 765	7 643	22 475	76	1	32	14	13	16
Murzuq	28 081 733	11 774	39 410	150	29	41	32	32	16
Ghat	5 083 983	56	178	2	0	0	1	1	0
Total	**59 907 958**	**40 940**	**146 761**	**500**	**110**	**143**	**96**	**86**	**65**

Table 14. Area of clusters allocated in six districts of Fezzan, Libya

Districts	Total area (ha)	Number of selected clusters					
		Total	Strata				
			Gain	High (no change)	Medium (no change)	Low (no change)	Loss
Aljufra	11 601 364	11	4	2	3	2	0
Wadi Ashshati	10 176 191	11	0	4	5	2	0
Sebha	1 721 922	25	11	3	1	0	10
Ubari	3 242 765	17	0	4	2	3	8
Murzuq	28 081 733	25	3	5	7	10	0
Ghat	5 083 983	1	0	0	0	1	0
Total	**59 907 958**	**90**	**18**	**18**	**18**	**18**	**18**

Table 15. Number of selected parcels in six districts of Fezzan, Libya

Districts	Total number of parcels	Gain		High no change		Medium no change		Low no change		Loss	
		Number of parcels	Area (ha)	Number of parcels	Area (ha)	Number of parcels	Area (ha)	Number of parcels	Area (ha)	Number of parcels	Area (ha)
Aljufra	55	20	72	10	55	15	92	10	77	0	0
Wadi Ashshati	55	0	0	20	100	25	254	10	89	0	0
Sebha	125	55	521	15	139	5	119	0		50	1 102
Ubari	85	0	0	20	129	10	56	15	205	40	1 498
Murzuq	125	15	78	25	190	35	165	50	427	0	0
Ghat	5	0	0	0	0	0	0	5	50	0	0
Total	**450**	**90**	**671**	**90**	**613**	**90**	**687**	**90**	**848**	**90**	**2 600**

Field data collection

Field campaigns were conducted in Fezzan during December 2022 and in the northwest region during June 2023. In total, 450 and 150 samples were collected in Fezzan and northwestern regions during December 2022 and June 2023 respectively (see previous section for sample calculation). Field data collection was conducted using the Kobo Toolbox (Kobo Toolbox, 2023) (Annex I). A training programme took place from 10 to 15 September 2022, for the ground data collection team, using a mobile application for data collection, to train the country team on post-processing of the data collected and to plan the next steps. Prior to the fieldwork, a number of districts were selected to sample different landscapes in areas with large agricultural areas. The data were collected using the Kobo Toolbox application. In total around 600 individual valid data points were submitted into the server.

The field data collected under the IagWat project included the following information:

- Agriculture:
  - Crop type.
  - Total agriculture area served by infrastructure (ha).
  - Average yield per hectare (tonne/ha).
  - Date of plantation.
  - Date of harvesting.
  - Total agricultural area (ha).
  - Water source.
  - Crop production (kg/ha).
  - Crop market price (LD/kg).

- Farming system:
  - Type of farming system.
  - Typology name.

- Infrastructure:
  - Function (operational status).
  - Partially functional status.
  - Infrastructure damage (please specify other damages).
  - Visual damage impacts (please specify other visual damage impacts).

- Local wells:
  - Number of wells.
  - Number of functional wells.
  - Number of partially functional wells.
  - Number of non-functional wells.
  - Depth (m).
  - Water quality (ppm).
  - Status of well construction.

- Pivot irrigation equipment:
  - Water source.
  - Power transmission
  - Controls.
  - Electrical parts.
  - Accessories.
  - Water distribution components.

- Drip irrigation:
  - Water source.
  - Pump and prime mover.
  - Filtration devices.
  - Control devices.
  - Chemical injectors.
  - Pipe network.

- Sprinkler irrigation:
  - Water source
  - Pumping unit.
  - Pipes.
  - Couplers.
  - Sprinkler head.
  - Pressure gauge.
  - Water meters.
  - Fertilizer applicator.

