Use of remote sensing to estimate quantities of groundwater used for irrigation

Training manual

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Beirut

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Executive summary

As global water resources face increasing challenges as a result of climate change and population increase, the accurate estimation of groundwater use is critical for sustainable water management, especially in arid and semi-arid areas such as the Arab region. This manual presents a comprehensive step-by-step procedure for estimating groundwater use from irrigated agriculture in dry regions using remote sensing techniques. The manual is designed to give users the knowledge and tools necessary to use advanced remote sensing technologies for efficient and precise groundwater estimation in data-scarce regions.

The initial sections of the manual establish the theoretical significance of remote sensing in groundwater estimation and outline essential prerequisites (Chapter I – Introduction). In Chapter II, users are instructed to register for access to platforms such as Google Earth Engine and EarthExplorer. Chapter III explains how to acquire 30m Landsat evapotranspiration maps from EarthExplorer, with detailed instructions on searching, sorting and downloading the data. Chapter IV describes ArcGIS techniques for calculating evapotranspiration from downloaded data over distinct spatial units. Users are then equipped with Earth Engine code for rainfall analysis (Chapter V), enabling the derivation of effective rainfall (and consequently groundwater use) by integrating evapotranspiration and precipitation data, whether remotely sensed or measured (Chapter VI). Chapter VII describes the validation of results, emphasizing the importance of data accuracy and reliability in groundwater use estimation. This comprehensive resource is intended to be useful to water resource professionals, researchers and policymakers, and to provide a robust framework for understanding and implementing remote sensing techniques for sustainable water management in the face of growing environmental challenges.

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1. Introduction

Groundwater is the primary freshwater source for over half of the Arab States. Water in the region is scarce, and limited groundwater resources are being exploited at an unsustainable pace, surpassing natural replenishment rates. The excessive withdrawal of groundwater, particularly by the agricultural sector, coupled with low efficiency practices, has contributed to a substantial decrease in groundwater reserves across more than two-thirds of the Arab region. According to satellite data, the spatial extent of this decline doubled between 2002 and 2018-2019.[1]

In the face of the increasing scarcity of groundwater, it is crucial for countries in the Arab region to adopt innovative tools to ensure it is used sustainably, without jeopardizing its availability for future generations.

This manual describes methods that can help water managers to assess the amount of groundwater used in agriculture in arid environments, helping them to increase the efficiency of irrigation and make better decisions about water allocation and use. This is specifically pertinent in areas where water meters on groundwater wells are unavailable or difficult to read.

The first step in quantifying agricultural water use in arid and semi-arid regions is determining the evapotranspiration rate. Evapotranspiration represents the combined water loss from soil evaporation and plant transpiration. In water-scarce regions, irrigation, often sourced from groundwater, is the primary driver of evapotranspiration. Evapotranspiration measurements can therefore serve as a proxy for estimating groundwater irrigation demand, especially where surface water is unavailable. Field surveys can then be used to assess irrigation efficiency to identify potential water savings.

The process starts with the following preliminary steps:

1. **Locating the area of interest.**
2. **Identifying the agricultural land.**
3. **Identifying the irrigated land.**
4. **Identifying the source of irrigation water (surface or ground).**
5. **Mapping any surface water diversions from streams.**
6. **Mapping any wells is advantageous but not essential.**

Sometimes, a portion of evapotranspiration comes from rainfall stored in the root zone of plants. This component needs to be estimated using a soil water balance approach. In the equation below, ΔGW is the change in groundwater storage:

$$\Delta GW = \text{precipitation} - \text{evapotranspiration} - \text{surface flow} - \text{change in soil water storage/time}$$

[1] ESCWA, 2022.

For areas where surface flow is negligible over long periods, the values of the last two terms in the equation can also be assumed to be negligible, and the amount of groundwater use (or gain) can be considered to be equal to the difference between precipitation and evapotranspiration.

Where in-situ data is not sufficient, remote sensing products can be used to determine precipitation. One such product is Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS), which is a 35+ year quasi-global rainfall data set with values going back to 1981. CHIRPS uses 0.05° resolution satellite imagery and in-situ station data to create gridded rainfall time series for trend analysis and seasonal drought monitoring. Version 2.0 is currently available. CHIRPS is available at multiple temporal scales (daily, pentad and monthly).

Another precipitation dataset is the Integrated Multi-satellitE Retrievals for GPM (IMERG) algorithm, which combines information from the GPM satellite constellation to estimate precipitation over the majority of the Earth's surface. IMERG data are available at the daily level, and cover areas of interest in the Middle East and Northern Africa region since 2000 (where the date is fused with TRMM since 2000). The IMERG Final Run product provides research-quality gridded global multi-satellite precipitation estimates with time interpolation, gauge data, and climatological adjustment.[2] Its spatial resolution is half of that of CHIRPS (0.1° x 0.1°, or roughly 10 km by 10 km). In this manual, CHIRPS is used because of its higher resolution.

This manual describes procedures for determining evapotranspiration in a study area using remote sensing. It will describe how publicly available thermal and multispectral imagery can be analysed to provide estimates of actual crop water use.It is currently possible to determine evapotranspiration from at least five freely available relatively high-resolution satellite imagery products:

1. **Visible Infrared Imaging Radiometer Suite (VIIRS)[3] (1 km).**
2. **Moderate Resolution Imaging Spectro-radiometer (MODIS) (1 km).**
3. **Landsat 8 and 9[4] (30m).**
4. **Sentinel-2 (10-20m) fused with Sentinel-3 (1 km thermal band) or VIIRS (375m thermal band) or MODIS (1 km thermal band).**
5. **The Ecosystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) (70m).**

MODIS and VIIRS imagery are both available on a daily basis, and the resolution of the resulting evapotranspiration product is 1 km. The evapotranspiration product is readily available through a Google Earth Engine interface. It is derived using the Operational Simplified Single Source Energy Balance (SSEBOP),[5] and is available for the full coverage of VIIRS imagery, starting in 2013.

If a higher spatial resolution product is required, then 30 m Landsat imagery or the 20 m Sentinel-2 imagery can be used to determine evapotranspiration. The Landsat satellites, Landsat 8 and Landsat 9, provide eight-day coverage of the Earth. Cloudy images need to be removed, or cloudy areas masked, before the imagery can be used for estimating evapotranspiration. Landsat 4-9 C2 provisional evapotranspiration products are currently available from the United States Geological Survey's EROS Science Processing Architecture (ESPA) on-demand interface.

The following chapters will describe the procedures in greater depth. Chapter 2 describes how to access satellite data. Chapter 3 contains step-by-step instructions for downloading the data. Chapters 4 and 5 explain how to estimate evapotranspiration and precipitation, while Chapter 6 discusses the determination of effective precipitation. Finally, Chapter 7 covers model calibration and validation.

2 https://gpm.nasa.gov/data/directory.
3 https://doi.org/10.1002/jgrd.50771.
4 https://doi.org/10.5066/P9OGBGM6.
5 Senay evapotranspiration al., 2013, 2022.

2. Using this manual

This chapter will explain how to register for Google Earth Engine and EarthExplorer. Google Earth Engine will be used to determine rainfall over the study area, and Earth Explorer will be used to download Landsat evapotranspiration maps. Both evapotranspiration and rainfall data are needed to estimate groundwater use.

A. Register for a Google Earth Engine account

First, you need to register for a Google Earth Engine account. It takes 1–3 days for Google to authorize your Earth Engine Account. You need to have a Gmail account to be able to register for Google Earth Engine. Follow these steps to request an account:

Step 1:
Go to the Google Earth Engine registration page. https://signup.earthengine.google.com/.

Step 2:
Click on "Sign up for Earth Engine".

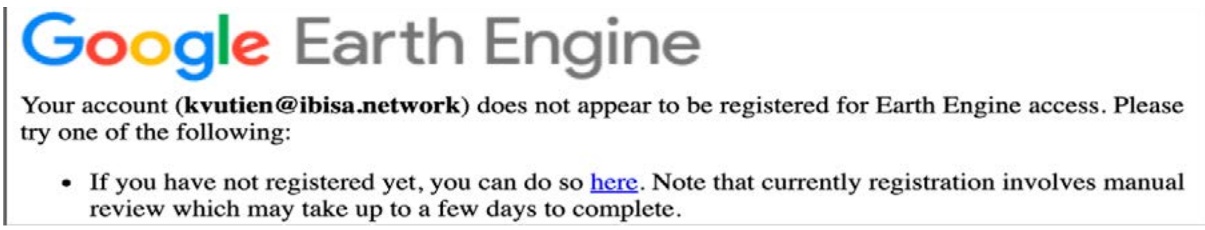
Step 3:
Enter your Google account information and click "Next." If you do not have a Google account, you need to create one now.

Step 4:
Create an account, and then sign in and go to the page above. Agree to the terms and conditions and click "Continue".

Step 5:
Choose to register with your individual Google account.

Step 6:
Click "Finish". To save time, you can choose to give an existing Google email account. Click "Next". You will be instructed to associate your new Earth Engine credentials with your existing email account. (figure 1 A).

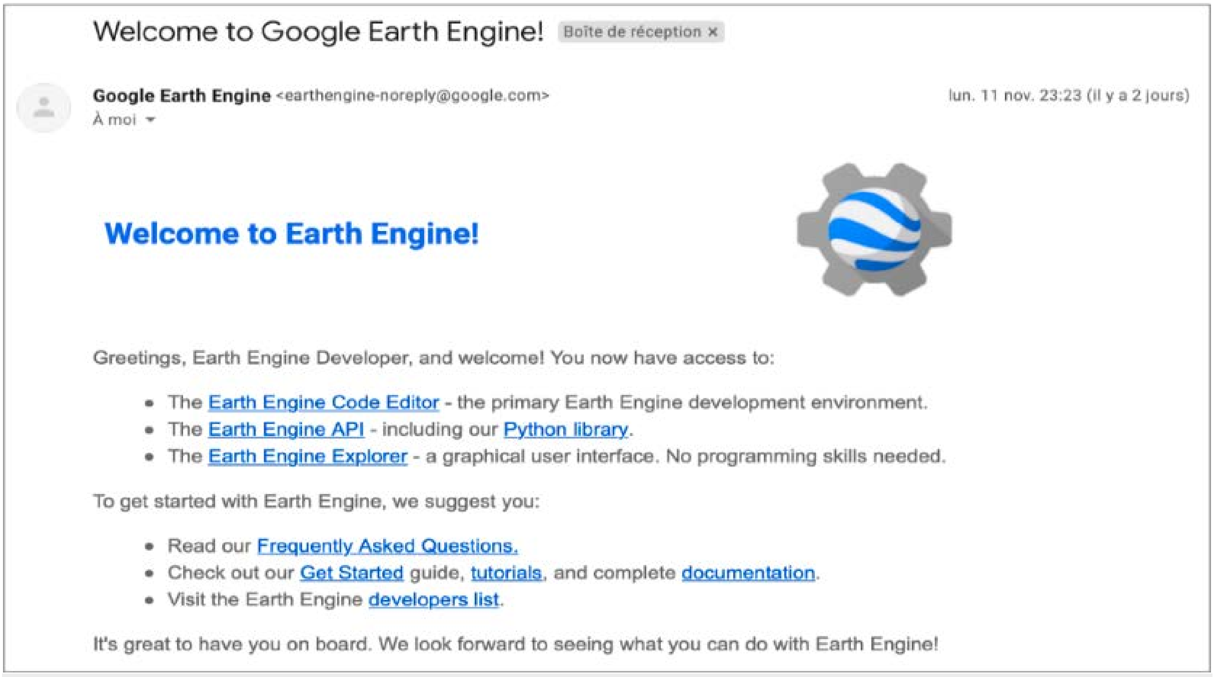
Figure 1. Google Earth Engine registration A. Example Google Earth Engine account request



Source: https://earthengine.google.com/.

