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AI4Water

Optimization methods under development

Index

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General Overview

General Overview - Problem to be solved

- Agriculture **consumes large amounts of water**

- **Water is a scarce resource** and should be effectively used for irrigation

- Farmers could benefit from a tool that suggests:
  - **when to irrigate**
  - **how much water should be used**

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General Overview - Objective

- Optimize irrigation strategies:

  (01/05/2025, 5mm), (02/05/2025, 3.2mm), …

General Blue April 2026

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
			1	2	3	4
5	6	7	8	9	10	11
12	13	14	15	16	17	18
19	20	21	22	23	24	25
26	27	28	29	30		

- Balance two opposed objectives:
  - 🌱 **Crop yield / 💲Crop benefit**
  - 💧 **Water use**
- Other objectives could be added: **minimizing salinization of wells/groundwater**

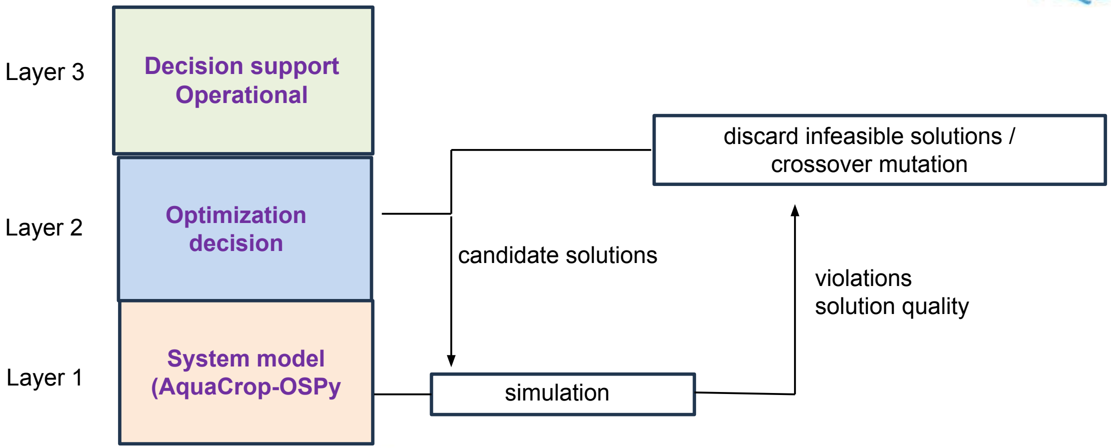
General Overview - Optimization Framework

- To simulate crop response to irrigation, we use a **physical crop model**

Three-Layer Approach

- **System Model** → simulates crop behavior (AquaCrop-OSPy) →
- **Optimization Model** → generates irrigation strategies

Food and Agriculture Organization of the United Nations



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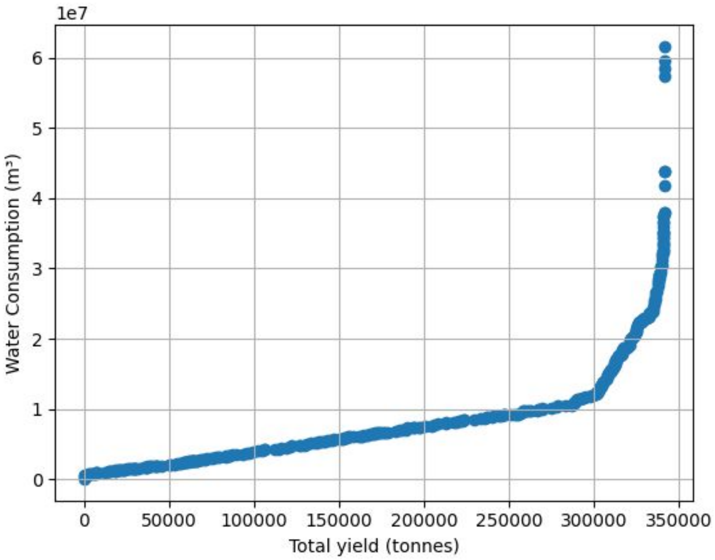
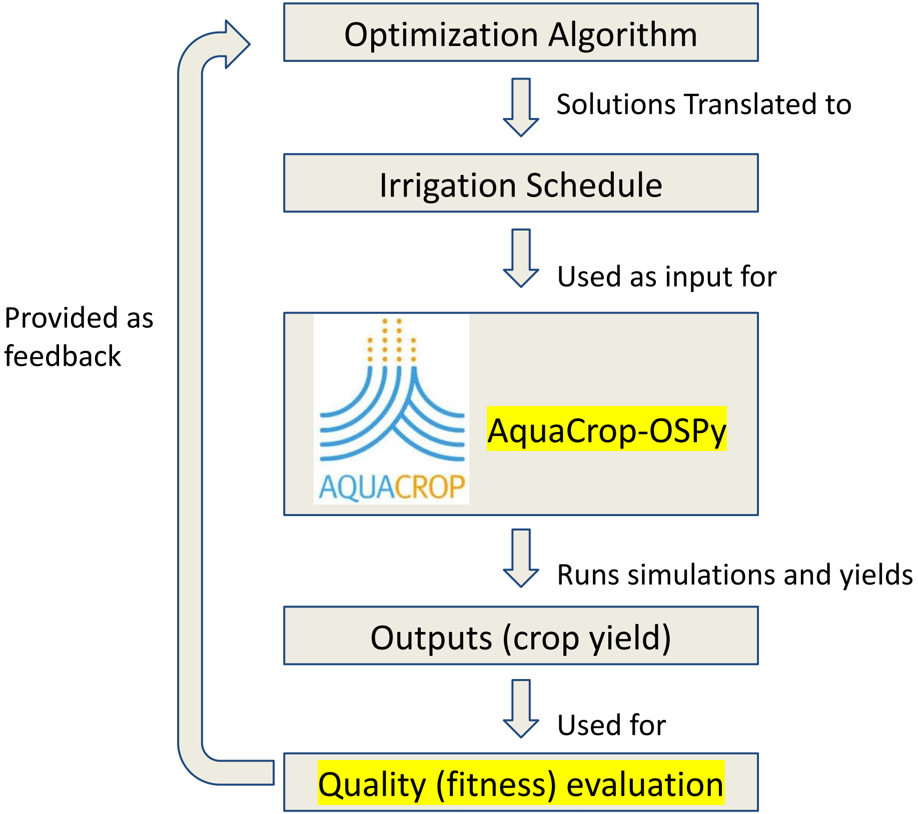
General Overview - Optimization Framework