The field data collected under the MerWat project included information about vegetation cover, non-vegetated cover, irrigation systems, fertilization, grazing, pests, burnt areas, and waterbodies. The following is a summary of the different categories:

- Vegetation cover:
  - Vegetated areas (V).
  - Natural and semi-natural vegetation (Vns).
  - Terrestrial natural and semi-natural vegetation (Vnt).
  - Tree-dominated areas (Tt).
  - Shrub-dominated areas (St).
  - Terrestrial natural and semi-natural aquatic or regularly flooded vegetation (Vnar).
  - Wood-dominated areas (War).
  - Herbaceous-dominated areas (Har).
  - Cultivated/managed vegetation (Vc).
  - Tree crops (Tcr).
  - Forest plantation (Fpc).
  - Pastoral plantation (Ppc).
  - Other small-sized forest plantations (Opcr).

- Cultivated irrigated areas (Ci).
- Tree crops (Tci).
- Other fruit trees (Ofti).
- Herbaceous crops (Hci).
- Cereal crops (Cci).
- Vegetable crops (Vci).
- Fodder crops (Fci).

- Irrigation system:
  - Irrigation system type.

- Other parameters:
  - Fertilization.
  - Grazed percentage.
  - Pest percentage.
  - Burnt percentage.

- Non-vegetated cover types:
  - Non-vegetated areas (Nv).
  - Terrestrial non-vegetated (Nvt).
  - Natural surfaces (Nst).
  - Rocks, coarse fragments (Rc).
  - Soil, sand deposits (Ss).
  - Sandy desert (Sd).
  - Artificial surface (Ast).
  - Built-up, non-linear (Bnl).
  - Infrastructure (I).

- Waterbody types:
  - Permanent waterbody (Pwb).
  - Seasonal waterbody (Swb).
  - Organic deposits (Od).
  - Artificial waterbodies (Aw).
  - Hydrologic structures (Has).
  - Reservoirs (Res).

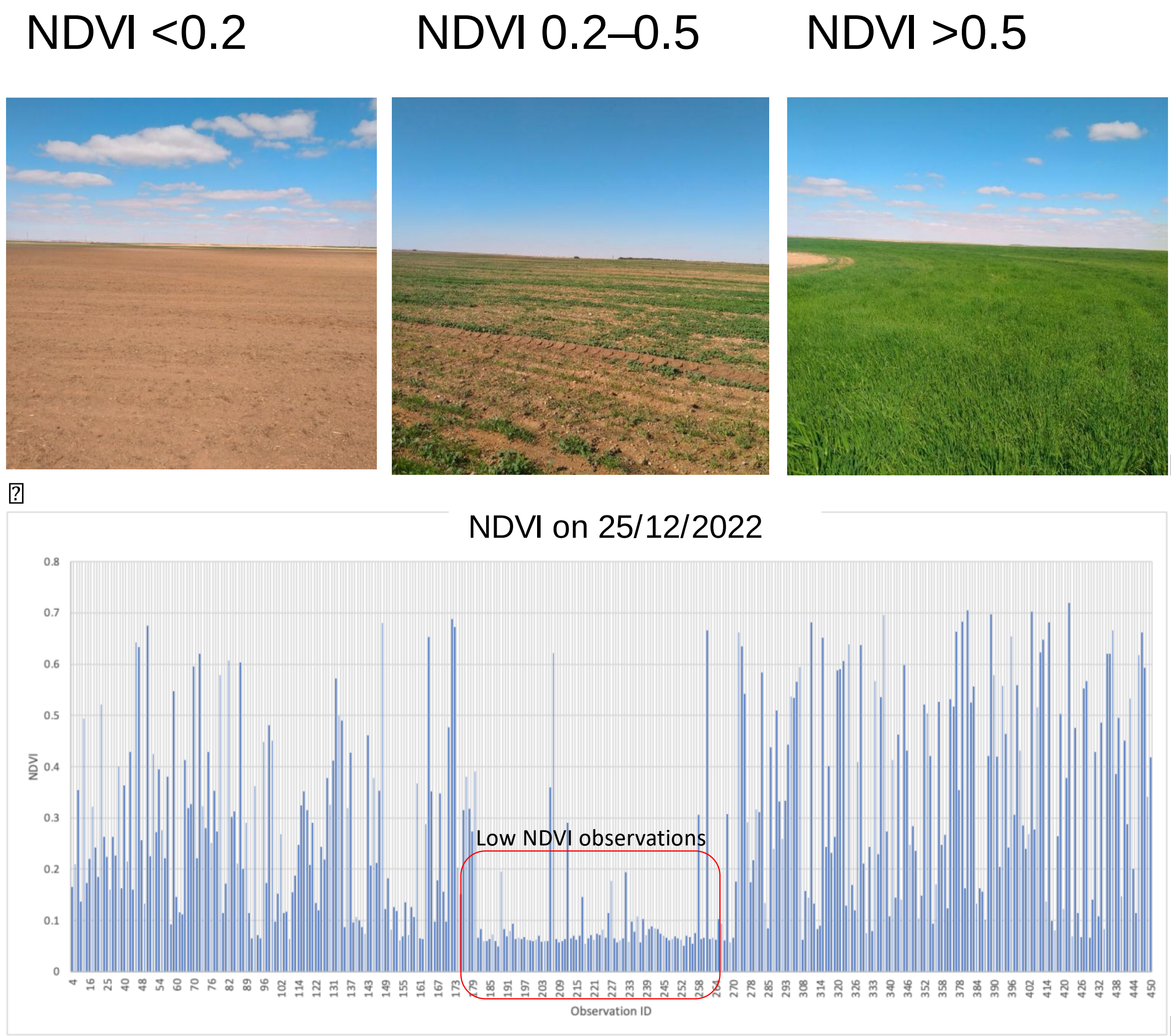
- Type of water dynamics:
  - Presence of water (start of month).
  - Presence of water (end of month).
  - Percentage of waterbody coverage.
  - Water depth.
  - Water salinity.