Step 7:
Wait for an email from Google Earth Engine confirming that your account has been created.

B. Google Earth Engine account access confirmation


Welcome to Google Earth Engine! Boîte de réception ×

Google Earth Engine <earthengine-noreply@google.com> lun. 11 nov. 23:23 (il y a 2 jours)
À moi

Welcome to Earth Engine!

Greetings, Earth Engine Developer, and welcome! You now have access to:

- The Earth Engine Code Editor - the primary Earth Engine development environment.
- The Earth Engine API - including our Python library.
- The Earth Engine Explorer - a graphical user interface. No programming skills needed.

To get started with Earth Engine, we suggest you:

- Read our Frequently Asked Questions.
- Check out our Get Started guide, tutorials, and complete documentation.
- Visit the Earth Engine developers list.

It's great to have you on board. We look forward to seeing what you can do with Earth Engine!

Source: https://earthengine.google.com/.

Step 8:
Once you receive the confirmation email, click on the link to activate your account.

Step 9:
Sign in to your Google Earth Engine account.

Step 10:
Start exploring Earth Engine.

B. Register for an Earth Explorer account

An Earth Explorer account is needed to order Landsat evapotranspiration data. The Earth Explorer user interface is an online search, discovery and ordering tool developed by the United States Geological Survey. To order products such as Landsat evapotranspiration data, you need to sign in to Earth Explorer using your username. To create an account, visit https://ers.cr.usgs.gov/register. Registration takes about 5 minutes, and you will receive an activation email. Click on the link to confirm your registration.

When you have registered, use your username to sign in to Earth Explorer.

3. Ordering and downloading evapotranspiration maps

In this chapter, users will learn how to search for, order and display Landsat evapotranspiration data using Earth Explorer. While many sources of lower-resolution evapotranspiration maps are available globally, Landsat-derived evapotranspiration is the highest-resolution evapotranspiration data available, and is the one most frequently used by researchers. There are many models used for estimating evapotranspiration from Landsat. SEBAL (Bastiaanssen, 1998; Jaafar and Ahmad, 2020); METRIC (Allen and others, 2007; Jaafar and Ahmad 2020); SSEBOP (Senay, 2018), ETLook (AKA WAPOR, Bastiaanssen 2012); HSEB (Jaafar and others, 2022a); TSEB (Anderson and others, 2012; Jaafar and others, 2022b), are examples of such models that used Landsat to generate evapotranspiration using the thermal band. Here we will use SSEBOP, because it is possible to order the Landsat evapotranspiration data from Earth Explorer.

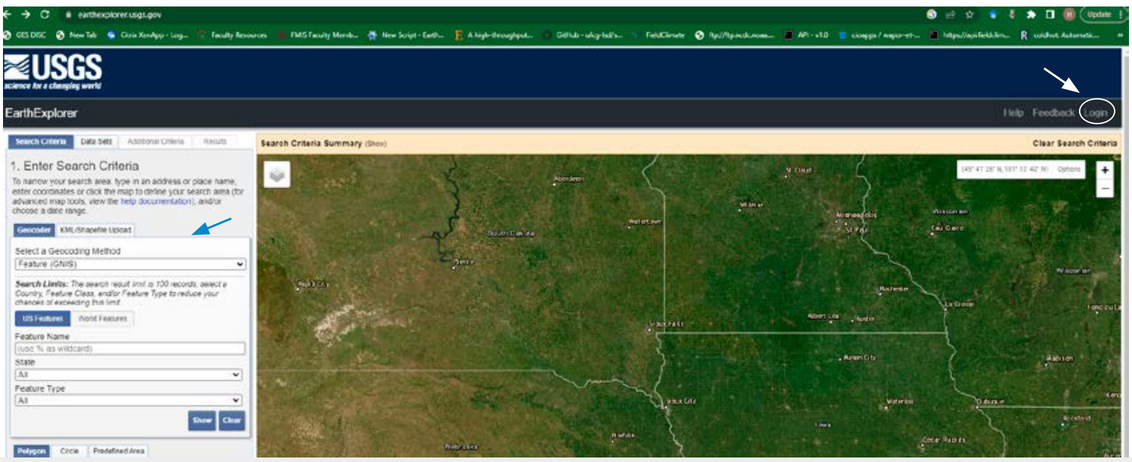
A. Ordering Landsat evapotranspiration data

The first step in submitting an order for science data production is to create a scene list as a text file (*.txt). The list must be a text file, and it must have a Landsat product ID. This information is generated by performing a spatial and temporal inventory search in Earth Explorer and exporting search results to a spreadsheet from which filenames can be extracted.

Step 1:
Obtaining a Landsat scene list

Sign in to https://earthexplorer.usgs.gov/ (figure 2).

Figure 2. Sign-in page for Earth Explorer

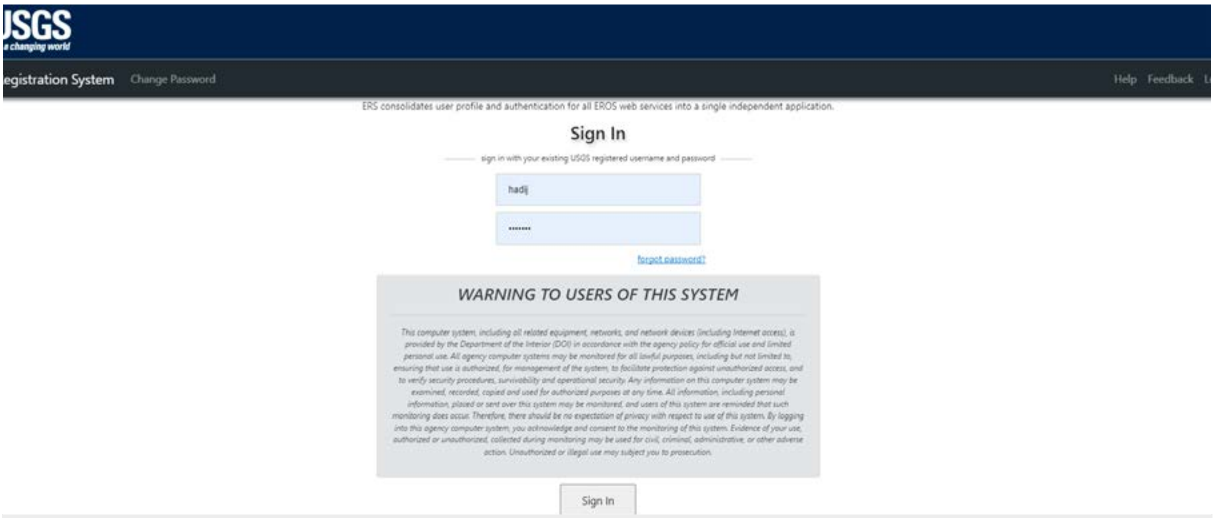


Source: https://earthexplorer.usgs.gov/.

The login button is in the top-right corner.

To access the bulk ordering interface, you need to sign in in with your username and password (figure 3).

Figure 3. Sign-in page for EROS registration system



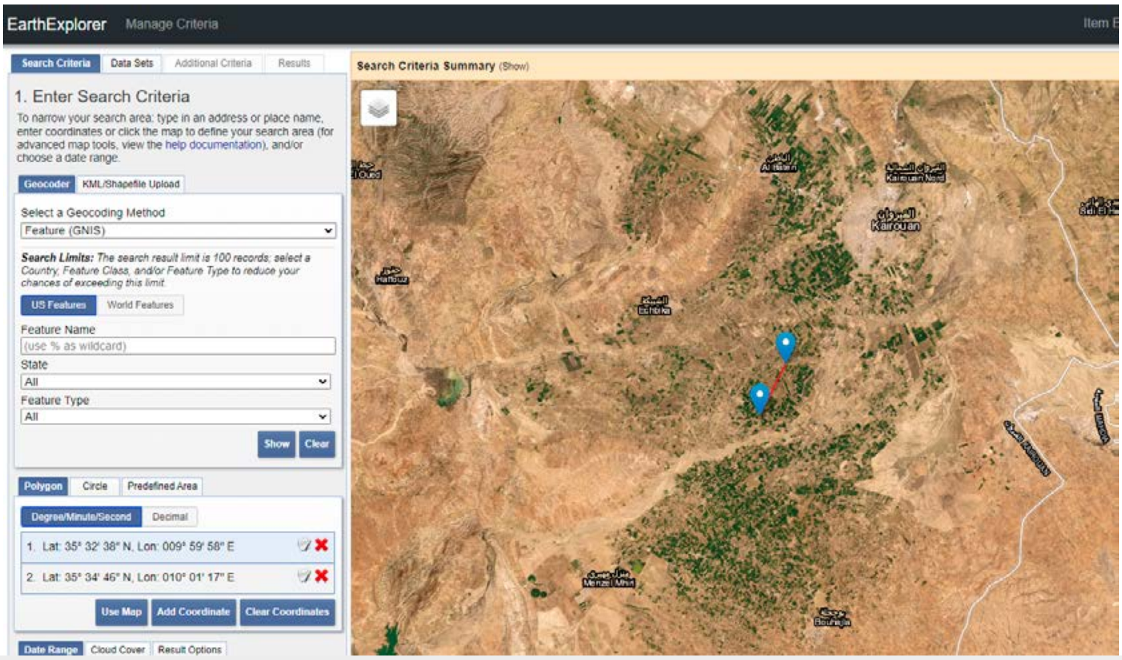
Source: https://earthexplorer.usgs.gov/.

Step 2:

Locating your area

Zoom in into your area of interest using the map. Click on the map to place a point in your area, or upload your shapefile or KML using the KML/shapefile button (figure 4).

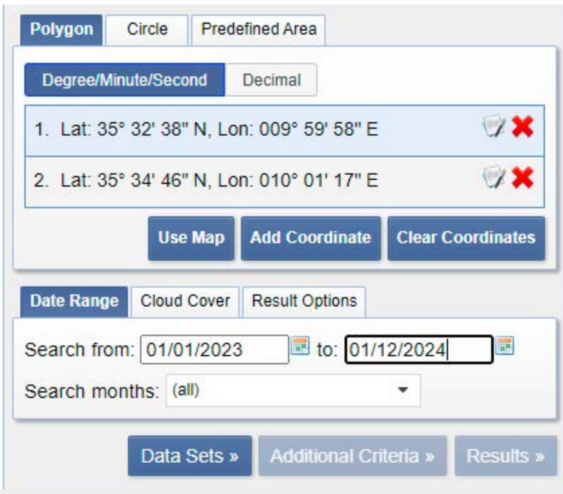
Figure 4. Locating an area of interest in Earth Explorer



Source: https://earthexplorer.usgs.gov/.

