Parcel-Scale Water Stress Detection with FAO-56

Dynamic Water Balance, Remote Sensing and Irrigation Scheduling

AGRI_GIS - Emerging GIS Tools for Agriculture | Technical Review

ABSTRACT

This technical review summarises a parcel-scale methodology for automated water-stress detection and irrigation support based on the FAO-56 soil-water balance. The workflow integrates agricultural parcel data, daily meteorological observations, SoilGrids hydraulic properties and Sentinel-2 phenology to estimate dynamic crop coefficient (Kc), root depth (Zr), total available water (TAW), readily available water (RAW), root-zone depletion (Dr) and the water-stress coefficient (Ks). It was applied to rainfed wheat and barley in Lleida for the 2020-2021 season and evaluated against NDVI, NDMI, MSI and land-surface temperature. The same framework was then extended to irrigation scheduling through a dynamic irrigation term.

1. OBJECTIVE AND STUDY AREA

The objective is to build a reproducible, open-data workflow that detects periods of crop water limitation at parcel scale and can later support irrigation decisions. The main case study covers winter wheat and barley in the province of Lleida, Spain, where dry Mediterranean conditions and strong seasonal evaporative demand make soil-water availability a major control on crop development.

From the 2021 agricultural parcel dataset, 150 wheat and 150 barley parcels were initially selected. After automatic quality control of the satellite-derived phenological curves, the final analytical sample contained 107 wheat parcels and 86 barley parcels.

Figure 1. Study-area location. Lleida is highlighted within the Iberian Peninsula. Source: adapted from Mirsaeva (2026).

2. DATA SOURCES

The workflow combines parcel geometry and crop declarations with climate, terrain, soil and Earth-observation data. All spatial inputs are harmonised at parcel level so that each polygon receives a daily time series of crop demand, precipitation, soil-water capacity and remotely sensed indicators.

Input	Source / resolution	Role in the workflow
Agricultural parcels	DUN 2021, polygon data	Crop type, parcel geometry and sampling
Meteorology	XEMA, 58 stations, daily	Precipitation, ET0 and temperature
Terrain	CNIG MDT200, 200 m	Parcel elevation and terrain context
Soil hydraulics	SoilGrids 2.0, 250 m	Field capacity, wilting point and AWC
Phenology	Sentinel-2 in Google Earth Engine	SOS, MidIn, Peak, MidOut and EOS
Validation indices	Sentinel-2, Landsat, MODIS	NDVI, NDMI, MSI and LST

3. PHENOLOGY FROM SENTINEL-2 NDVI

Phenology is estimated independently for each parcel from Sentinel-2 surface reflectance. NDVI is calculated from B8 (near infrared) and B4 (red) after cloud and scene-classification filtering. The median parcel value is used to build a robust seasonal curve. Five operational dates are then extracted: SOS, MidIn, Peak, MidOut and EOS.

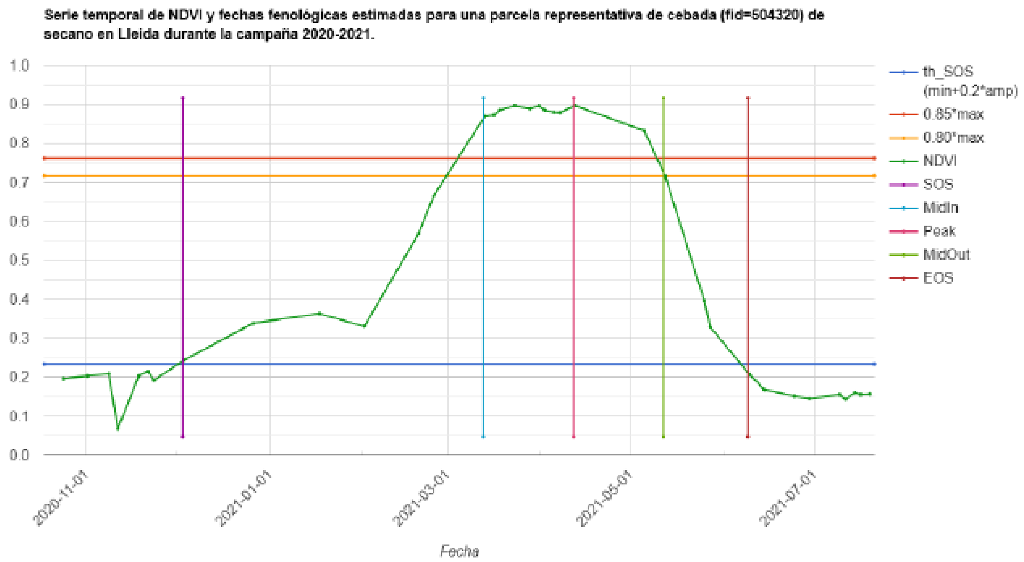


Figure 2. Example NDVI time series with automatically detected phenological dates for a barley parcel. Source: adapted from Mirsaeva (2026).

