FAO-56 Smart Irrigation Engine: User & Technical Guide

This document explains the functionality, inputs, core scientific logic, and output interpretation of the Smart Irrigation Engine, which uses the globally accepted FAO-56 Penman-Monteith standard for moisture modeling.

1. Overview and Goal

The primary goal of this application is to provide farmers and agronomists with a precise, science-based daily irrigation recommendation by calculating the water stress level in the plant root zone.

The recommendation is based on four major components:

1. **Weather Data (Location):** To determine atmospheric water demand (ET_0).
2. **Crop and Soil Parameters:** To determine plant water demand (ET_c) and soil water holding capacity (TAW & RAW).
3. **Water Balance Model:** To track daily soil water deficit.
4. **ML Forecast (XGBoost):** To predict ET_c and future irrigation triggers.

2. Input Parameters

The user interface is structured into three main sections:

2.1. 📍 Location & Crop

These inputs define the environmental and biological conditions for the simulation.

Parameter	Description	Technical Use
Latitude / Longitude	Geographic coordinates of the field.	Used to fetch historical and real-time weather data (temperature, humidity, solar radiation, wind speed) essential for the ET_0 calculation.
Crop Type	The plant being grown (e.g., Wheat, Maize).	Determines the base Crop Coefficient (K_c) curve and rooting depth for the water balance model.
Growth Stage	Current phenological stage (Initial, Mid, Late).	Modifies the K_c value to calculate the actual crop water demand (ET_c).

2.2. 🚜 Soil & Hydraulics

These inputs define the physical properties of the land and the mechanics of water application.

Parameter	Description	Technical Use
Soil Type	Soil texture (Sandy, Loam, Clay).	Determines the soil's critical water holding parameters: Field Capacity (FC), Permanent Wilting Point (PWP), and consequently the TAW and RAW thresholds.
Field Area	The size of the field.	Used in the final output calculation to convert water depth (mm) to total water volume (Liters) required for pumping.
Pump Power (HP) & Condition	Horsepower and efficiency (condition) of the pump.	Determines the effective flow rate of the pump (Liters/Hour), which is crucial for calculating the **Pump Runtime** (Hours).
Irrigation Method	How water is applied (e.g., Drip, Flood).	Determines the **Application Efficiency** (e.g., 60% for Flood, 90% for Drip). This is critical for calculating the **Gross Irrigation** required to satisfy the deficit.

2.3. Optional: Initial Conditions

Parameter	Description	Technical Use
Initial Soil Deficit (mm)	User-defined starting deficit.	Overrides the system's auto-estimation to set the starting point of the water balance simulation.
Auto-estimate Initial Deficit	System calculates initial deficit from historical data.	Default setting that uses historical weather to estimate how much water the soil might have lost leading up to the current date.

3. The Core Physics Engine (How it Works)

The engine operates on the fundamental principle of **Soil Water Balance**, often visualized as a water budget.

3.1. Calculating Water Demand (ET_c)

1. **Reference Evapotranspiration (**ET_0**):** This is the potential water loss from a standard grass surface, calculated using the **FAO-56 Penman-Monteith equation** based on local weather data.
2. **Crop Water Demand (**ET_c**):** This is the actual water consumed by the crop.

   $$\text{ET}_c = \text{K}_c \times \text{ET}_0$$

   Where K_c (Crop Coefficient) is adjusted based on the **Crop Type** and **Growth Stage**.

3.2. The Decision Threshold (RAW)

The engine does not wait until the plant is dead to recommend irrigation. It recommends watering when the deficit reaches the **Readily Available Water (RAW)** threshold.

- **Total Available Water (TAW):** The total amount of water the plant can physically extract from the soil.
- **Readily Available Water (RAW):** The portion of TAW that the plant can extract without experiencing *any* stress (RAW = $\text{TAW} \times p$, where p is the depletion fraction).

The Core Trigger: The system recommends irrigation when:

$$\text{Current Deficit} > \text{RAW Threshold}$$

4. Understanding the Output

The output is always displayed for **Today's Date** (Index 0 of the simulated data).

Output Metric	Value	Meaning
ET0 (Today)	X.XX mm	The evaporative demand of the atmosphere today.
Soil Deficit	X.XX mm	The current water shortage in the root zone (amount lost since Field Capacity).
Threshold (Help text)	RAW: Y.YY mm	The point at which the irrigation trigger is met.
Action	**START PUMP** or **NO ACTION NEEDED**	**The Key Decision:** If $\text{Soil Deficit} > \text{RAW}$, the action is START PUMP (Red Alert).
Pump Runtime	Z.ZZ Hours	The calculated time required to run the pump to bring the deficit back to zero, accounting for pump flow rate and application efficiency.

Logic Flow for Pump Runtime Calculation:

1. **Net Depth Required:** Current Deficit (mm)
2. **Gross Depth Required:** $\text{Net Depth} / \text{Application Efficiency}$ (mm)
3. **Water Volume Required (L):** $\text{Gross Depth (m)} \times \text{Area (m}^2) \times 1000$
4. **Pump Runtime (Hours):** $\text{Water Volume (L)} / \text{Effective Pump Flow (L/hr)}$

5. Forecasting and ML

The engine includes a forward-looking forecast to help with planning.

- **ML Model: XGBoost** is used to forecast future ET_c values based on weather prediction.
- **Hydraulic Trends Graph:** Shows how the ET_c (Crop Demand) and the **Soil Water Deficit** are expected to change over the next week.
- **Predicted Next Irrigation:** This feature analyzes the forecasted deficit data to find the *first day* when the $\text{Deficit} > \text{RAW}$ condition is met.

- **Forecast Runtime:** This is the estimated pump time needed to fully refill the root zone on the predicted trigger date.

6. Engine Metadata (JSON)

This section is for advanced users, validation, and debugging. It shows the raw, non-interpreted engine data.

Key	Content
parameters	All constant physical inputs used in the calculation (e.g., K_c, RAW, TAW, $\text{area\_m}2$).
state_today	The exact calculated state of the system for the current day (Date 0). This confirms the values displayed in the main metrics.
recommendation_today	The exact output values (hours, liters) calculated based on **state_today**.
validation	Metrics (RMSE, MAE) showing the predictive accuracy of the ML forecasting model.