Step 3:
Set your date range as the period of analysis. There is an eight-day gap between two consecutive Landsat 8 and Landsat 9 scenes (figure 5).

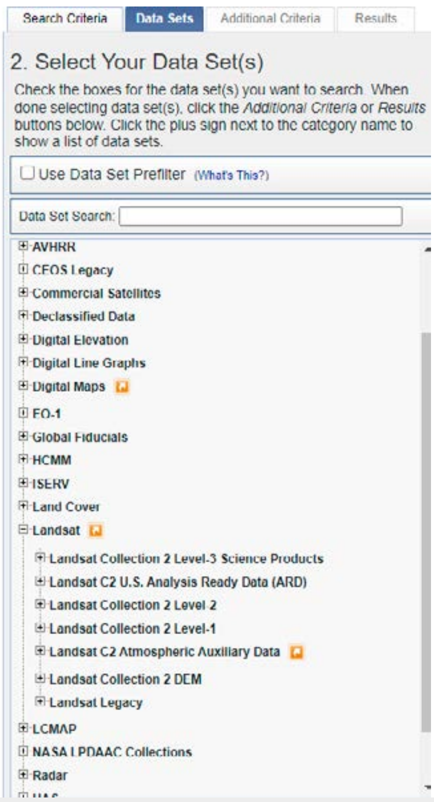
Figure 5. Setting the dates for the imagery search



Source: https://earthexplorer.usgs.gov/.

Step 4:
Click on "Data sets" and click on the "+" next to "Landsat" to expand the list of options (figure 6).

Figure 6. Expanding dataset options



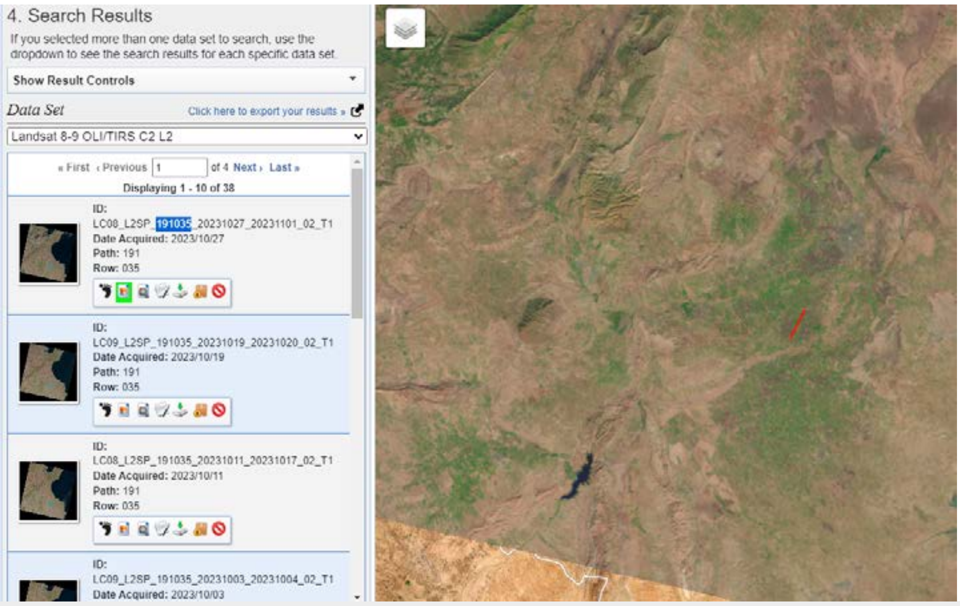
Source: https://earthexplorer.usgs.gov/.

Step 5:

Select “Landsat Collection 2 Level 1” and click on “Results”.

Determine the Landsat scene’s path and row number. For the example below, which is in Tunisia (figure 7), these are path 191 and row 035. Downloaded scenes will include these numbers in their filenames. Verify that the product is a level 2 Landsat collection.

Figure 7. Search results shown in Earth Explorer window



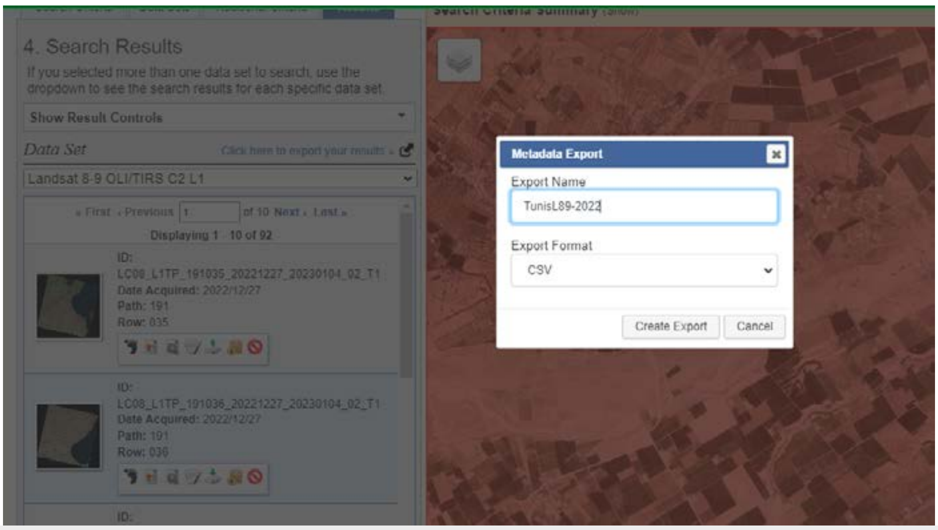
Source: https://earthexplorer.usgs.gov/.

Step 6:

Click on “Export results” and choose CSV format (figure 8).

- Move to the “Data set” tab to select the datasets you want to search for.

Figure 8. Exporting search results to .csv format



Source: https://earthexplorer.usgs.gov/.

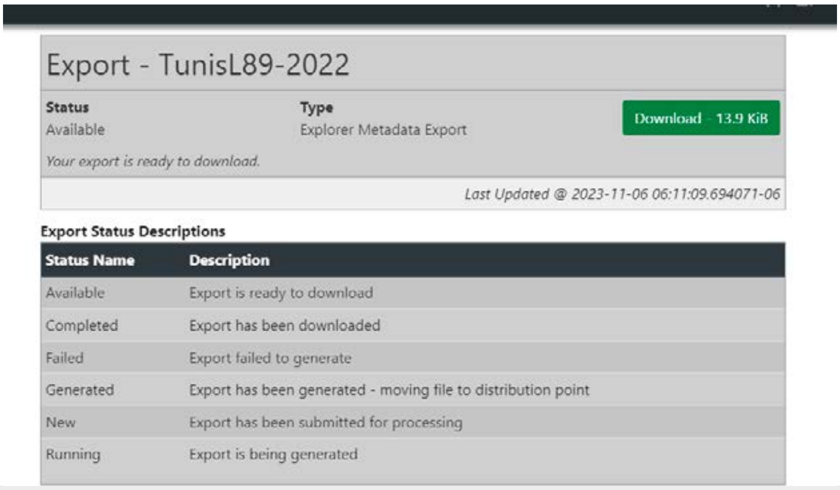
To order Landsat evapotranspiration products, select from the available images. Avoid images with cloud cover over your study area. Figure 9 shows the submission page.

Figure 9. Export submitted for processing

Source: https://earthexplorer.usgs.gov/.

Step 7:
Click on “Open Export Status Page”. You will be directed to the screen shown in figure 10 below.

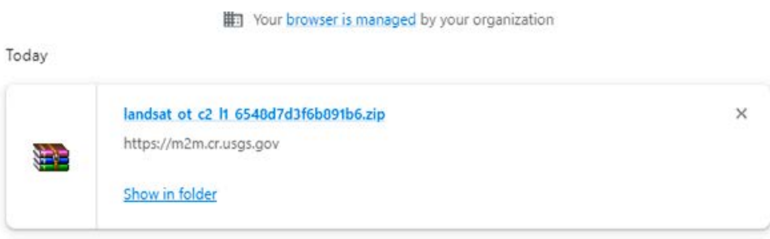
Figure 10. Result of export status after submission



Source: https://earthexplorer.usgs.gov/.

Step 8:
Click on the “Download” button and locate the zipped file in your downloads directory. Unzip it and open it in a spreadsheet (figure 11).

Figure 11. Snapshot of the downloaded file location

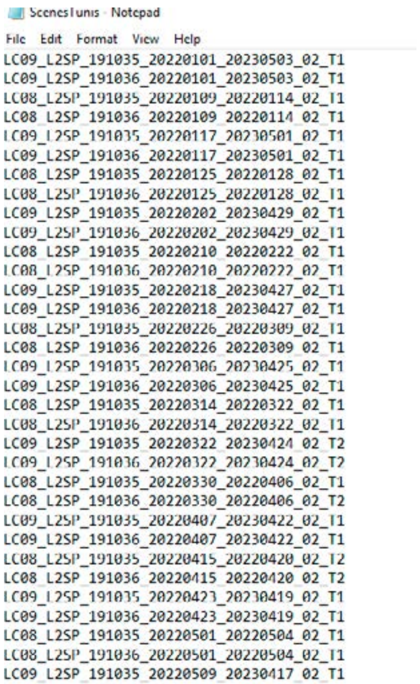


Source: https://earthexplorer.usgs.gov/.

Step 9:
Copy the contents of the first column with the Landsat product identifier.

Step 10:
Create a new .txt file and paste the copied list into it. Save the file (figure 12) to create a scene list.

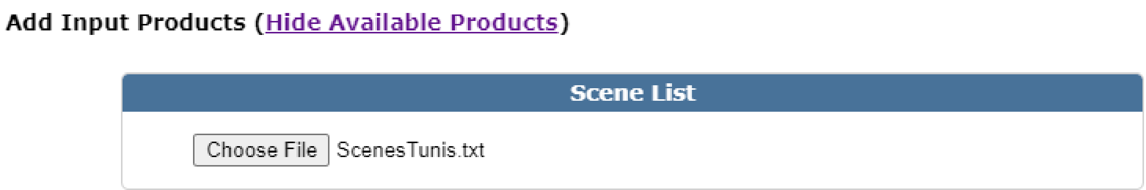
Figure 12. Text file with imagery names for download


ScenesTunis - Notepad
File Edit Format View Help
LC09_L2SP_191035_20220101_20230503_02_T1
LC09_L2SP_191036_20220101_20230503_02_T1
LC08_L2SP_191035_20220109_20220114_02_T1
LC08_L2SP_191036_20220109_20220114_02_T1
LC09_L2SP_191035_20220117_20230501_02_T1
LC09_L2SP_191036_20220117_20230501_02_T1
LC08_L2SP_191035_20220125_20220128_02_T1
LC08_L2SP_191036_20220125_20220128_02_T1
LC09_L2SP_191035_20220202_20230429_02_T1
LC09_L2SP_191036_20220202_20230429_02_T1
LC08_L2SP_191035_20220210_20220222_02_T1
LC08_L2SP_191036_20220210_20220222_02_T1
LC09_L2SP_191035_20220218_20230427_02_T1
LC09_L2SP_191036_20220218_20230427_02_T1
LC08_L2SP_191035_20220226_20220309_02_T1
LC08_L2SP_191036_20220226_20220309_02_T1
LC09_L2SP_191035_20220306_20230425_02_T1
LC09_L2SP_191036_20220306_20230425_02_T1
LC08_L2SP_191035_20220314_20220322_02_T1
LC08_L2SP_191036_20220314_20220322_02_T1
LC09_L2SP_191035_20220322_20230424_02_T2
LC09_L2SP_191036_20220322_20230424_02_T2
LC08_L2SP_191035_20220330_20220406_02_T1
LC08_L2SP_191036_20220330_20220406_02_T2
LC09_L2SP_191035_20220407_20230422_02_T1
LC09_L2SP_191036_20220407_20230422_02_T1
LC08_L2SP_191035_20220415_20220420_02_T2
LC08_L2SP_191036_20220415_20220420_02_T2
LC09_L2SP_191035_20220423_20230419_02_T1
LC09_L2SP_191036_20220423_20230419_02_T1
LC08_L2SP_191035_20220501_20220504_02_T1
LC08_L2SP_191036_20220501_20220504_02_T1
LC09_L2SP_191035_20220509_20230417_02_T1

Source: Authors.

