Soil moisture based real-time irrigation

International Mini-Workshop on DDDAS (Dynamic Data Driven Application Systems)
Providing Water

• Canal modeling
• Necessary sensing
• Gate operating

• Central-Pivot modeling
• Sprinkler modeling
• Optimal central-pivot operating

Demanding Water

• Crop modeling
• Soil modeling
• Water demand

• Soil moisture sensing
Project Overview

- Canal Operating
- Field Modeling
- Field Operating
- Field Sensing
Water Rights → Water Demand

Weather

Canal Operating

Field Modeling

Available Water

Water need

Water provided

Sensor Trajectory

Calibration

Field Operating

Field Sensing
Field modeling

- Problem definition: What are the sources of water loss and what are the dynamics of these losses? How can we predict the evolution of the moisture?

[Diagram showing infiltration, evapotranspiration, crop growth]
Water balance model

- Rain
- Transpiration
- Evapo-transpiration
- Evaporation
- Irrigation
- Runoff
- Root Zone
- Water Storage
- Drainage
- Below Root Zone
Water balance equations

\[ S_{t+1} = S_t + (R_n + I_e) - D - ET \]

\( S_t \) = soil water storage at time \( t \) (day, h, mn)
\( R_n \) = Net rain (Initial rain - Interception - Runoff)
\( I_e \) = Irrigation
\( D \) = Water losses below the root zone
\( ET \) = evaporation and transpiration
Water infiltration equations

- Diffusion process with coupled flow:

\[
\begin{aligned}
\frac{\partial v}{\partial t} &= -\gamma \frac{\partial v}{\partial z} \\
\frac{\partial c}{\partial t} &= \frac{\partial}{\partial x} \left( D \frac{\partial c}{\partial x} \right) + \frac{\partial}{\partial y} \left( D \frac{\partial c}{\partial y} \right) + D \frac{\partial^2 c}{\partial z^2} - \frac{\partial (vc)}{\partial z}
\end{aligned}
\]

- With: 
  \( c(x,y,z,t) \) is the soil moisture 
  \( v(x,y,z,t) \) is the velocity of soil moisture 
  \( D(x,y) \) is the diffusion rate
Surface dynamics

• Due to the permeability of the soil, maybe water stays on the ground:

\[ q(x, y, t) = \int_0^t (F(x, y, u) + R(u) - EV(u) - v_{\text{max}}) \, du \]

\[ \begin{cases} 
  v_{\text{max}} & \text{if } q(x, y, t) > 0 \\
  F(x, y, t) + R(t) - EV(t) & \text{otherwise}
\end{cases} \]

• The soil moisture is carried by water

\[ c(x, y, 0, t) = k_v v(x, y, 0, t) \]
Evapotranspiration models

- The Priestley-Taylor ET model
- The McNaughton-Black ET model
- The Penman ET model
- The Penman-Monteith ET model
- The Shuttleworth-Wallace ET model
- Etc…
Evapotranspiration models comparison

Comparison of the increasing complexity of the models in terms of number of parameters required

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Units</th>
<th>PT</th>
<th>MB</th>
<th>Penman</th>
<th>PM</th>
<th>SW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate of change of vapor pressure with temperature</td>
<td>Δ</td>
<td>kPa K⁻¹</td>
<td></td>
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<tr>
<td>Total available energy</td>
<td>A</td>
<td>W m⁻²</td>
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<td>Psychrometric constant</td>
<td>γ</td>
<td>kPa K⁻¹</td>
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<tr>
<td>Air temperature</td>
<td>T_a</td>
<td>°C</td>
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<tr>
<td>Specific heat at constant pressure</td>
<td>c_p</td>
<td>J kg⁻¹ K⁻¹</td>
<td></td>
<td></td>
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<tr>
<td>Air density</td>
<td>ρ</td>
<td>kg m⁻³</td>
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<tr>
<td>Vapor pressure deficit</td>
<td>D</td>
<td>kPa</td>
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<tr>
<td>Bulk stomatal resistance of the canopy</td>
<td>r_cs</td>
<td>s m⁻¹</td>
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<tr>
<td>Wind speed</td>
<td>u</td>
<td>m s⁻¹</td>
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<td>Aerodynamic resistance above the canopy</td>
<td>r_aa</td>
<td>s m⁻¹</td>
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<td>Bulk boundary layer resistance of the vegetation</td>
<td>r_va</td>
<td>s m⁻¹</td>
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<tr>
<td>Aerodynamic resistance for substrate and canopy</td>
<td>r_sa</td>
<td>s m⁻¹</td>
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<td>Surface resistance of the substrate</td>
<td>r_ss</td>
<td>s m⁻¹</td>
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<tr>
<td>Available soil energy</td>
<td>A_s</td>
<td>W m⁻²</td>
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PT, Priestley—Taylor; MB, McNaughton—Black; PM, Penman—Monteith; SW, Shuttleworth—Wallace.

- Trade-off between accuracy and available information
Real-time model

• For every depth, we can create a map of the soil moisture
Model recalibration

Model

UAV picture

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Christophe TRICAUD - CSOIS - USU
Field Operating

• Problem definition: Given how the water is spatially needed on the field, how do I operate the center-pivot and the sprinklers?
Center pivot model

• If all sprinklers can be actuated independently:
  \[ \text{Irrigation}(x,y,t) = f(\omega, r, q_1, q_2, \ldots, q_n) \]

• If all sprinklers have the same outflow:
  \[ \text{Irrigation}(x,y,t) = f(\omega, q, r) \]

• Effect of wind
Control System Design

• Specification
  – Ensure soil moisture level within the root zone
  – Minimize water use
  – Minimize water loss

• Requirements
  – Optimal control
  – Robust control
Control Scheme

- Measured soil moisture
- Estimated soil moisture
- Water

Central pivot

Field

Model

Model Inverse

Outflow setpoint per sprinkler
Research directions

• Optimal sensing for parameter estimation of distributed parameters system
  – Optimal UAV trajectory (2d sensing)
  – Combination of UAV and soil moisture probes

• Optimal control of central pivot
  – Model inverse to get sprinkler setpoint
  – Importance of hardware specification
Example: Dr. Moore & Dr. Chen Iterative learning control approach

Iterative Learning Control Approach to a Diffusion Control Problem in an Irrigation Application

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Questions?
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