Outputs

We obtain a **Pareto front** highlighting the balance between objectives.





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General Overview - Model inputs

AquaCrop Inputs

Climate Data

- Temperature
- Rainfall
- Reference evapotranspiration

Crop Information

- Crop type
- Growth stages and duration

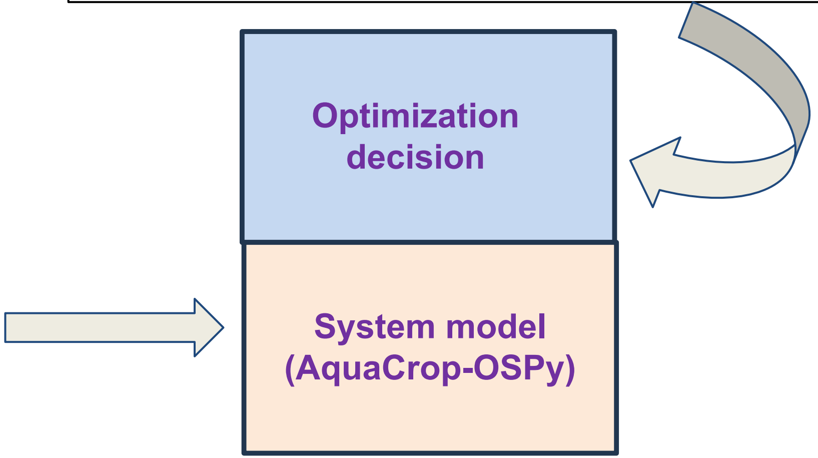
Soil Properties

- Soil type and characteristics
- FC, PWP, Ksat, CN, REW,...

Optimization Algorithm Inputs

Irrigation Constraints

- Maximum water availability (hydrological or prediction model)
- Irrigation frequency



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Optimization Techniques

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Optimization Techniques - Definition

- An optimization problem is a mathematical task where **the goal is to find the best solution among many possible options**, according to a **defined objective function**.

$$f(x) \longrightarrow \text{Objective or fitness function}$$

$$x^* = \min(f(x)) \qquad x^* = \max(f(x))$$

- It involves selecting values for decision variables that either maximize or minimize **this objective while satisfying given constraints**.

$$x \in S \longrightarrow \text{Set of feasible solutions}$$

Optimization Techniques - Categorization

	Exact Methods	Heuristic/Metaheruistic Methods
Optimality	Optimal solution	Near-optimal solution
Examples	Dynamic Programming, Simplex Method, …	Genetic Algorithms, Simulated Annealing, …

Computationally expensive!

- ⚠️ **Problem**: optimizing a 200-day irrigation schedule can be modeled as a search in $\mathbb{R}^{200}$

$$[5.2, 3.5, \ldots 6.3] \in \mathbb{R}^{200}$$

Optimization Techniques - Genetic Algorithms

- A literature review shows that **evolutionary algorithms**, **especially Genetic Algorithms**, are widely used in water management and water resources optimization.

- They have proven to be effective for handling complex, nonlinear, and **high-dimensional optimization problems in this domain.**

- Therefore, they are considered a **promising and suitable approach** for the optimization tasks in the AI4Water project.