Quality control

The objective of quality control was to validate and enhance the quality of collected field data. To ensure data accuracy, the quality control procedures involved the following measures:

1. **Photo interpretation**: This involved visually analysing the remote sensing images to validate the correctness of the assigned polygon codes and identify any potential discrepancies.
2. **Assessing the temporal stability of the NDVI profiles of different classes at the sampling locations**. By examining the consistency of NDVI values over time, the accuracy of the assigned crop classes could be verified. Figure 22 shows the NDVI of field samples collected. Areas with a low NDVI signify that crops were just sown or at the start of their growing season. Field samples with low NDVI (negative) were discarded in the analysis.
3. **Extracting NDVI values at the sampling locations**: This involved obtaining the specific NDVI values for the identified sampling locations, which served as additional validation for the accuracy of the assigned crop classes.

Figure 21. Validation of ground data using NDVI



Source: Authors' own elaboration.
Photo credit: © FAO/ Bashir Nwer

Status of irrigation infrastructure

The analysis explores the status and condition of key agricultural infrastructure crucial for distribution and irrigation. This encompasses a variety of infrastructures, each with its specific utility and impact on the agricultural productivity of the region.

Pipes (PIP)

Pipes (PIP) form the baseline infrastructure facilitating the distribution of water across vast expanses of agricultural land. The assessment illustrates the pivotal role they play in ensuring a consistent water supply, essential for the cultivation of crops. The condition of the pipes, as revealed by the field and remote sensing analysis, significantly influences the efficiency of water distribution, impacting the overall productivity and sustainability of agriculture in the region.

Pivot irrigation equipment (PIV)

Pivot irrigation (PIV) is a modern and efficient irrigation system, substantially contributing to the optimization of water use. The analysis highlights the functionality of pivot irrigation in enhancing water distribution, ensuring that crops receive adequate water, particularly during dry spells. The status of this equipment, as captured through remote sensing, reflects its effectiveness and the potential need for upgrades or maintenance to uphold its operational efficiency.

Local wells (WEL)

Local wells (WEL) represent a traditional yet significant water source for many agricultural areas within Fezzan. The assessment highlights their indispensable role in providing a reliable water supply, especially in regions where other water sources may be scarce. The condition and accessibility of these wells directly correlate with the ability of local farmers to sustain their agricultural practices.

Irrigation pipes (IPI)

Irrigation pipes (IPI) are integral components of the irrigation framework, channelling water from the sources to the fields. The analysis underscores their condition and the extent to which they effectively fulfil their function. It also sheds light on areas where the infrastructure may require repairs or replacements to prevent water loss and ensure efficient irrigation.

Drip irrigation (DIP)

Drip irrigation (DIP) stands out as a crucial water-conservative irrigation method in arid regions like Fezzan. The assessment demonstrates its impact in minimizing water wastage and promoting the efficient use of water resources. The operational status of the drip irrigation systems, as gauged through the analysis, provides insights into their effectiveness and potential areas for improvement.