Step 11:
To order the evapotranspiration data, click this link: https://espa.cr.usgs.gov/.

Figure 13. Adding input products for data order

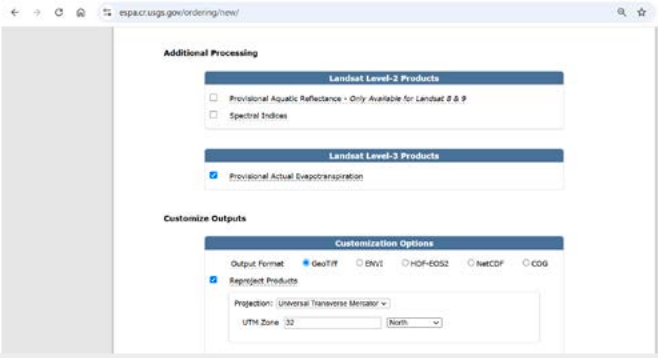


Source: https://espa.cr.usgs.gov/ordering/new/.

Choose the file you saved by clicking "Choose file" and browsing to its location (figure 13).

Check the options on the page (provisional actual evapotranspiration) as shown in figure 14, then enter your UTM zone. UTM stands for Universal Transverse Mercator; it is a common type of projection that is usually used when converting from a geographic coordinate system to a projected coordinate system. It is based on dividing the Earth into 60 UTM zones, each 6 degrees in width. For example, a longitude of 35.5 lies in the UTM zone of 36.

Figure 14. Selecting and ordering projected evapotranspiration data

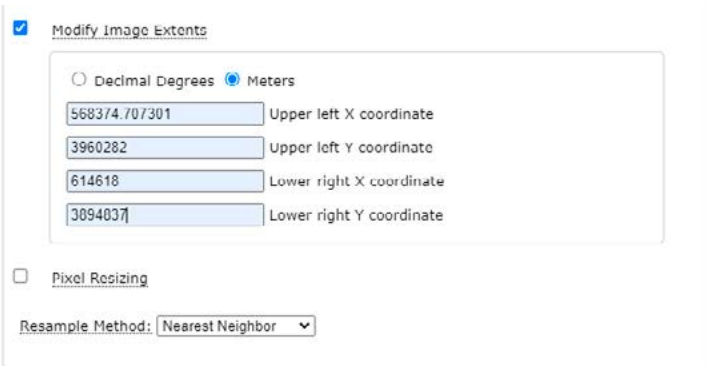


Source: https://espa.cr.usgs.gov/.

Click on “Modify extents” to have the data clipped to your boundary (figure 15).

Use the extents either from the extents of your shapefile in ArcGIS or from Google Earth.

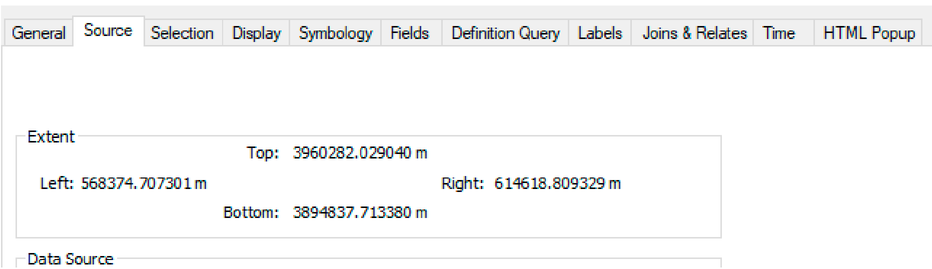
Figure 15. Modifying image extents to match the imported study area shapefile



Source: https://espa.cr.usgs.gov/.

You can view the extents of your shapefile in the “Source” tab of the layer in ArcGIS (figure 16).

Figure 16. Source layer extents in ArcGIS



Source: ESCWA, using ArcGIS software.

Click on “Submit”. You should receive a confirmation email.

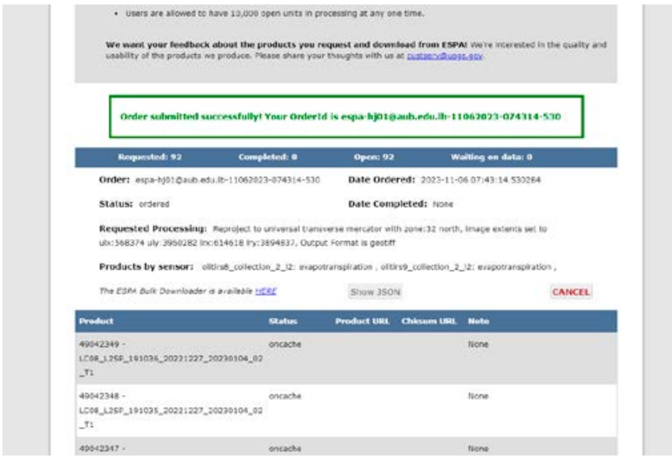
Step 12:
Order tracking

A new tab named “Show order” will be added, displaying the product ID and its status (figure 17).

Once the order is completed, you will receive another email notifying you that your data is ready to be downloaded.

The time needed to get the order varies according to the number of products ordered. In this case, ordering 45 products takes about 1 hour, and each zip product takes about 2 hours to download, depending on the speed of your internet connection.

Figure 17. Order submission confirmation screen



Source: https://espa.cr.usgs.gov/.

B. Downloading and viewing the evapotranspiration maps

Step 13:
Downloading Landsat evapotranspiration data

As files complete processing, they can be downloaded. The download site contains compressed file archives (tar.gz) containing the requested files.

Available products

The files included in Landsat C2 ETA product ordered package are listed below:

- **Actual evapotranspiration (ETA):** provides a per-pixel estimate of daily water transfer from the Earth’s surface to the atmosphere in units of water depth (mm).
- **Evapotranspiration fraction (ETF):** represents a unitless fraction of a reference value for potential evapotranspiration based on the crop alfalfa, nominally varying between 0 and 1.
- **Evapotranspiration uncertainty (ETUN):** provides evapotranspiration product uncertainty in units of water depth (mm) using auxiliary evapotranspiration data.

- **Pixel quality assessment (QA_PIXEL):** the bit combinations that define certain quality conditions.
- **METAdata:** includes actual evapotranspiration information in XML format (Product_ID.xml) and Level-1 metadata both in .txt and XML format. Product specifications are shown in table 1.

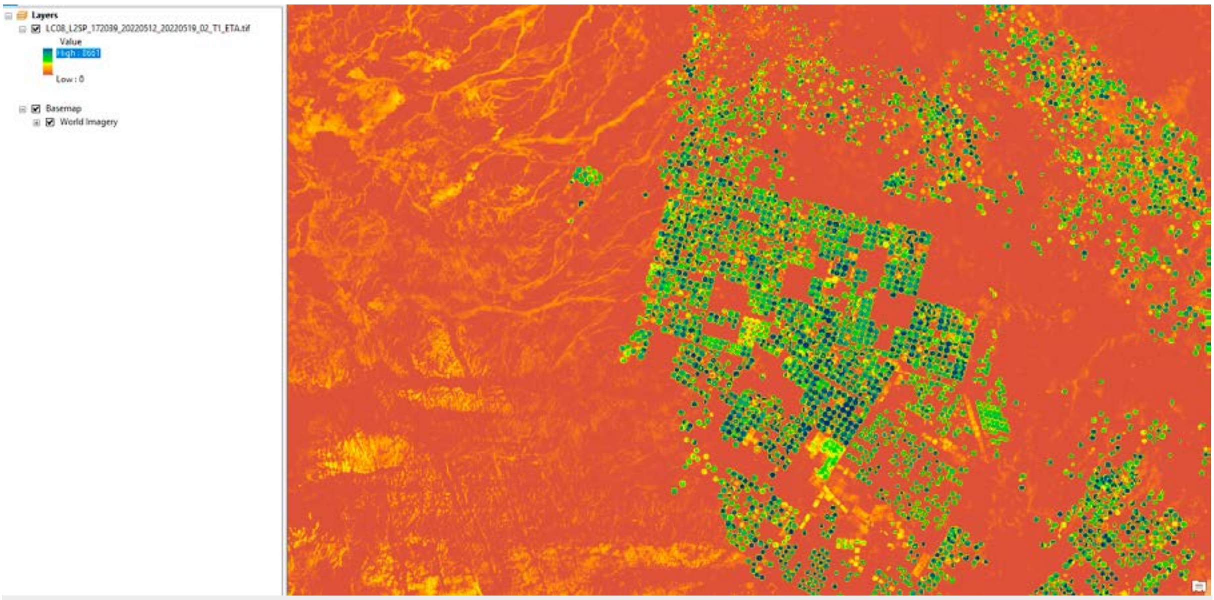
Table 1. List of Landsat C2 provisional actual evapotranspiration product specifications [2]

Description	Band name	Valid range	Scale factor	Unit
Actual evapotranspiration (ETA)	ProductID_ETA	0–20,000	0.001	mm
ET fraction (ETf)	ProductID_ETF	0–10,000	0.0001	unitless
ET uncertainty (ETUN)	ProductID_ETUN	0–15,000	0.001	mm
Pixel QA	ProductID_QA_PIXEL	0–65,535	N/A	Bit Index

Source: Anderson, Martha C. and others (2012).

Figure 18 shows an example of the actual evapotranspiration product for the agriculture fields of Skaka, Saudi Arabia, opened in ArcGIS.

Figure 18. Example of Landsat C2 L2 provisional actual evapotranspiration for Skaka, Saudi Arabia



Source: ESCWA, using ArcGIS software.

4. Estimating evapotranspiration

This chapter describes how to calculate mean evapotranspiration, a proxy for water use, within a defined agricultural area.

Data requirements:

- Agricultural land boundaries: a shapefile or geodatabase representing the agricultural fields within the study area is required. Alternatively, a polygon can be manually drawn to delineate the study area.
- Irrigation status: a distinction needs to be made between irrigated and rain-fed fields based on the presence of irrigation infrastructure and the rainfall patterns in the study area.