Automatic controls reject weak or implausible curves. The adopted criteria include at least 12 valid observations, NDVI amplitude ≥ 0.20, a minimum 10-day mid-season plateau, crop-specific cycle-duration ranges and a peak date between March and July. Additional filters constrain SOS relative to the regional sowing date and remove zero-duration phases.

> Why parcel-specific phenology matters. The detected dates drive the daily evolution of Kc and root depth instead of relying only on a generic regional crop calendar. This makes the water balance responsive to differences in crop development among parcels.

4. INTEGRATED FAO-56 WORKFLOW

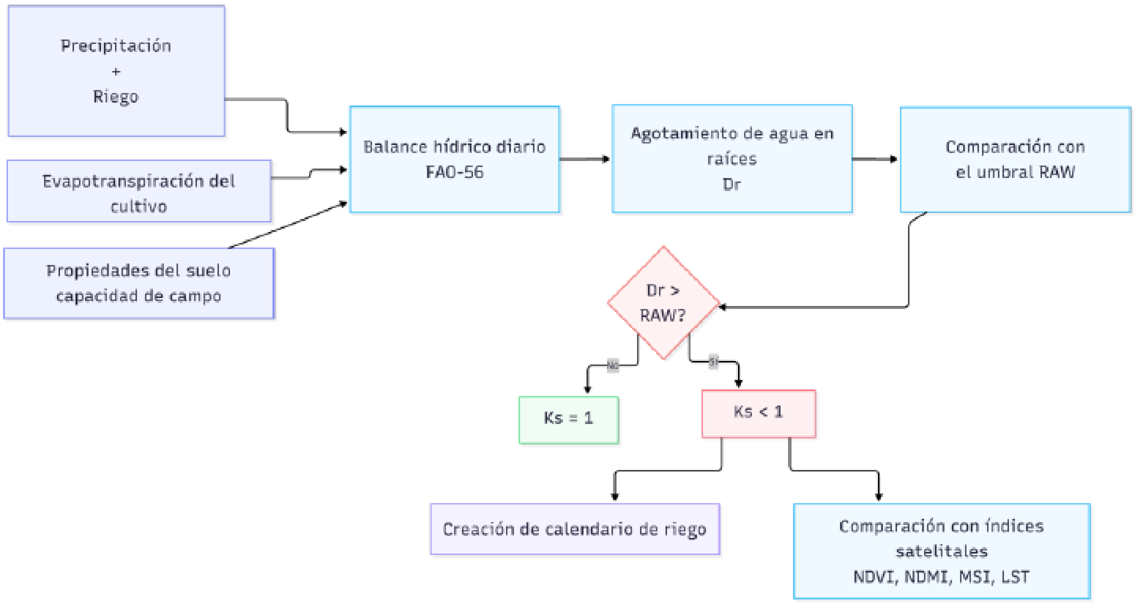


Figura 3. Diagrama de flujo metodológico desarrollado en este trabajo.

Figure 3. Methodological workflow linking water inputs, crop demand, soil storage, stress detection, irrigation scheduling and remote-sensing evaluation. Source: adapted from Mirsaeva (2026).

4.1 Dynamic crop and soil parameters

The model updates crop demand and root-zone storage through the season. Kc follows the FAO-56 single-coefficient approach, while root depth increases linearly from the end of the initial stage to the end of crop development. Soil-water capacity is derived from the difference between field capacity and permanent wilting point in SoilGrids layers, accumulated only through the fraction of soil explored by roots.

Parameter	Wheat	Barley	Operational meaning
Kc, initial	0.30	0.30	Low-cover establishment stage
Kc, mid	1.15	1.15	Maximum crop water demand
Kc, end	0.40	0.25	Senescence / late season
Zr, initial	0.15 m	0.15 m	Initial effective root depth
Zr, maximum	1.25 m	1.25 m	Adopted effective maximum depth
p reference	0.55	0.55	Depletion fraction before stress

Soil-water storage

Available water capacity for each layer is computed from field capacity and wilting point. Daily TAW(t) increases as roots explore deeper soil. RAW(t) = p(t) × TAW(t), where p is adjusted from the FAO-56 reference value according to daily crop evapotranspiration. Stress begins when root-zone depletion exceeds RAW.