Mixed irrigation system (MIX)

A mixed irrigation system (MIX) is a blend of different irrigation techniques tailored to the unique needs of the region. The assessment illustrates how this system leverages the advantages of various irrigation methods to optimize water use. The data, drawn from field and remote sensing analysis underscores the operational efficacy of the mixed irrigation systems in meeting the diverse water needs of the agricultural landscape in Fezzan.

Sprinkler irrigation (SPR)

Sprinkler irrigation (SPR) is a pivotal irrigation technique employed across the Fezzan region, mirroring a rain-like watering system that is both efficient and conducive for various crop types. Utilizing a combination of field observations and remote sensing data, the analysis explores the operational status and effectiveness of the sprinkler irrigation systems in place and defines the impact of sprinkler irrigation on the agricultural output of the region.

The evaluation underscores the strategic importance of sprinkler systems in ensuring a uniform distribution of water across the fields. This uniformity plays a crucial role in averting waterlogging and ensuring that soil moisture levels are conducive for crop growth. The remote sensing analysis, particularly the NDVI, highlights the correlation between the efficiency of sprinkler irrigation systems and the health and productivity of the crops.

Furthermore, the assessment shows the extent to which the sprinkler irrigation systems have been maintained and upgraded to meet the evolving needs of the agricultural landscape in Fezzan. It also shows the operational status of these systems and highlights areas where maintenance or upgrades are imperative to sustain the efficiency of water distribution.

The data used through this comprehensive analysis provides a basis for comparing the efficiency of sprinkler irrigation with other irrigation techniques employed in the region, highlighting the potential benefits of sprinkler systems in conserving water, especially in a region where water resources are scarce.

Moreover, the examination of sprinkler irrigation systems provides insights into the potential challenges and bottlenecks that may impede optimal water distribution. The analysis provides a foundation for understanding and addressing the challenges inherent in maintaining an effective sprinkler irrigation system, such as the clogging of sprinkler nozzles or uneven terrain affecting water distribution.

Conclusions

This study on water management infrastructure in Libya highlights the critical role of integrating remote sensing and field data to assess and optimize efficiency. This comprehensive approach across the four key categories (extraction/collection, storage, transportation, and distribution/irrigation), ensures a robust understanding of the current infrastructure status and informs strategies for sustainable water management.

Libya has 21 desalination plants with a combined daily capacity of 525.68 m^3. However, nearly 50 percent of the wells in major well fields are non-functional due to technical faults, a lack of maintenance and vandalism. The key infrastructure includes 1 300 production and monitoring wells, located primarily in the south, along with several critical dams. The desalination plants face significant operational inefficiencies and maintenance challenges, impacting their ability to supply water reliably. Many plants suffer from issues such as a lack of maintenance, reduced productivity and frequent stoppages, which limit their contribution to the water supply and irrigation.

Major reservoirs, such as the Grand Omar Mukhtar Reservoir, have substantial storage capacities ranging from 4 Mm^3 to 24 Mm^3. These reservoirs play a vital role in water storage for agricultural and domestic use. The storage capacity of these reservoirs is significant, but sedimentation and reduced efficiency are critical issues during peak demand periods, especially in summer. These reservoirs face challenges such as leakage, pollution and structural damage, which necessitate regular maintenance and rehabilitation efforts to ensure their optimal functioning.

The GMR forms the backbone of Libya's water transportation infrastructure, with an extensive network of 1 586 km of canals designed to transport water from southern aquifers to northern regions. This network includes several pumping stations essential for maintaining water flow. The canal network's efficiency is compromised by leaks and sedimentation, while pumping stations face mechanical and electrical issues. The integrity of the transportation system is crucial for ensuring a consistent and reliable water supply. Regular assessments and maintenance are necessary to address issues like sedimentation and mechanical failures.

The irrigation infrastructure includes various systems such as pipes, pivot irrigation equipment, local wells, irrigation pipes, drip irrigation systems, mixed irrigation systems, and sprinkler irrigation systems. These systems are vital for distributing water to agricultural fields, but they face significant challenges. Field and remote sensing analyses reveal that the condition and maintenance of these systems directly impact water distribution efficiency and overall agricultural productivity. Irrigation systems like pivot and drip irrigation are effective but require regular maintenance and technological upgrades to maintain efficiency. Local wells are crucial for a reliable water supply, especially in areas with scarce resources, and mixed irrigation systems help meet diverse agricultural water needs.