Optimization Techniques - Genetic Algorithms

- A **Genetic Algorithm** is an optimization technique inspired by natural evolution, where a **population of candidate solutions evolves over generations using selection, crossover, and mutation to improve solution quality**.
- **What is a solution?**

$$\underbrace{\left[\underbrace{5.2}_{\text{Gene 1}}, \underbrace{3.6}_{\text{Gene 2}}, \ldots \underbrace{6.3}_{\text{Gene 200}}\right]}_{Chromosome} \xrightarrow{\text{decoding}}$$

$$\text{Phenotype} = \left[(01/05/2025, 5.2\,mm), (02/05/2025, 3.6\,mm), \ldots\right] \Longrightarrow$$

AQUACROP

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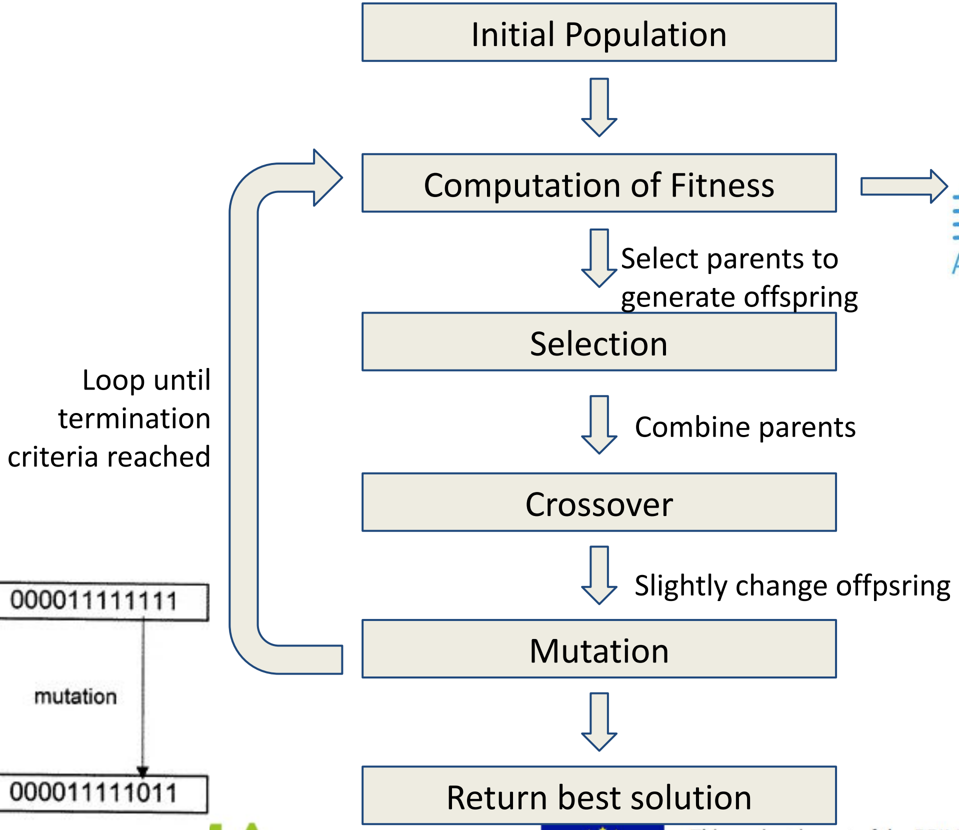
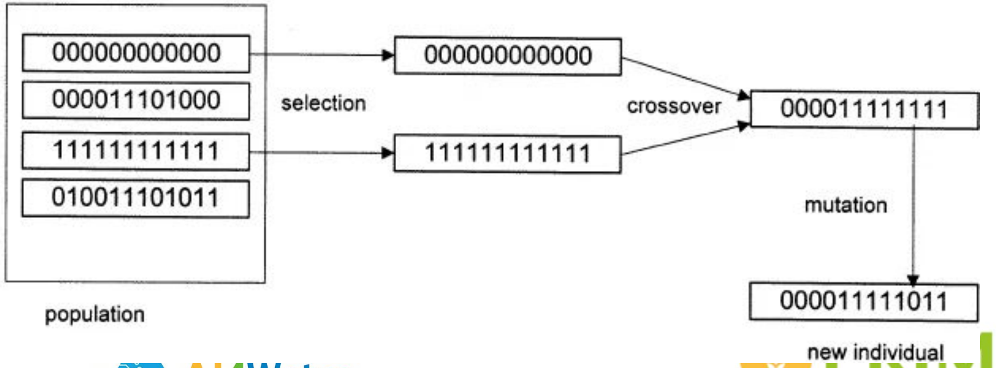
Optimization Techniques - Genetic Algorithms

Start with a **random population** of possible solutions.