Core state variables

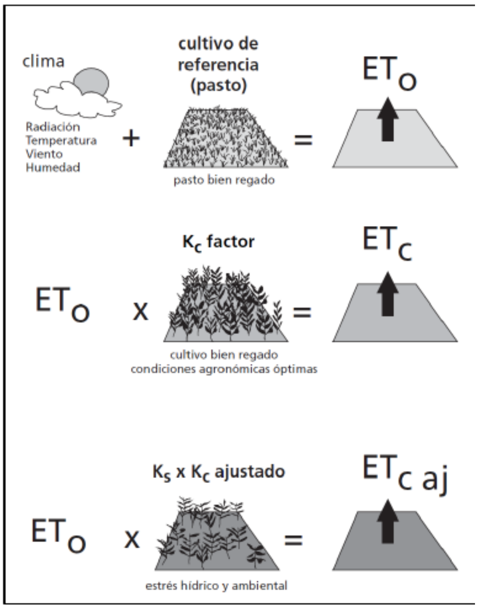
Dr - root-zone water depletion (mm). TAW - total water potentially extractable by roots. RAW - depletion threshold below which water extraction remains non-limiting. Ks - stress coefficient, equal to 1 without water limitation and decreasing toward 0 as depletion approaches TAW.

5. DAILY WATER BALANCE AND STRESS COEFFICIENT

For rainfed parcels, irrigation, capillary rise and explicit runoff are set to zero. The simplified daily balance updates depletion from precipitation and stress-adjusted crop evapotranspiration, while excess water beyond field capacity is treated as deep percolation. Depletion is constrained to the interval $0 \le Dr \le TAW(t)$.

FAO-56 implementation

Daily balance: $D_{r,i} = D_{r,i-1} - P_i + ET_{c,adj,i} + DP_i$ | Crop demand: $ET_c = K_c \times ET_0$ | Adjusted demand: $ET_{c,adj} = K_s \times ET_c$



Stress coefficient

When $Dr \le RAW$, $Ks = 1$. Once Dr exceeds RAW, Ks decreases progressively according to the remaining fraction of extractable water:

$$Ks = (TAW - Dr) / (TAW - RAW)$$

This factor reduces potential crop evapotranspiration whenever the root zone can no longer supply water at the non-stressed rate.

Figure 4. Conceptual link from reference evapotranspiration (ET0) to crop evapotranspiration (ETc) and stress-adjusted ETc. Source: Allen et al. (1998), reproduced in Mirsaeva (2026).

6. REMOTE-SENSING CONSISTENCY CHECK

Only observations coinciding with stress days ($Ks < 1$) are used for the main comparison. Sentinel-2 is prioritised, Landsat is used when Sentinel-2 is unavailable and MODIS provides temporal continuity. LST is obtained from daily MODIS thermal products.

Crop	Index	Pearson r	Spearman ρ	Best global R^2
Wheat	NDVI	0.477	0.495	0.241
Wheat	NDMI	0.370	0.381	0.146
Wheat	MSI	-0.358	-0.379	0.136
Wheat	LST	-0.692	-0.702	0.496
Barley	NDVI	0.447	0.466	0.215
Barley	NDMI	0.368	0.380	0.147
Barley	MSI	-0.355	-0.378	0.139
Barley	LST	-0.627	-0.647	0.421

The signs are physically consistent: NDVI and NDMI decrease as stress intensifies, while MSI and LST increase. LST provides the strongest global relationship with Ks. Spectral indices improve markedly when stress is accumulated over the preceding 7, 14 and 21 days, confirming that vegetation reflectance reacts with a temporal lag.

7. WATER-STRESS DIAGNOSIS

The daily balance was applied to 107 wheat parcels and 86 barley parcels for the 2020-2021 campaign, generating 22,206 daily wheat records and 17,394 barley records. Stress was absent during the initial stage, appeared in a small fraction of parcels during development, and became widespread during mid- and late-season.