Remote sensing played an essential role in preparing the datasets for farm boundary delineation, land cover mapping, and crop type mapping. These datasets are necessary for monitoring crop health and water productivity, enabling precise identification of issues and informed decision-making. Using a NDVI derived from remote sensing imagery, alongside field data, has provided invaluable and comprehensive insights into the health and vigour of vegetation. This integration allows for water productivity to be assessed, water use to be rationalized and ensures that irrigation practices are optimized for maximum efficiency and sustainability.

Recommendations

The recommendations for improving Libya's water management infrastructure are as follows:

- Prioritize repairs and maintenance of pipes, pivot irrigation equipment and sprinkler systems to prevent water loss and address structural damage in dams and reservoirs to enhance storage capacity.
- Upgrade and maintain drip and mixed irrigation systems and implement advanced technologies for real-time monitoring of irrigation systems.
- Utilize crop type maps from remote sensing to rationalize water use and regularly assess canal network leakage using earth observation data.
- Implement robust security measures to protect infrastructure from vandalism and theft, and train local technicians and farmers on effective maintenance and operation, leveraging geospatial insights.
- Develop policies to encourage the use of geospatial technologies for sustainable water management and align water distribution with crop requirements based on remote sensing data, ensuring efficient use and enhancing crop productivity.
- Establish platforms for knowledge sharing and collaborative problem-solving among different stakeholders including local farmers, government agencies, and external experts.

Going forwards, these measures will support agricultural productivity, ensure a reliable water supply, and promote sustainable water management in Libya.

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Annex I: Infrastructure questionnaires for field data collection

Table A1.1. Component 1: Extraction/collection (well fields [WF])

Date:	**Field data collection form**						**Province:**		
Enumerator name:							**Village:**		
Type of survey:							**District:**		
Component	1						Parcel coordinates	Lat.	Lon.
Category name	Extraction\collection								
Typology name	**Well fields**								
Agriculture									
Crop type									
Total agricultural area served by infrastructure (ha)									
Infrastructure damage									
Visual damage									
Number of wells									
Number of functional wells									
Number of partially functional wells									
Number of non-functional wells									
Pumping units									
Pipelines									
Power stations									
Equipment control and alarm system									

Comments

Required actions for restoration..........................

Plans for restoration............................

Table A1.2. Component 1: Extraction/collection (dams [DAM])

Date:		**Field data collection form**						**Province:**		
Enumerator name:								**Village:**		
Type of survey:								**District:**		
Component		1						Parcel coordinates	Lat.	Lon.
Category name		Extraction\collection								
Typology name		**Dams**								
Agriculture										
Crop type										
Total agricultural area served by infrastructure (ha)										
Overall infrastructure damage										
Infrastructure damage										
Visual damage impacts										
Current average annual storage/capacity (Mm^3)										
Dam crest										
Dam heel										
Dam toe										
Dam parapet walls										
Dam gallery										
Dam spillway										
Dam abutment										
Dam sluice way										

Comments

Required actions for restoration..........................

Plans for restoration..........................

Table A1.3. Component 1: Extraction/collection (water desalination plant [SWD])

Date:		**Field data collection form**					**Province:**		
Enumerator name:							**Village:**		
Type of survey:							**District:**		
Component	1						Parcel coordinates	Lat.	Lon.
Category name	Extraction and collection								
Typology name	**Water desalination plant**								
Agriculture									
Crop type									
Total agricultural area served by infrastructure (ha)									
Overall infrastructure damage									
Infrastructure damage									
Visual damage impacts									
Potential daily capacity (m^3)									
Existing daily capacity (m^3)									
Pre-treatment filter									
Membranes									
Control panel									
Heat exchanger									
Hot water storage tank									
Fresh water storage tank									

Comments

Required actions for restoration....................

Plans for restoration......................