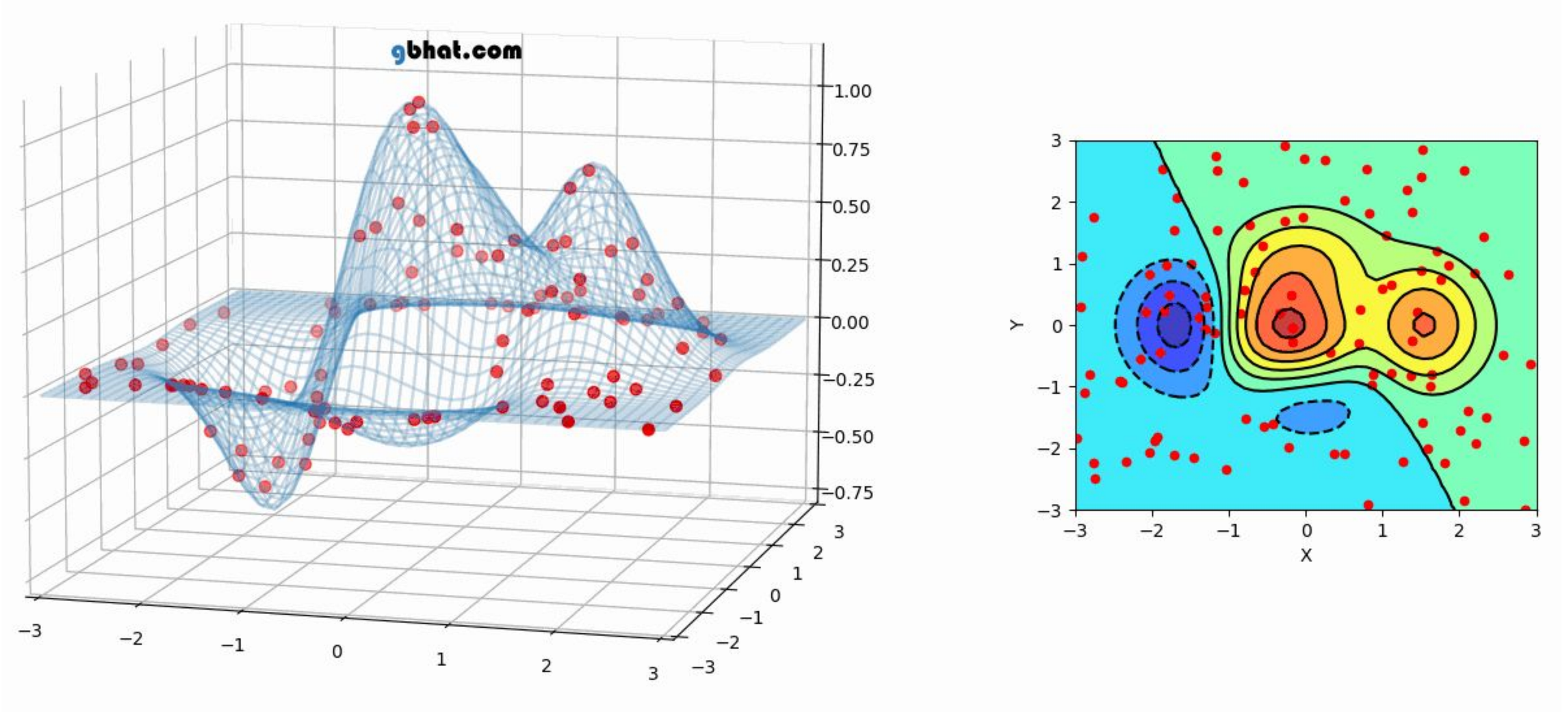
Evaluate how good each solution is (fitness).

Select the better solutions to form the next generation.





Optimization Techniques - Genetic Algorithms



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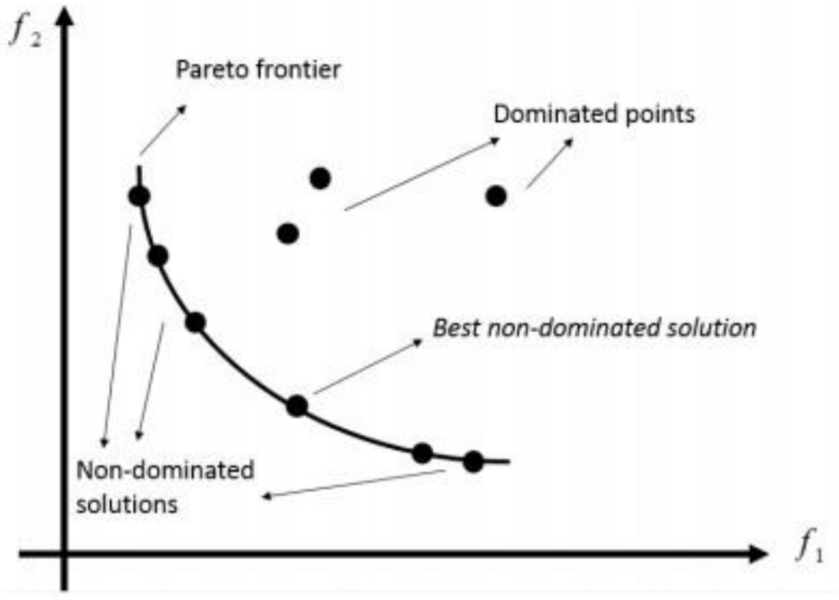
Optimization Techniques - Multiobjective optimization