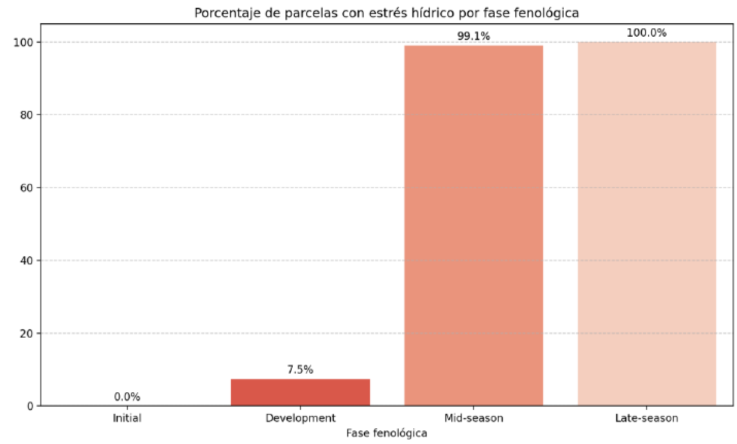


Figura 33. Porcentaje de parcelas de trigo con estrés hídrico por fases.
Fuente: elaboración propia.

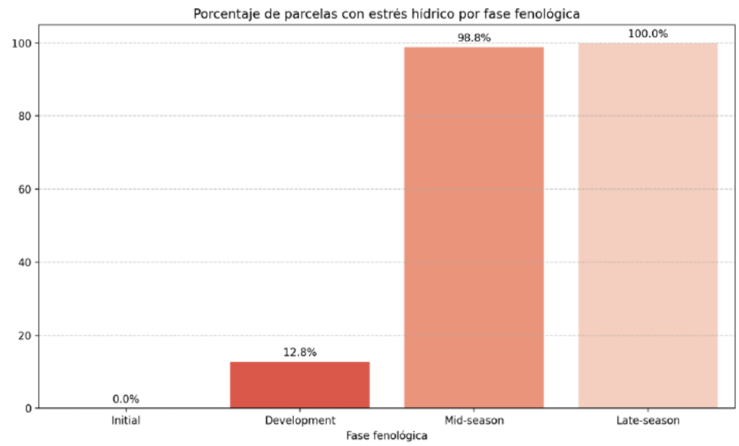


Figura 34. Porcentaje de parcelas de cebada con estrés hídrico por fases.
Fuente: elaboración propia.

Figure 5. Percentage of wheat and barley parcels with Ks < 1 by phenological stage. Source: adapted from Mirsaeva (2026).

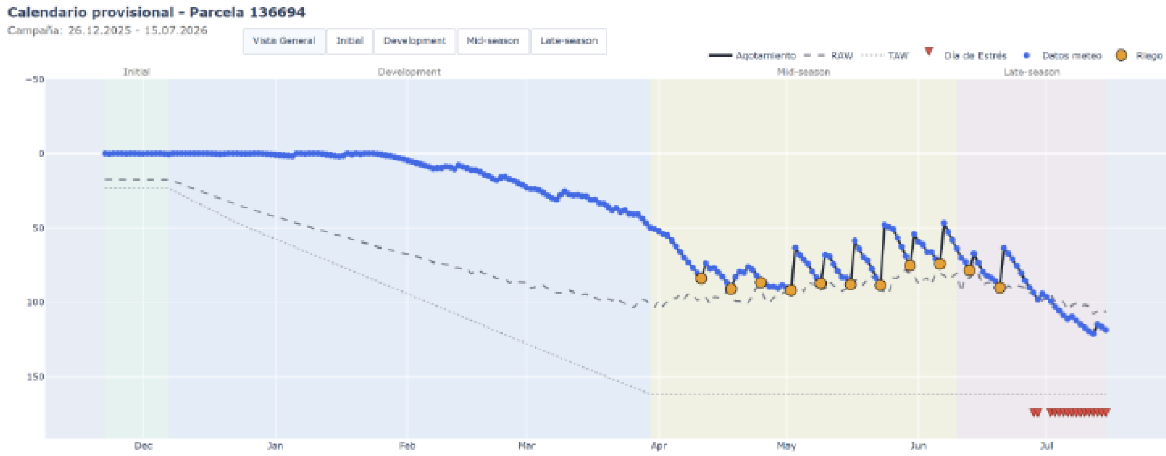
Crop / phase	Development	Mid-season	Late-season	Mean stress days*
Wheat	7.48%	99.07%	100%	12.3 / 42.2 / 28.0
Barley	12.79%	98.84%	100%	12.7 / 39.3 / 24.3

**Mean stress days are shown for Development / Mid-season / Late-season.*

Main seasonal result. Mid-season is the critical period. Nearly all parcels experience at least one stress episode, and the mean duration reaches about 42 days in wheat and 39 days in barley. Late-season stress is also universal, although part of it overlaps natural senescence and should not automatically be interpreted as agronomically critical.