Table A1.4. Component 2: Storage (large agricultural reservoirs [LAR])

Date:		**Field data collection form**	**Province:**	
Enumerator name:			**Village:**	
Type of survey:			**District:**	

Component	3	Parcel coordinates	Lat.	Lon.
Category name	Storage			
Typology name	**Large agricultural reservoirs**			

Agriculture								
Crop type								
Total agricultural area served by infrastructure (ha)								
Overall infrastructure damage								
Infrastructure damage								
Visual damage impacts								
Capacity (Mm^3)								
Current capacity (Mm^3)								
Reservoir dam								
Pumping unit								
Water inlet chamber								
Water outlet chamber								
Pipelines								
Electric power transmission and distribution								

Comments

Required actions for restoration.....................

Plans for restoration.......................

Table A1.5. Component 2: Storage (agricultural reservoirs [tanks] [TAN])

Date:		**Field data collection form**					**Province:**		
Enumerator name:							**Village:**		
Type of survey:							**District:**		
Component	3						Parcel coordinates	Lat.	Lon.
Category name	Storage								
Typology name	**Agricultural reservoir (tanks)**								
Agriculture									
Crop type									
Total agricultural area served by infrastructure (ha)									
Overall infrastructure damage									
Infrastructure damage									
Visual damage impacts									
Capacity (Mm^3)									
Current capacity (Mm^3)									
Reservoir construction									
Pipelines									
Pumping unit									
Electric power transmission and distribution									

Comments

Required actions for restoration …………………………

Plans for restoration ……………………………………………

Table A1.6. Component 3: Transportation (pumping stations [PS])

Date:		**Field data collection form**						**Province:**	
Enumerator name:								**Village:**	
Type of survey:								**District:**	
Component	3							Parcel coordinates	Lat. / Lon.
Category name	Transportation								
Typology name	**Pumping stations**								
Agriculture									
Crop type									
Total agricultural area served by infrastructure (ha)									
Overall infrastructure damage									
Infrastructure damage									
Visual damage impacts									
Number of pumps									
Number of functional pumps									
Number of partially functional pumps									
Number of non-functional pumps									
Pipelines									
Electric power transmission and distribution									

Comments

Required actions for restoration……………………………

Plans for restoration…………………………………………….

Table A1.7. Component 3: Transportation (main canal [MC])

Date:		**Field data collection form**						**Province:**		
Enumerator name:								**Village:**		
Type of survey:								**District:**		
Component	3							Parcel coordinates	Lat.	Lon.
Category name	Transportation									
Typology name	**Water flow monitoring points**									
Agriculture										
Crop type										
Total agricultural area served by infrastructure (ha)										
Overall infrastructure damage										
Infrastructure damage										
Visual damage impacts										
Number of water flow monitoring points										
Number of functional water flow monitoring points										
Number of partially functional water flow monitoring points										
Number of non-functional water flow monitoring points										
Pipeline condition										
Pipe materials										

Comments

Required actions for restoration..........................

Plans for restoration...

Table A1.8. Component 3: Transportation (water flow monitoring points [WFM])

Date:		**Field data collection form**	**Province:**	
Enumerator name:			**Village:**	
Type of survey:			**District:**	

Component	3	Parcel coordinates	Lat.	Lon.
Category name	Transportation			
Typology name	**Water flow monitoring points**			

Agriculture								
Crop type								
Total agricultural area served by infrastructure (ha)								
Infrastructure damage								
Visual damage impacts								
Number of water flow monitoring points								
Number of functional water flow monitoring points								
Number of partially functional water flow monitoring points								
Number of non-functional water flow monitoring points								
Water flow monitoring point construction								
Electric power transmission and distribution								

Comments

Required actions for restoration...............................

Plans for restoration...

Table A1.9. Component 4: Distribution/irrigation (pipes [PIP])

Date:		**Field data collection form**	**Province:**	
Enumerator name:			**Village:**	
Type of survey:			**District:**	

Component	4	Parcel coordinates	Lat.	Lon.
Category name	Distribution/irrigation			
Typology name	**Pipes**			

Agriculture								
Crop type								
Total agricultural area served by infrastructure (ha)								
Overall infrastructure damage								
Infrastructure damage								
Visual damage impacts								
Pipeline condition								
Pipe materials								

Comments

Required actions for restoration ……………………………..

Plans for restoration ……………………………………………….