Conflicting objectives → Set of optimal solutions → ***Pareto front***

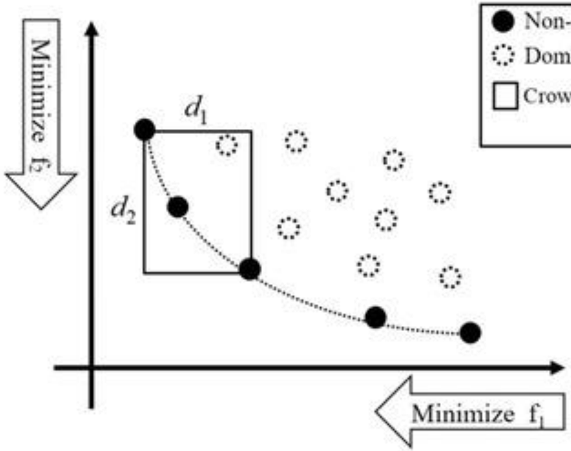
Set of ***Pareto Dominant*** **(non-dominated)** solutions (no other solution is better in ALL of the objectives)

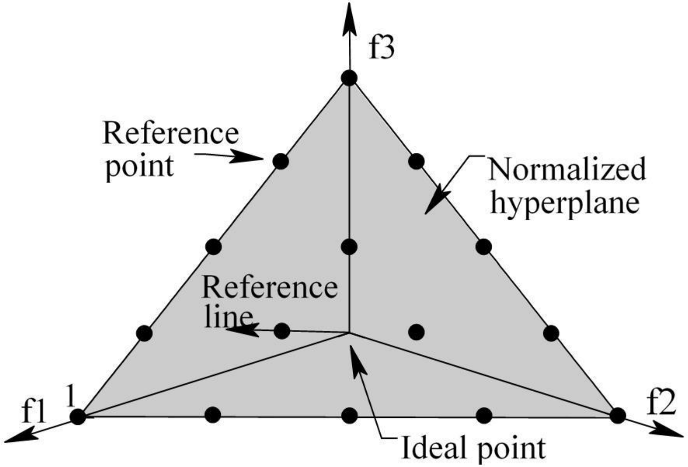
No single optimum — only trade-offs



Optimization Techniques - NSGA-II & NSGA-III

	NSGA-II	NSGA-III
No. of objectives	2-3	3+
Diversity	Crowding Distance	Reference Directions
Key Idea	Spread solutions on Pareto front	Spread solutions through reference directions



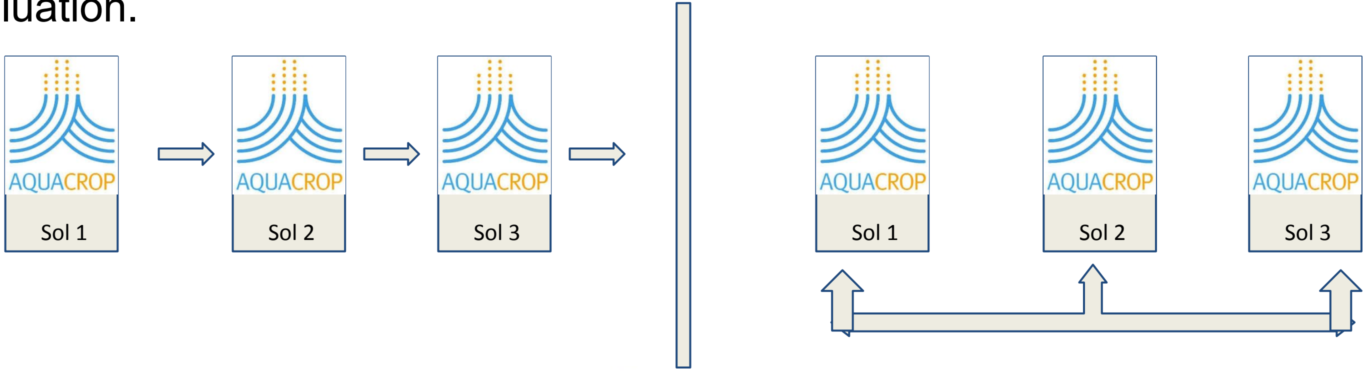


Optimization Techniques - `pymoo`

We are currently using the implementations provided by the pymoo library for **NSGA-II, NSGA-III, and GA**.

This library offers **robust, well-tested, and efficient implementations** of a wide range of evolutionary algorithms.

Its **object-oriented design** makes it easy to extend with custom functionality, and it provides built-in tools to **parallelize computationally intensive tasks**, such as fitness evaluation.