Classification of agricultural fields:

- Normalized difference vegetation index (NDVI) threshold: a suitable normalized difference vegetation index threshold can be used to differentiate agricultural areas from other types of land cover.
- Temporal classification: analysing temporal changes in satellite imagery can aid in identifying agricultural fields based on unique seasonal growth patterns.
- Pre-classified imagery: sentinel-2 imagery often includes pre-classified land cover maps which can be readily used.

Zonal statistics calculation:

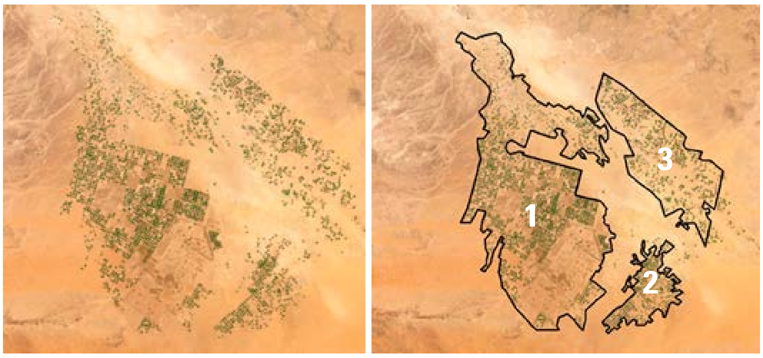
- Once the agricultural fields are identified, zonal statistics are applied in ArcMap to determine the mean evapotranspiration for each Landsat scene.

Procedure

1. Import evapotranspiration raster: add the evapotranspiration raster data to the ArcMap environment.
2. Define area of interest: delineate the agricultural fields within the study area, as shown in figure 19. In this case, agricultural fields in Skaka (total area 8,098.5 km2) have been delineated, comprising three regions: region 1 (5,560.56 km2), region 2 (649.13 km2), and region 3 (1,888.79 km2).
3. Zonal statistics tool: use the "Zonal Statistics as Table" tool to calculate the mean evapotranspiration value for each Landsat scene within the defined agricultural field polygons.

The "Zonal Statistics as Table" tool calculates statistics (mean, standard deviation, sum) for the cell values of a raster layer within the zones defined by another dataset (in this case, the agricultural field polygons).

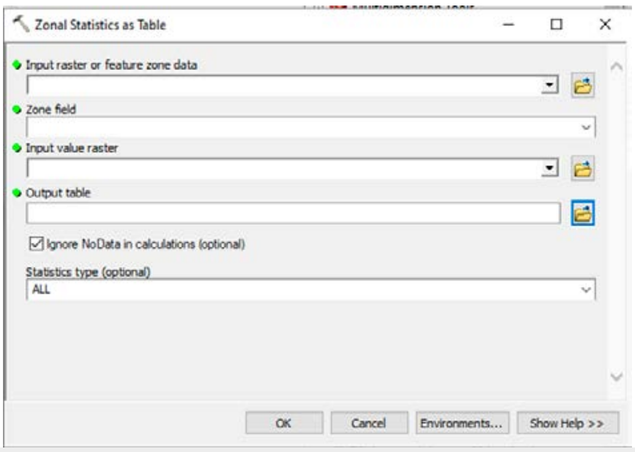
Figure 19. Creating shapefile for the region of interest



Source: ESCWA, using ArcGIS software.

In ArcToolbox, navigate to “Spatial Analyst Tools”, expand “Zonal”, and choose “Zonal Statistics as Table”. The “Zonal statistics as a Table” pane will open, as shown in figure 20.

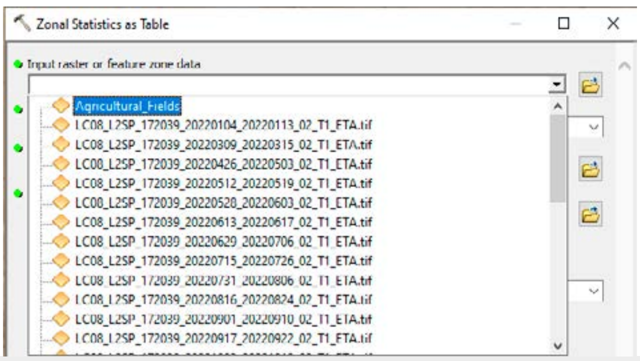
Figure 20. “Zonal Statistics as a Table” pane



Source: ESCWA, using ArcGIS software.

In the “Zonal Statistics as Table” pane, select the zone dataset from the “Input raster or feature zone data” drop-down list (figure 21).

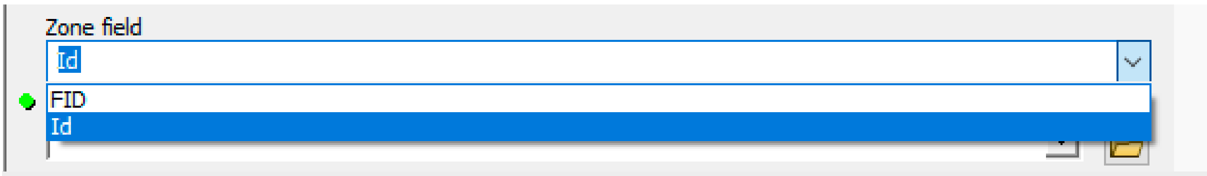
Figure 21. Dropdown list for zonal statistics calculations



Source: ESCWA, using ArcGIS software.

In the "Zone Field" parameter, select the field with the zone values from the drop-down list (figure 22).

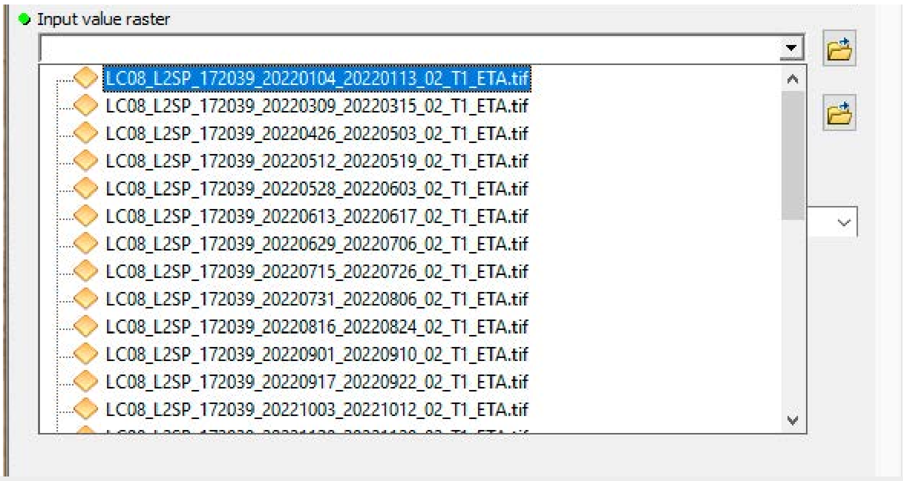
Figure 22. ID selection for zonal statistics



Source: ESCWA, using ArcGIS software.

In the "Input value raster" parameter, select the raster from the drop-down list (figure 23).

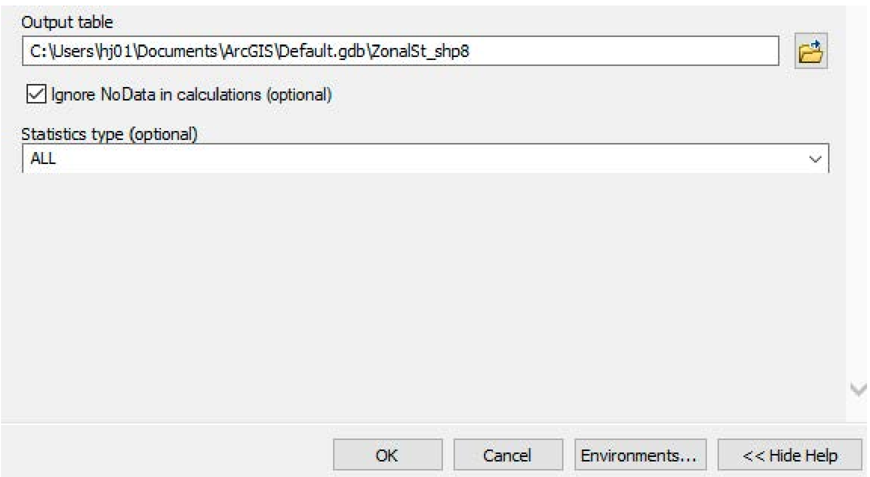
Figure 23. Selecting images for zonal statistics calculations



Source: ESCWA, using ArcGIS software.

In the "Output table" parameter, specify a location and name for the output table (figure 24).

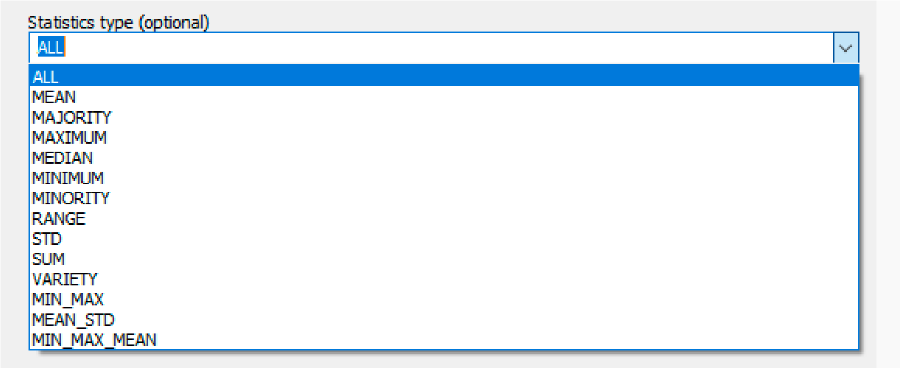
Figure 24. Specifying a name for the output table



Source: ESCWA, using ArcGIS software.

1. In the “Statistics type” parameter, select a suitable predefined subset from the drop-down list to calculate multiple statistics at once (figure 25).

Figure 25. Selecting output statistical metrics

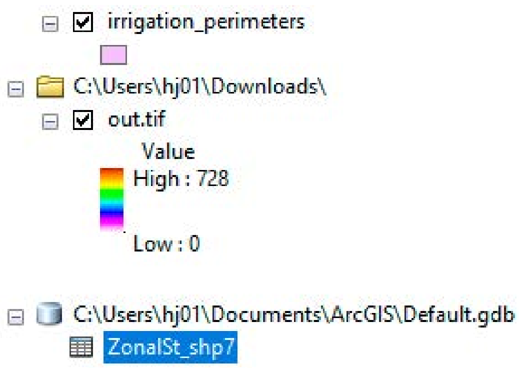


Source: ESCWA, using ArcGIS software.

2. Click on “OK”.

3. ArcGIS will then add the output zonal statistical table to the table of contents (figure 26).

Figure 26. Snapshot of ArcGIS table of contents with the zonal statistics table added



Source: ESCWA, using ArcGIS software.

4. Double-click on the table icon to open and view the table (figure 27). The data shows the mean, minimum, maximum, median and standard deviation of actual evapotranspiration over the regions of interest.