8. OPERATIONAL IRRIGATION SCHEDULING

The same water-balance structure is extended to irrigated wheat by activating the irrigation term. A demonstration for parcel 136694 uses parcel-specific phenology, Kc, root depth and soil-water storage. Historical daily climate averages provide the preliminary forecast, and the balance can later be recalculated with observed weather before each irrigation turn.



Fecha	Fase	Neto (mm)	Bruto (mm)
18/04/2025	Mid-season	11.2	18.7
25/04/2025	Mid-season	3.6	6.1
02/05/2025	Mid-season	31.3	52.2
09/05/2025	Mid-season	23.5	39.2
16/05/2025	Mid-season	29.9	49.8
23/05/2025	Mid-season	43.4	72.4
30/05/2025	Mid-season	26.6	44.3
06/06/2025	Mid-season	33.6	55.9
13/06/2025	Late-season	16.6	27.7
20/06/2025	Late-season	28.1	46.9

Figure 6. Provisional irrigation calendar for parcel 136694. Irrigation events reduce soil-water depletion and keep it below the stress threshold where possible. Source: adapted from Mirsaeva (2026).

A fixed 7-day irrigation turn is used in the operational example. The required net irrigation is calculated from current depletion plus expected ETc minus expected precipitation, targeting a final depletion at or below RAW. Gross irrigation is obtained by correcting the net dose for application efficiency.

> **Worked example - 11 April 2026**
>
> With Dr = 83.93 mm, expected 7-day ETc = 30.85 mm, expected precipitation = 7.13 mm and target depletion = 94.31 mm, the model gives 13.34 mm net irrigation. At 60% application efficiency, the corresponding gross dose is 22.24 mm. When observed weather is introduced, the recommendation is recalculated dynamically.

9. METHODOLOGICAL ASSESSMENT AND IMPROVEMENTS

Limitation / improvement	Expected benefit
Replace coarse global soil layers with local soil measurements or detailed maps	More accurate TAW and RAW at parcel scale
Validate phenology and soil water with field observations	Independent calibration of satellite and model assumptions
Use short-range weather forecasts instead of historical means for future days	More responsive irrigation recommendations
Pilot the system with irrigation communities and compare against real applied water	Operational validation and user feedback

The proposed technological implementation was estimated at €9,700, while the complete project budget including technical work, equipment and indirect costs was €17,214.88. The investment estimate represents a future operational deployment rather than a cost required for the academic study.

10. CONCLUSIONS

The study demonstrates a reproducible parcel-scale workflow for detecting agricultural water stress with FAO-56 using open geospatial data. Its main contribution is the dynamic adaptation of key parameters to each parcel: crop phenology from Sentinel-2, Kc through the detected crop stages, root depth through time, and soil-water storage from hydraulic properties.

The 2020-2021 rainfed analysis produces an agronomically coherent seasonal pattern. Stress is limited during early growth and becomes dominant in mid-season and late-season as precipitation becomes insufficient relative to crop demand. Remote-sensing data support the physical consistency of the model. NDVI and NDMI are positively related to Ks, MSI and LST are inversely related, and LST shows the strongest global explanatory power. The stronger relationships obtained for 7- to 21-day accumulated stress show that optical vegetation indices mainly reflect accumulated rather than instantaneous water limitation.

For irrigated agriculture, the framework can be converted from diagnosis to decision support. By recalculating root-zone depletion and forecasting the interval to the next irrigation turn, the method estimates both timing and dose while keeping depletion below the stress threshold. The study therefore provides a technical basis for a future parcel-level irrigation monitoring platform.

> The most robust operational use is a decision-support system that combines daily water balance, satellite-derived crop development and progressively updated weather information. Field observations remain essential for calibration, especially for soil hydraulic properties, phenology and real irrigation response.

11. REFERENCES AND FURTHER READING

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• Google Earth Engine / Copernicus Sentinel-2 / Landsat / MODIS data were used for the satellite time-series processing described in the source project.

Keywords: GIS · Remote Sensing · Water Stress · FAO-56 · Soil Water Balance · Sentinel-2 · NDVI · NDMI · MSI · LST · Irrigation Scheduling · Precision Agriculture