Characterization of the soil

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Characterization of the soil (I)

AquaCrop Inputs

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Optimization Algorithm Inputs

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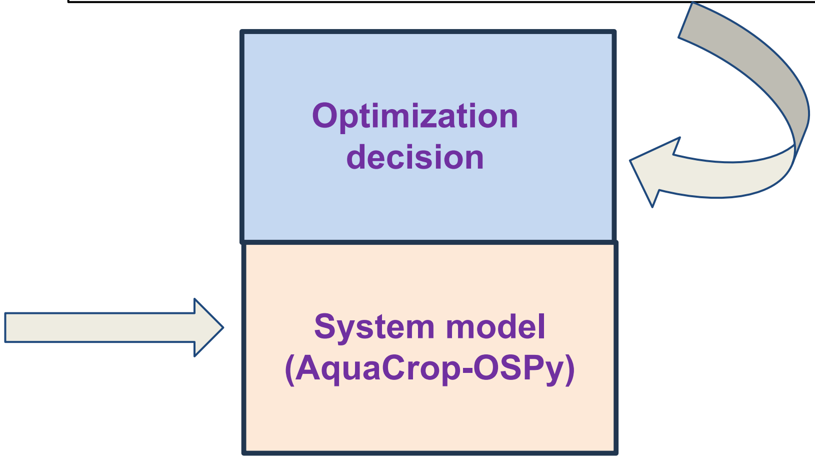
- Irrigation frequency



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Characterization of the soil (II)

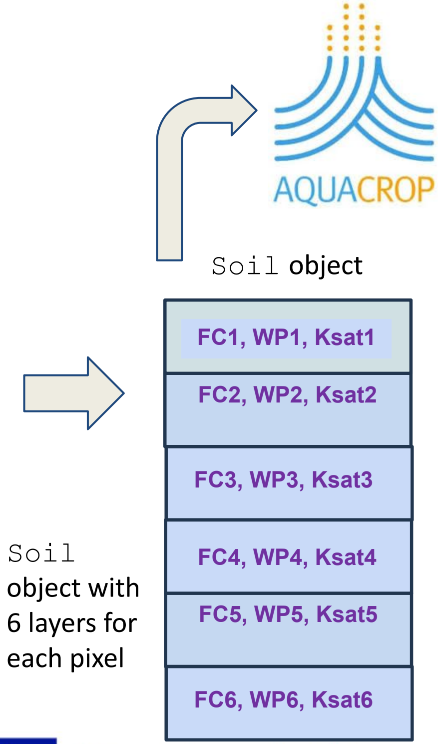
Soil influences crop performance → directly affects **crop yield and irrigation needs**

Data Source

Soil properties obtained from **SoilGrids.** High-resolution spatial data across the study area. Considers six soil layers, from 0 cm to 200 cm of depth.

Output

A grid-like structure where each cell contains a fully defined `Soil` object representing the local soil profile.



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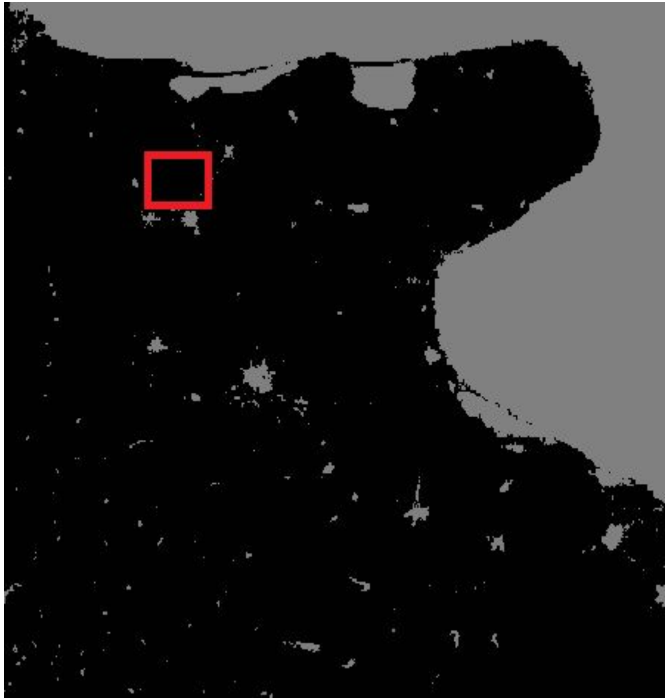
Characterization of the soil (III)

⚠️ **Problem** ⚠️

AquaCrop can only assign **one crop per soil → full AquaCrop simulation is required for every pixel**, leading to very high computational cost.



Potential solution

Apply **clustering techniques** to group similar contiguous pixels into clusters, and generate a single representative `Soil` object per cluster.