Figure 27. Output statistics attribute table

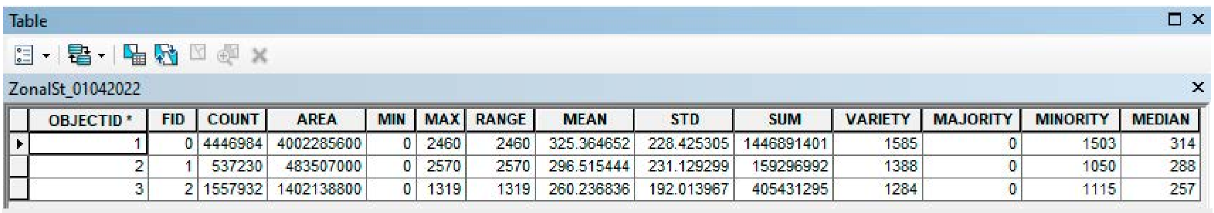


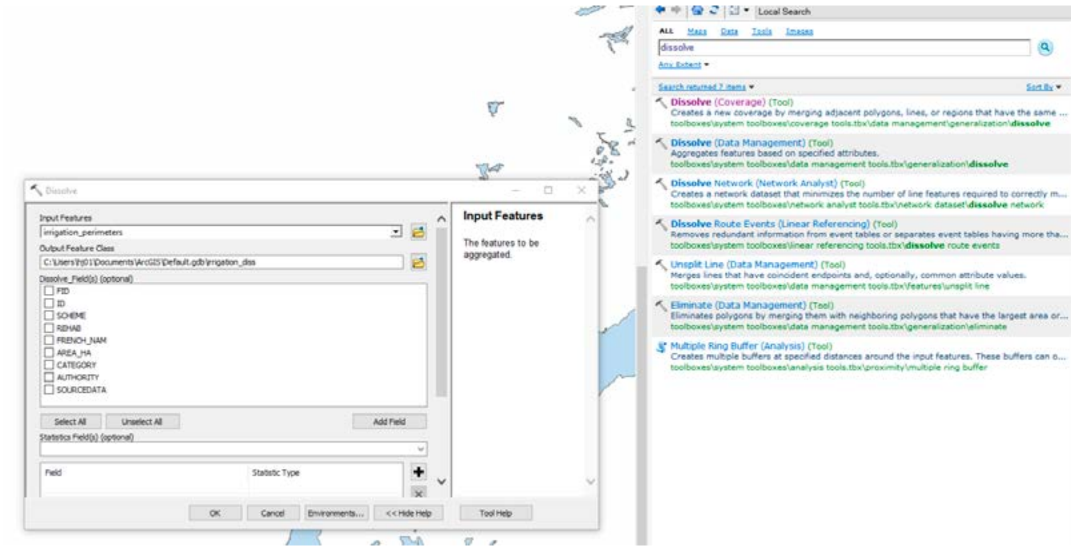
Table
ZonalSt_01042022

OBJECTID *	FID	COUNT	AREA	MIN	MAX	RANGE	MEAN	STD	SUM	VARIETY	MAJORITY	MINORITY	MEDIAN
1	0	4446984	4002285600	0	2460	2460	325.364652	228.425305	1446891401	1585	0	1503	314
2	1	537230	483507000	0	2570	2570	296.515444	231.129299	159296992	1388	0	1050	288
3	2	1557932	1402138800	0	1319	1319	260.236836	192.013967	405431295	1284	0	1115	257

Source: ESCWA, using ArcGIS software.

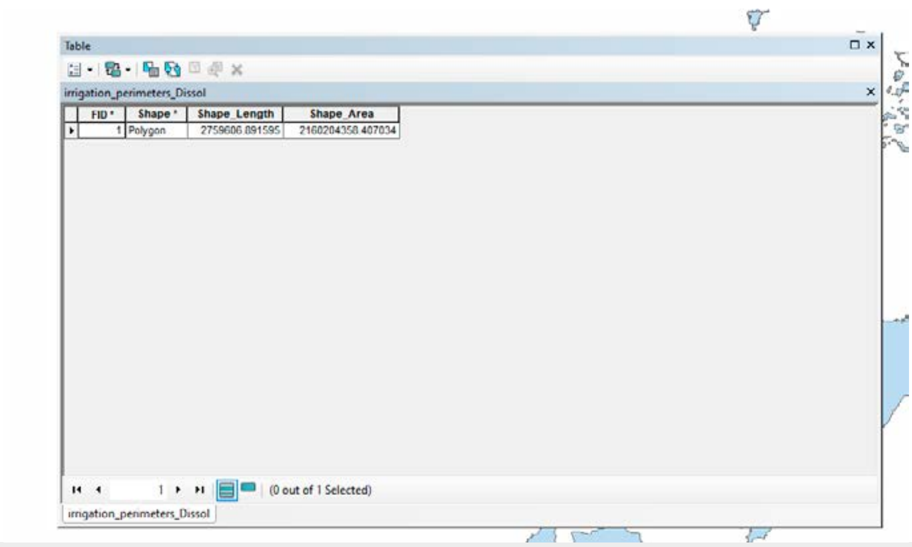
In many cases, the shapefile of the agricultural field will contain several polygons. In that case, zonal statistics will be calculated for each polygon in the shapefile or the feature class. If you wish to derive one value for the mean evapotranspiration over all of the polygons at once, first dissolve the polygons of the shapefile or the feature class using the "Dissolve (Coverage)" tool in ArcGIS (figure 28). Make sure you leave all the boxes in the "Dissolve_Fields" column unselected. This will return a shapefile with one feature or polygon, with an attribute table showing one feature (figure 29).

Figure 28. The "Dissolve" tool in ArcGIS



Source: ESCWA, using ArcGIS software.

Figure 29. The "Dissolved shapefile attribute" table in ArcGIS

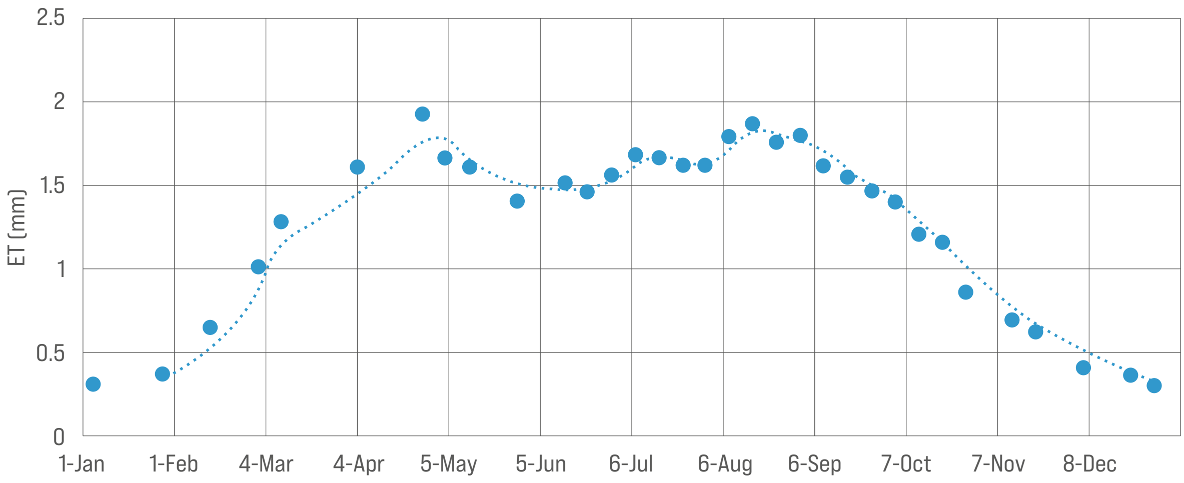


Source: ESCWA, using ArcGIS software.

You can now run the "Zonal statistics" tool as a table over the new shapefile.

Figure 30 shows evapotranspiration (in mm) from the Landsat scenes for 2022 over the dissolved agricultural area of Skaka, after dividing by the scale factor of 1,000.

Figure 30. Time series of mean evapotranspiration (mm/day) for the agricultural area in Skaka for 2022



Source: ESCWA.

5. Estimating rainfall

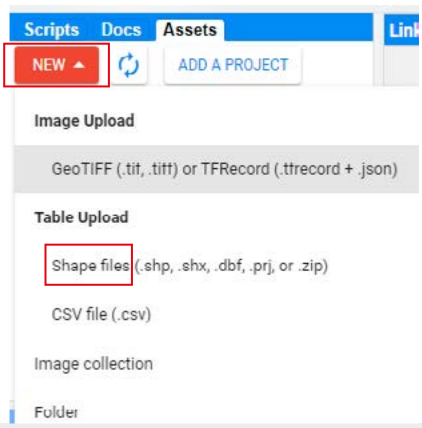
1. Introduction and overview of Google Earth Engine

- This chapter focuses on calculating the mean monthly rainfall over the study area, the Skaka agricultural area.
- Google Earth Engine platform: we will use Google Earth Engine, a powerful cloud-based platform with vast amounts of satellite imagery and remote sensing data. Google Earth Engine allows users to write JavaScript code for computation.
- Code access: the provided code for calculating monthly rainfall from CHIRPS in Google Earth Engine can be accessed at this link: https://code.earthengine.google.com/ee5dfecef43d9c58bbedc5d136af4492.

2. Defining the study area

- Import area of interest: define the Skaka agricultural area in Google Earth Engine either by:
  - Uploading a shapefile (figure 31):
    - Navigate to the "Assets" tab in Google Earth Engine.
    - Select "New" and choose "Shape files" under "Table upload."
    - Upload the shapefile representing the Skaka agricultural area.
  - Drawing directly in Google Earth Engine:
    - Use Google Earth Engine's drawing tools to draw the Skaka agricultural area on the map directly.

Figure 31. Uploading your shapefile as an asset in Google Earth Engine

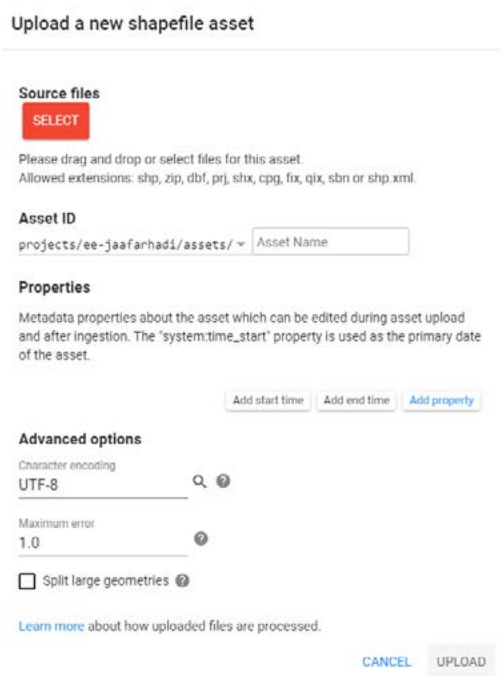


Source: ESCWA, using https://earthengine.google.com/.

3. Steps for uploading and importing shapefiles to Google Earth Engine

- Upload your shapefile
  - Click on "Select" in the new window (figure 32).
  - Browse to the location of your zipped shapefile on your computer.
  - Click on "Upload".