Table A1.10. Component 4: Distribution/irrigation (pivot irrigation [PIV])

Enumerator name:							**Village:**		
Type of survey:							**District:**		
Component	4						Parcel coordinates	Lat.	Lon.
Category name	Distribution/irrigation)								
Typology name	**Pivot irrigation**								
Agriculture									
Average yield (tonne/ha)									
Date of planting									
Date of harvesting									
Total agricultural area served by infrastructure (ha)									
Water source									
Overall infrastructure damage									
Infrastructure damage									
Visual damage impacts									
Power transmission									
Controls									
Electrical parts									
Accessories									
Water distribution components									

Comments

Required actions for restoration...............................

Plans for restoration..

Table A1.11. Component 4: Distribution/irrigation (local wells [WEL])

Date:		**Field data collection form**						**Province:**	
Enumerator name:								**Village:**	
Type of survey:								**District:**	
Component	4							Parcel coordinates	Lat. / Lon.
Category name	Distribution/irrigation								
Typology name	**Local wells**								
Agriculture									
Average yield (tonnes/ha)									
Date of planting									
Date of harvesting									
Total agricultural area served by infrastructure (ha)									
Water source									
Overall infrastructure damage									
Infrastructure damage									
Visual damage impacts									
Number of wells									
Number of functional wells									
Number of partially functional wells									
Number of non-functional wells									
Depth (m)									
Water quality (ppm)									
Status of well construction									

Comments
Required actions for restoration ....
Plans for restoration...

Table A1.12. Component 4: Distribution/irrigation (irrigation pipes [IPI])

Enumerator name:								**Village:**		
Type of survey:								**District:**		
Component	4							Parcel coordinates	Lat.	Lon.
Category name	Distribution/irrigation									
Typology name	**Drip irrigation**									
Agriculture										
Average yield (tonne/ha)										
Date of planting										
Date of harvesting										
Total agriculture area served by infrastructure (ha)										
Water source										
Overall infrastructure damage										
Infrastructure damage										
Visual damage impacts										
Water source										
Pipeline condition										
Pipe materials										

Comments

Required actions for restoration...........................

Plans for restoration..

Table A1.13. Component 4: Distribution/irrigation (drip irrigation [DIP])

Enumerator name:									**Village:**		
Type of survey:									**District:**		
Component	4								Parcel coordinates	Lat.	Lon.
Category name	Distribution/irrigation										
Typology name	**Drip irrigation**										
Agriculture											
Average yield (tonne/ha)											
Date of planting											
Date of harvesting											
Total agriculture area served by infrastructure (ha)											
Water source											
Overall infrastructure damage											
Infrastructure damage											
Visual damage impacts											
Water source											
Pump and prime mover											
Filtration devices											
Control devices											
Chemical injectors											
Pipe network											

Comments

Required actions for restoration.........................

Plans for restoration...

Table A1.14. Component 4: Distribution/irrigation (mixed irrigation [MIX])

Date:		**Field data collection form**					**Province:**		
Enumerator name:							**Village:**		
Type of survey:							**District:**		
Component	4						Parcel coordinates	Lat.	Lon.
Category name	Distribution/irrigation								
Typology name	**Sprinkler irrigation**								
Agriculture									
Average yield (tonne/ha)									
Date of planting									
Date of harvesting									
Total agriculture area served by infrastructure (ha)									
Water source									
Overall infrastructure damage									
Infrastructure damage									
Visual damage impacts									
Water source									
Pumping unit/pump and prime mover									
Pipes/pipe network									
Couplers									
Sprinkler head/filtration devices									
Pressure gauge/control devices									
Water meters									
Fertilizer applicator/chemical injectors									

Comments

Required actions for restoration..........................

Plans for restoration..

Table A1.15. Component 4: Distribution/irrigation (sprinkler irrigation [SPR])

Date:		**Field data collection form**					**Province:**		
Enumerator name:							**Village:**		
Type of survey							**District:**		
Component	4						Parcel coordinates	Lat	Lon
Category name	Distribution/irrigation								
Typology name	**Sprinkler irrigation**								
Agriculture									
Average yield (tonne/ha)									
Date of planting									
Date of harvesting									
Total agriculture area served by infrastructure (ha)									
Water source									
Overall infrastructure damage									
Infrastructure damage									
Visual damage impacts									
Water source									
Pumping unit									
Pipes									
Couplers									
Sprinkler head									
Pressure gauge									
Water meters									
Fertilizer applicator									

Comments
Required actions for restoration..........................
Plans for restoration..

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