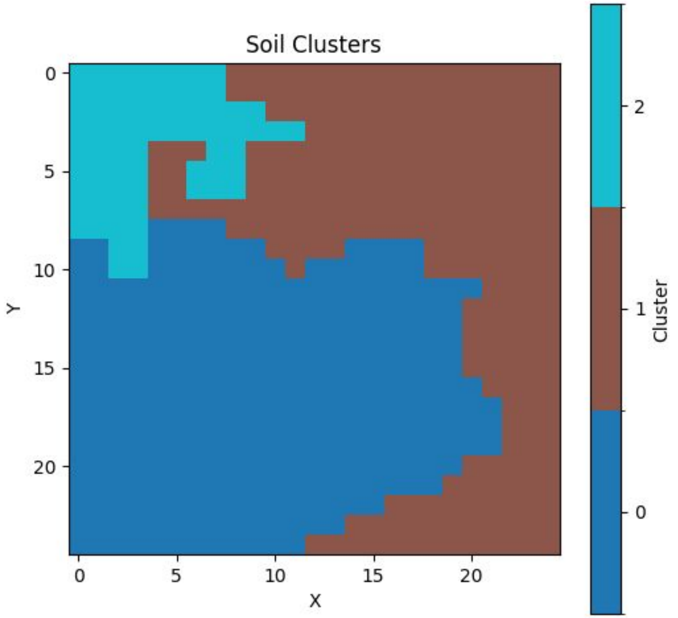
Characterization of the soil (IV)

Method

- Extract key soil properties and generate a ***feature vector.***

$$[CN, REW, FC_1, WP_1, Ksat_1, \ldots, FC_6, WP_6, Ksat_6]$$

- Apply clustering (*Agglomerative Clust.)*:
  - Group soils with similar characteristics
  - Ensure spatial consistency (neighboring cells)



Outcome

- Each cluster is summarized into a **single representative soil profile using the median values**

(Cluster1, Soil 1), (Cluster 2, Soil 2), (Cluster 3, Soil 3)

Optimization example

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Optimization for the Capitanata District (I)

- We apply the optimization framework to the **Capitanata district**
- Soil variability is represented using **representative clusters derived from SoilGrids**
- Each cluster is associated with a specific crop: tomato, wheat and cotton

(Cluster1, Soil1, Tomato), (Cluster2, Soil2, Wheat), (Cluster3, Soil3 Cotton)

⚙️ Optimization Scope

- The model optimizes **irrigation strategies** for each crop–soil combination

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Optimization for the Capitanata District (II)

Objective: **maximize crop yield** while **minimizing water consumption** under two irrigation strategies.

- **Full water availability**: no upper bound for daily water consumption → not constrained by water availability
- **Water-scarcity:** not enough water for all the crops → some water stress is expected.

Irrigation Frequency (Model Parameter)

- Defines **how often irrigation can be applied**
- Example:
  - Frequency = 1 → irrigation allowed every day **(01/05/2025, 5mm), (02/05/2025, 3.2mm)**
  - Frequency = 4 → irrigation allowed every 4 days **(01/05/2025, 5mm), (05/05/2025, 3.2mm)**

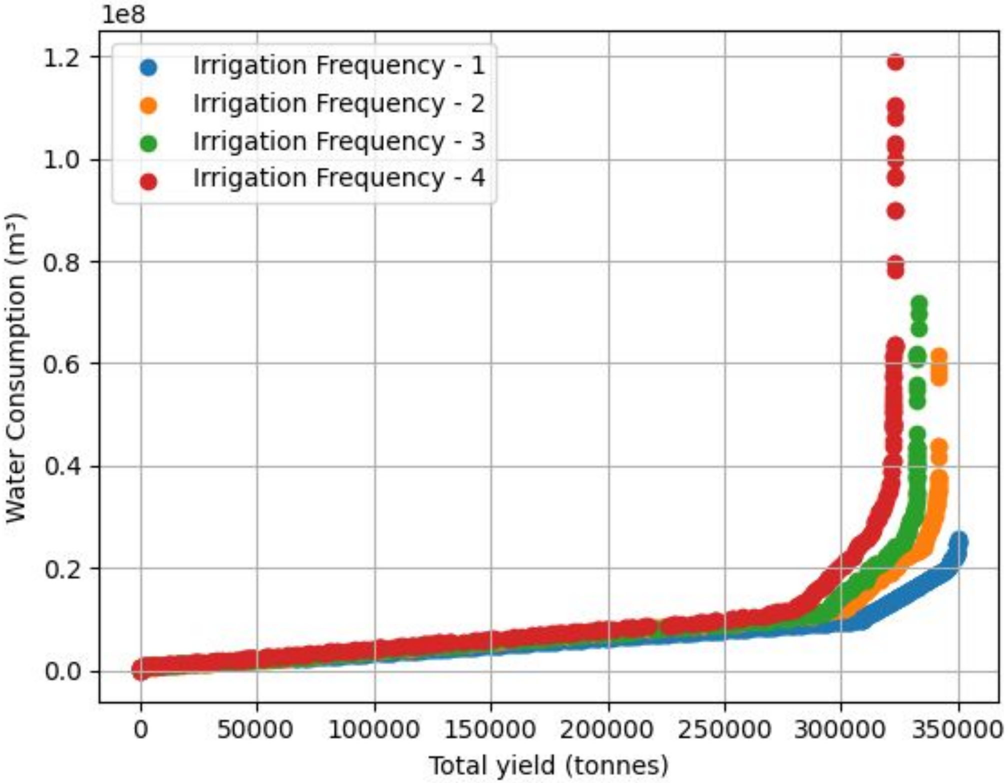
Results

Results - Full water availability

Linear growth region: Up to ~300k tonnes, yield increases linearly with water → efficient water use

Knee point: Beyond this threshold, diminishing returns appear

More water ≠ more yield after a point



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Results - Water scarcity

Impose a **global constraint on the total amount of water available during the season**, i.e 20.000.000 cubic meters available.