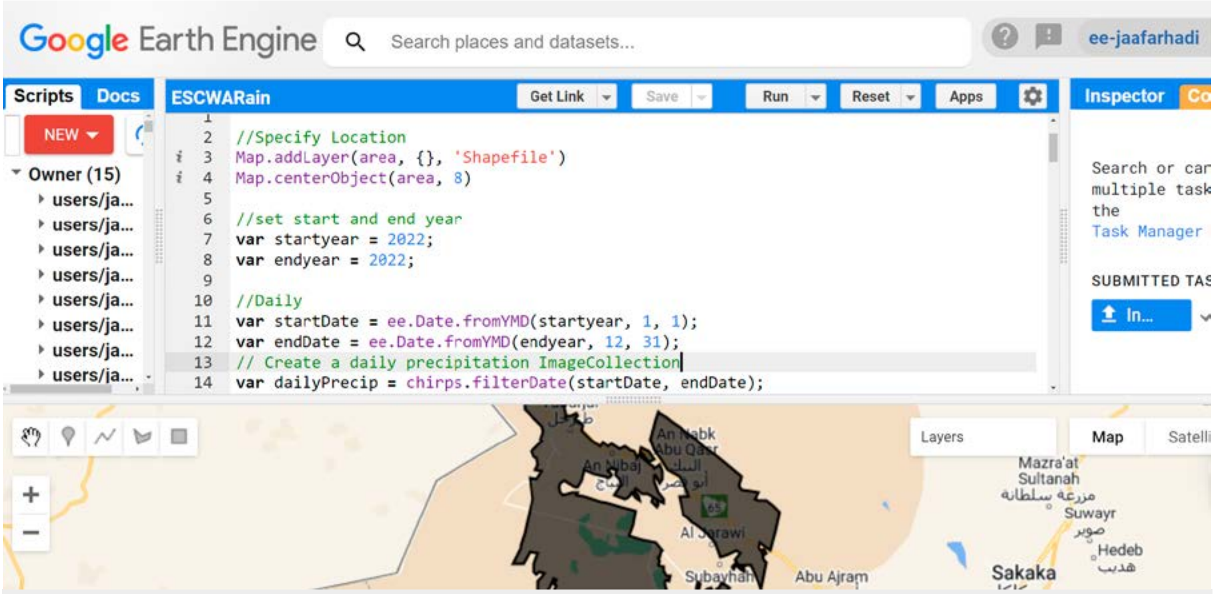
Figure 32. Selecting the shapefile in Google Earth Engine



Source: ESCWA, using https://earthengine.google.com/.

- Monitor the upload
  - The upload will start a task in the "Tasks" tab in Google Earth Engine.
- Access your shapefile
  - When the task is complete, your shapefile will be available in your "Assets" tab.
  - Click the "Refresh" button to update your assets list.
- Import your shapefile
  - Hover your mouse over your shapefile in the assets list.
  - Click the right-facing arrow to import the shapefile directly into your code editor.
- Configure your analysis
  - Modify the start and end year values in your code to match the dates of the imagery you downloaded.
- Run your code
  - Click the "Run" button (figure 33) to execute your analysis.

Figure 33. Overview of the Google Earth Engine code used to determine rainfall



Source: ESCWA, using https://earthengine.google.com/.

4. Code explanation

The above code calculates and visualizes daily, monthly, and weekly rainfall data from the CHIRPS dataset in Google Earth Engine.

(a) Setting up the environment:

- Map.addLayer(area, {}, 'Shapefile'): adds a shapefile representing the region of interest to the Google Earth Engine map.
- Map.centerObject(area, 8): centres the map on the specified region with a zoom level of 8.
- startyear, endyear: defines the start and end years for the analysis.
- startDate, endDate: creates ee.Date objects representing the start and end dates for daily precipitation calculation.

(b) Accessing CHIRPS data:

- chirps: accesses the CHIRPS dataset using the ee.ImageCollection("UCSB-CHG/CHIRPS/DAILY") function.
- dailyPrecip = chirps.filterDate(startDate, endDate): filters the CHIRPS dataset to include only images within the specified date range.

(c) Daily precipitation chart:

- title: defines the chart title and axis labels.
- ui.Chart.image.seriesByRegion(): creates a time-series chart by averaging daily precipitation values within the region of interest.
- imageCollection: dailyPrecip: specifies the ImageCollection to be used for charting.

- regions: area: defines the region for which the mean precipitation is calculated.
- reducer: ee.Reducer.mean(): uses the mean reducer to calculate the average precipitation within the region.
- band: 'precipitation': specifies the band containing the precipitation data.
- scale: 2500: sets the spatial resolution for averaging.
- xProperty: 'system:time_start': uses the timestamp as the x-axis of the chart.
- seriesProperty: 'SITE': uses the 'SITE' property (if available) for grouping data.
- setChartType('ColumnChart'): sets the chart type to a column chart.

(d) Monthly precipitation calculation:

- years, months: creates lists representing the years and months within the analysis period.
- monthlyPrecip: calculates monthly precipitation by:
  - Looping through each year (years.map()).
  - Looping through each month (months.map()).
  - Filtering the CHIRPS data for the specific year and month.
  - Summing the filtered images to get the total monthly precipitation.
  - Setting the 'year', 'month' and 'system:time_start' properties for each image.
- flatten(): flattens the nested list of images into a single image collection.

(e) Monthly precipitation chart:

- Similarly to the daily precipitation chart, uses the ui.Chart.image.seriesByRegion() function to visualize monthly precipitation values.

(f) Weekly precipitation calculation:

- weeks: creates a list representing the weeks of the year.
- weeklyPrecip: calculates weekly precipitation by:
  - Looping through each year (years.map()).
  - Looping through each week (weeks.map()).
  - Calculating the start and end dates of the week.
  - Filtering the CHIRPS data for the specific week.
  - Summing the filtered images to get the total weekly precipitation.
  - Setting the 'year', 'week' and 'system:time_start' properties for each image.

(g) Weekly precipitation chart:

- Similarly to the daily and monthly precipitation charts, uses ui.Chart.image.seriesByRegion() to visualize weekly precipitation values.

5. Visualization and exporting results

(a) Visualization:

- To visualize the calculated monthly rainfall data on the Google Earth Engine map, create an ee.Image from the monthlyPrecip ImageCollection.
- Then, use the Map.addLayer() function to add the image to the map with a suitable colour map.
- You can use ee.Image.visualize() to create a colour map and specify the colour range for different precipitation values.

(b) Exporting:

- Export as a table: use Export.table.toDrive() to export the monthly precipitation data as a table to your Google Drive.
- Export as an image: use Export.image.toDrive() to export the monthly precipitation image to your Google Drive. You can specify the output file format, compression, and other parameters.

(c) Alternative methods:

- Climate Engine: climate Engine is another platform that provides access to climate data, including rainfall data. However, Google Earth Engine offers a more flexible and powerful scripting environment with more advanced capabilities for data processing and analysis.
- Other datasets: you can also use other rainfall datasets such as ERA5 or TRMM within Google Earth Engine.

(d) Data sources:

- CHIRPS dataset: the specific dataset used is UCSB-CHG/CHIRPS/DAILY.
- Spatial resolution: 0.05 degrees (~5 km).
- Temporal resolution: daily.

(e) Data quality:

- Limitations: CHIRPS data is estimated based on satellite observations and relies on interpolation methods, which can introduce inaccuracies.
- Potential sources of error include:
  - Cloud cover affecting satellite observations.
  - Terrain effects influencing precipitation patterns.
  - Uncertainty in precipitation estimation methods.
- Data quality checks: the code does not include specific data quality checks. You can incorporate additional checks such as:
  - Removing outliers based on statistical analysis.
  - Applying spatial smoothing techniques to reduce noise.
  - Comparing with other rainfall datasets for validation.

Remember to adapt the code to your specific region of interest, analysis period and data quality requirements.

- Output exploration:
  - Begin by examining the console pane on the right-hand side of the page. Here, you will find the output of your Google Earth Engine analysis.
- Analysing the histogram:
  - The console will display a histogram visualizing the monthly rainfall data for 2022 over the selected area.
  - For a more detailed view, click the arrow icon (figure 34) to expand the histogram into a separate tab.
- Expanded histogram view:
  - Within the expanded view, you can closely inspect the histogram's distribution of rainfall values.
  - You can also download the histogram as a file for data analysis or as a PNG image for visual representation.

Figure 34. Monthly rainfall histogram in Google Earth Engine

Source: ESCWA, using https://earthengine.google.com/.

To begin, download the .csv file containing monthly rainfall data. This file, shown in figure 35, contains two columns:

- Column A: represents the month of the year.
- Column B: contains the corresponding monthly rainfall measurements in mm.

These data, given in figure 34, will be used for subsequent analysis.

Figure 35. Screenshot of the rainfall .csv file

	A	B
1	system:time_start	undefined
2	1-Jan-22	17.129
3	1-Feb-22	14.927
4	1-Mar-22	11.751
5	1-Apr-22	9.25
6	1-May-22	0.034
7	1-Jun-22	0.152
8	1-Jul-22	0
9	1-Aug-22	0
10	1-Sep-22	0.409
11	1-Oct-22	1.698
12	1-Nov-22	80.664
13	1-Dec-22	19.723
14		

Source: ESCWA.

6. Calibrating rainfall data for accurate estimation of groundwater use

To estimate groundwater use accurately, you must calibrate your rainfall data. This involves comparing rainfall data from local weather stations with the CHIRPS dataset, which provides spatially continuous rainfall estimates.

Calibration process

- Gather local data: obtain rainfall records from local weather stations covering your area of interest.
- Compare with CHIRPS: analyse the collected data alongside the corresponding CHIRPS rainfall estimates for the same locations.
- Identify bias: determine if the local station rainfall consistently deviates from CHIRPS estimates.
- Apply bias factor: if a consistent bias exists, apply a multiplicative bias factor to the CHIRPS estimates. For example, if local station rainfall is consistently 20 per cent higher than CHIRPS over several years, multiply the CHIRPS values by 1.2.
- Addressing spatial variations: if multiple stations show varying biases (for example, one higher and one lower), use interpolation techniques (spline or kriging) using a geographic information system (GIS) to estimate rainfall across the study area based on station records. This will account for spatial variations in rainfall.

7. Deriving monthly rainfall maps from station data using a GIS

While readily available rainfall datasets exist, there are situations where you may need to create maps from station measurements. The below outlines how to create maps of monthly rainfall data for a study area using rainfall station measurements and GIS software.

(a) Data preparation:

- Gather rainfall data: obtain monthly rainfall data for each station within and surrounding your study area. Ensure that data are complete and cover the desired time period.
- Format the data: organize data in a spreadsheet format with columns for station ID, coordinates (latitude and longitude), month, and rainfall amount.
- Check data accuracy: validate the data for consistency and potential errors.

(b) Importing data into the GIS:

- Create a new GIS project: open GIS software (such as QGIS or ArcGIS) and create a new project.
- Import station data: import the formatted spreadsheet containing rainfall data as a point layer.
- Define coordinate system: ensure the data is correctly projected into your study area's coordinate system.

(c) Creating rainfall grids:

- Choose an interpolation method: select an appropriate interpolation method for creating the rainfall grids. Common options include:
    - Inverse distance weighted: weights values based on inverse distance from the station.
    - Kriging: uses statistical models to account for spatial autocorrelation.
    - Thiessen polygons: divides the study area into polygons, with each station representing the centre of its polygon.
- Set interpolation parameters: adjust the parameters of your chosen method, such as search radius, number of stations used, and weighting factors.
- Create separate grids for each month: run the interpolation process for each month to create individual rainfall grids.