Total water is then distributed over time according to the crop water demand, using reference evapotranspiration (ET_0) as a proxy. **Irrigation Frequency = 1**

Example: budget of 100 cubic meters for 3 irrigation days.

Day	ET0 (mm)	Weight	Water Available(m^3)
1	2	2 / 10	20
2	3	3 / 10	30
3	5	5 / 10	50

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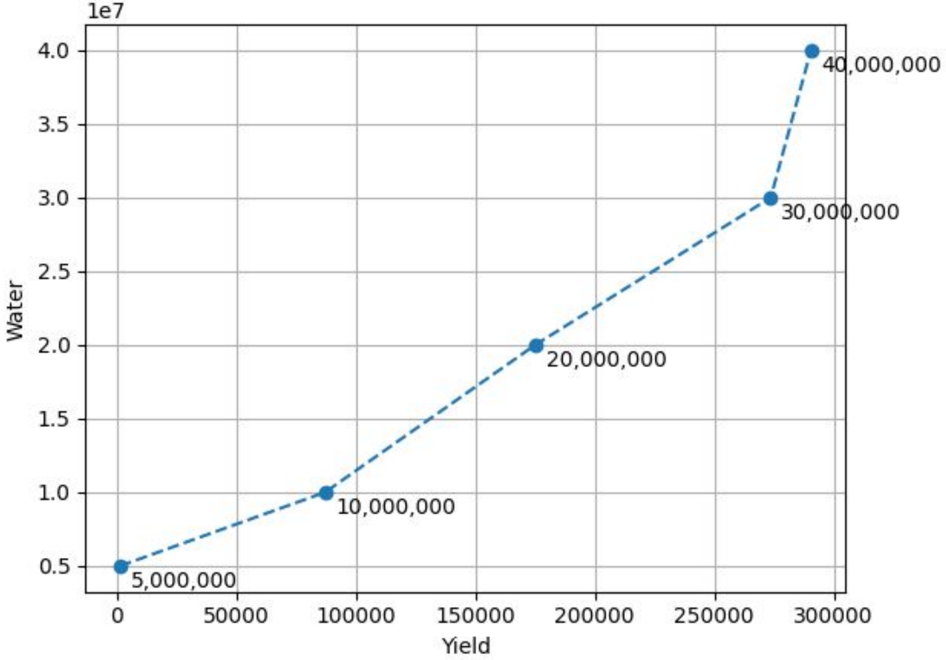
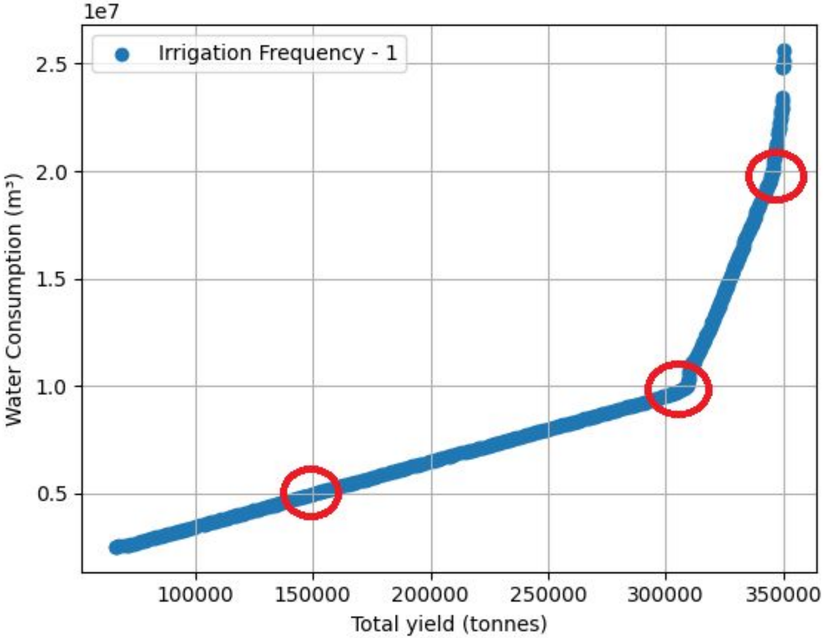
Results - Water Scarcity



Water Scarcity



Full Water Availability

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Thank you for your attention!

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