(d) Creating zonal statistics:

- Import study area boundary: import a shapefile or vector layer defining your study area's boundary.
- Use zonal statistics: use the "Zonal Statistics" tool to calculate the average rainfall for each month within each zone of your study area. This will generate a new layer with rainfall values for each zone and each month.
- Visualize the results: display the zonal statistics as a thematic map, where different colours represent different rainfall amounts. You can also create graphs and charts to visualize rainfall trends and patterns within your study area.

(e) Additional considerations:

- Data quality: the accuracy of your rainfall maps will depend on the quality and distribution of your station data.
- Spatial resolution: the resolution of your rainfall grids will depend on the density of stations and the chosen interpolation method.
- Temporal trends: consider analysing trends in monthly rainfall over time.

You can use rainfall station data and a GIS to create maps of monthly rainfall for your study area.

8. Impact of bias on groundwater use

The impact of rainfall bias on groundwater use from irrigation is generally low, particularly during dry periods when irrigation is most prevalent. However, calibration is still crucial to ensure the overall accuracy of your analysis.

Once you have determined the calibrated monthly rainfall for your study area, you can proceed to calculate groundwater use or effective rainfall by incorporating both rainfall and evapotranspiration data. This will provide a more accurate assessment of groundwater resource availability and use.

6. Determining groundwater use

A. Effective rainfall

1. Determining effective rainfall and groundwater abstraction

This chapter will describe how to calculate effective rainfall, which represents the amount of rainfall contributing to groundwater recharge. A negative effective rainfall indicates net groundwater abstraction, primarily as a result of irrigation.

2. Calculation

To determine effective rainfall, subtract monthly actual evapotranspiration from monthly rainfall. This evapotranspiration data was previously calculated in chapter IV. The monthly rainfall data is obtained from column B of the downloaded .csv file (table 2).

3. Interpretation

- Negative effective rainfall: a negative value indicates that actual evapotranspiration exceeds rainfall, implying that irrigation is supplementing water supply. In agricultural areas, this negative value represents an estimate of net groundwater abstraction, in mm, each month.
- Positive effective rainfall: if rainfall exceeds actual evapotranspiration, the excess water contributes either to deep percolation into groundwater or to surface runoff.
- Residual soil moisture: in regions with significant rainfall, a small amount of evapotranspiration (0-50 mm) during spring months might be sustained by residual soil moisture.

Note: This analysis assumes that groundwater is the sole source of irrigation water. In areas where surface water is also used, the calculated groundwater abstraction will represent an underestimation.

Table 2. Calculation of effective rainfall and groundwater use

Month	Monthly rainfall (mm)	Monthly actual evapotranspiration (mm)	Effective rainfall (mm/month)	Net groundwater use (mm/month)
January	17.1	10.6	6.5	-6.5
February	14.9	18.3	-3.4	3.4
March	11	35.6	-24.6	24.6

Month	Monthly rainfall (mm)	Monthly actual evapotranspiration (mm)	Effective rainfall (mm/month)	Net groundwater use (mm/month)
April	9.2	57.6	-48.4	48.4
May	0	48.4	-48.4	48.4
June	0.15	45.4	-45.25	45.25
July	0	51.2	-51.2	51.2
August	0	56	-56	56
September	0.41	48.3	-47.89	47.89
October	1.7	36	-34.3	34.3
November	80.7	20	60.7	-60.7
December	19.7	11.1	8.6	-8.6

Source: ESCWA.

B. Seasonal groundwater use for agriculture

This section focuses on calculating the estimated groundwater use for agricultural purposes when surface water sources (reservoirs, ponds, rivers, lakes) are not used for irrigation.

When surface water is used for irrigation, the negative effective rainfall represents the combined usage of both surface water and groundwater in agriculture.

To determine the net groundwater use for a specific region, follow these steps:

- Sum the negative depths of effective rainfall: identify and add together all instances where the effective rainfall is negative.
- Multiply by area: multiply the sum obtained in step 1 by the area of the region under consideration.

This calculation provides an estimate of the total volume of groundwater consumed for agricultural purposes during the season:

Net groundwater use =. |∑(effective rainfall)| (m) × area (m2)

- Add the monthly values together and then take the absolute value and divide it by 1000 to get the units in m (in this case 0.358 m).
- Multiply the obtained value by the area of the region (area of agricultural area in Skaka = 8.1×109 m^2).

1. Groundwater depletion in the Skaka agricultural area

In 2022, the Skaka agricultural area experienced a net groundwater depletion of approximately 2,904 million m^3. This figure represents the water volume required to compensate for evapotranspiration.

While the actual amount of water pumped for irrigation typically exceeds this net depletion as a result of system inefficiencies, we can estimate the overall level of water extraction using a two-step approach:

- Subtract surface water use: begin by subtracting any surface water used for irrigation from the total water applied.
- Account for irrigation efficiency: consider the efficiency of the irrigation system, encompassing both the irrigation system itself and the conveyance and distribution networks.

2. Example calculation

Using the example of the Skaka agricultural area, a negative effective rainfall balance of 358 mm for 2022 suggests a water deficit requiring irrigation. Assuming an 85 per cent irrigation efficiency for a centre pivot system and 90 per cent conveyance and distribution efficiency, the overall system efficiency is 76.5 per cent (0.85 x 0.9).

This translates to a required pumping volume of approximately 468 mm of water across the 800,000 ha irrigated using centre pivots. Consequently, the annual groundwater extraction for irrigation in the Skaka agricultural area is estimated to be 3,744 million m^3.

In shallow aquifers, water that percolates deeper than the root zone can eventually replenish the aquifer. Therefore, for these situations, we can neglect the extra water applied that percolates to this depth.

7. Comparison with field measurements

Optional comparison with groundwater level data

This manual primarily focuses on estimating groundwater use from irrigation. However, an optional procedure allows these estimates to be compared to net groundwater level changes, providing a more comprehensive understanding of groundwater dynamics.

If groundwater well data is available, comparing the estimated groundwater use with observed water table declines can be beneficial. This involves collecting data on groundwater well depths and comparing them with the estimated amount of water extracted.

Example: comparing effective rainfall to groundwater table measurements.

Figure 36 compares monthly water table data (2012–2016) with cumulative effective rainfall for the same period. Cumulative effective rainfall is calculated by adding the monthly effective rainfall values (e.g. cumulative effective rainfall in month 2 = effective rainfall in month 1 + effective rainfall in month 2).

For the example shown, the net change in water table between the first peak (1 January 2013) and the last peak (July 2016) is 62 m - 50 m = 12 m. This corresponds to the total water use from the aquifer minus the total recharge during that period. This represents an average annual drop of 4 m over the three-year period.

During the same period, the cumulative effective rainfall was 180 mm - (-60 mm) = 240 mm, or 80 mm per year.

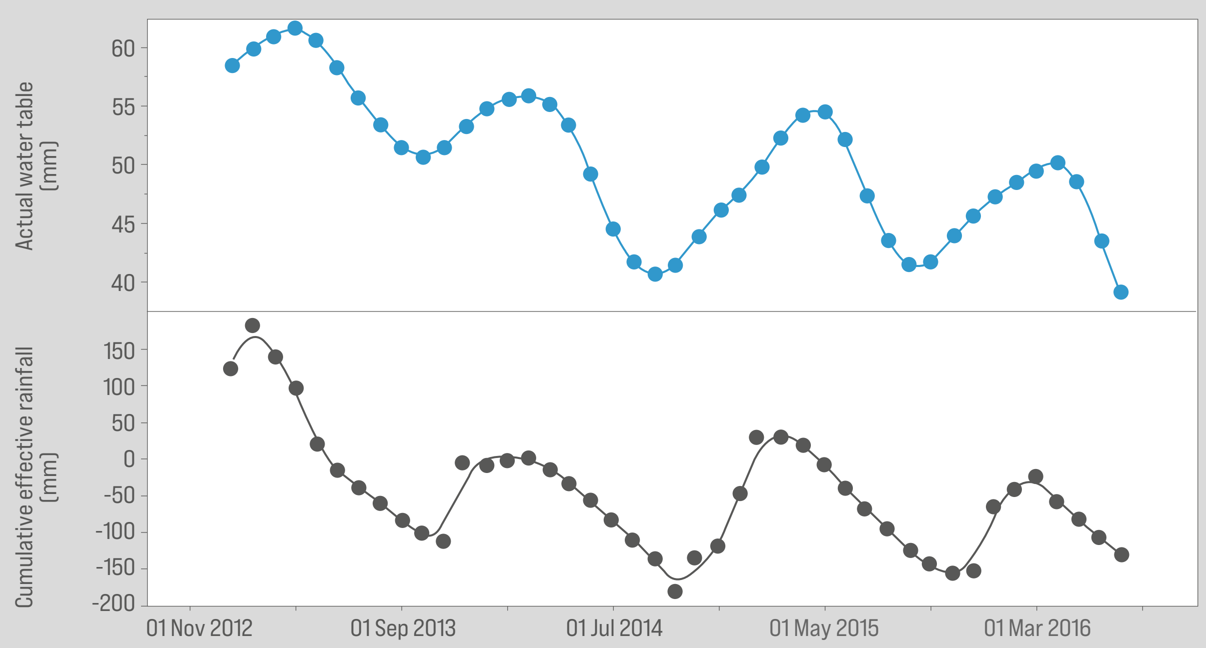
The 240 mm calculated using remote sensing of precipitation and evapotranspiration corresponded to a 12 m drop in water table from the shallow unconfined aquifer. Dividing the 0.24 m (converted from 240 mm) by the 12 m drop in the groundwater table provides an estimate of the aquifer specific yield (0.02 in this case). Conversely, knowing the specific yield of the aquifer allows the expected groundwater level drop to be calculated based on negative effective rainfall.

This analysis is a simplification and does not account for other factors that may influence groundwater levels, such as:

- Leakage or gain of water from other sources.
- Discharges to springs in the area.
- Streamflow-groundwater interactions.

Furthermore, using data from a single well may not fully represent the characteristics of the entire aquifer. These factors are beyond the scope of this manual.

Figure 36. Comparison between remotely sensed estimate of groundwater use and water table measurements



Source: ESCWA.

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In the face of increasing water scarcity, limited renewable groundwater resources continue to be exploited at an unsustainable rate, exceeding natural recharge rates. The excessive use of groundwater, especially by the agricultural sector, combined with low efficiency, has led to a decline in groundwater storage in most of the Arab region. It is projected that by 2050, available amounts of groundwater per capita will have decreased by more than half since the beginning of the century. Thus, the accurate estimation of groundwater use for irrigation is critical for sustainable water management, especially in arid and semi-arid areas such as the Arab region.

This training manual was developed to support water resource experts in Arab countries in accessing remote sensing data from open-source platforms and data available on the Arab Groundwater Knowledge Platform to better manage groundwater used for irrigation. It provides a step-by-step guide to estimating groundwater use from irrigated agriculture in dry regions using remote sensing techniques. The manual is designed to give users the knowledge and tools they need to use advanced remote sensing technologies to provide efficient and precise groundwater estimations in data-scarce regions.

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