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نوزدهمین کنگره علوم خاک ایران  
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۰۴۲۵۰-۳۲۰۳۱

مدیریت جامع نگر و هوشمند خاک و آب

Holistic and Smart Soil and Water Management

دانشکده کشاورزی و منابع طبیعی دانشگاه تهران

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## Simulating Coupled Soil Heat and Water Transport: A Comparison of HYDRUS-1D, SWAP, and an Analytical R Script

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### Abstract

Accurate simulation of coupled soil heat and water transport is crucial for optimizing irrigation and understanding land-atmosphere interactions in semi-arid regions. This study compares the performance of three modeling approaches—the physically-based HYDRUS-1D model, the integrated soil-water-atmosphere-plant model SWAP, and an analytical solution implemented in R—in simulating soil temperature and water dynamics during summer irrigation events. The models were applied under simplified semi-arid conditions with three irrigation events. Results indicate that HYDRUS-1D, with its detailed coupling of water flow and heat transport, effectively captured the rapid cooling effects immediately after irrigation. SWAP provided a robust representation of the system's energy balance, showing a dampening effect on diurnal temperature fluctuations due to increased soil moisture. The analytical R model, while computationally efficient and transparent, was limited by its assumption of constant soil properties, failing to dynamically represent irrigation-induced changes. The choice of model therefore depends on the specific research objective: HYDRUS-1D for detailed process analysis, SWAP for agro-ecosystem studies over growing season, and the R-based solution for theoretical explorations under steady-state conditions. Incorporating dynamic feedback between soil moisture and thermal properties is identified as a key factor for an accurate prediction of soil temperature.

**Keywords:** Soil Temperature Modeling, HYDRUS-1D, SWAP, R Programming, Heat Transport, Irrigation, Evaporative Cooling

### Introduction

Soil temperature is a fundamental state variable regulating critical processes in agricultural systems, microbial activity (Muhammad et al., 2025), root growth and activity (Fonseca et al., 2021), and nutrient cycling (Imran et al., 2025). In arid and semi-arid regions, summer irrigation is essential for crop production. Here the interaction between soil heat and water transport significantly affects energy balance, soil moisture redistribution, and ultimately crop water use efficiency. Accurate modeling of these processes is therefore essential for developing climate-resilient agricultural practices and optimizing water management e.g. irrigation scheduling.

Several process-based models have been developed to simulate soil water and heat transport under field conditions. Among them, HYDRUS-1D numerically solves the Richards equation for variably saturated water flow and the one-dimensional heat transport equation (Šimůnek et



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al., 2024; Šimůnek et al., 2012; Šimůnek and van Genuchten, 2008), offering a physically based representation of soil temperature–moisture interactions. Its strengths include flexibility in specifying soil hydraulic parameters, detailed representation of heat conduction and convection, and the ability to handle complex boundary conditions. However, it assumes a one-dimensional vertical profile and requires careful parameterization to avoid ill-posed prediction of soil temperatures and/or numerical instability.

SWAP (Soil–Water–Atmosphere–Plant) combines soil water flow, soil heat transport, solute transport, and crop growth in a single modeling framework (Heinen et al., 2021). It is particularly well-suited for simulating field-scale processes over longer periods under variable climatic conditions. Its conceptual framework accounts for the soil surface energy balance by partitioning net radiation into latent, sensible, and soil heat fluxes, while numerically solving the heat conduction. A key advantage of SWAP lies in its integration with crop models, enabling the simulation of feedbacks between crop development and soil microclimate. However, its complexity can be a limitation for purely theoretical or experimental scenarios where detailed crop modules are unnecessary. Compared to Hydrus 1D, SWAP assumes an isothermal water fluxes as thermal water fluxes are often negligible (Milly, 1984).

In contrast to these comprehensive packages, custom models developed in programming environments like R offer maximum flexibility. Users can implement specific numerical or analytical solutions, incorporate unique experimental data, and test sensitivity to individual parameters (Progga et al., 2023). The trade-offs include a significant coding effort, the need for thorough validation, and the absence of built-in modules for complex processes like crop growth

Given the distinct architectures and applications of these models, a systematic comparison of their performance in simulating coupled heat and water flow is needed. This study aims to compare HYDRUS-1D, SWAP, and a custom R-based model in simulating coupled soil heat and water transport following summer irrigation under semi-arid conditions, with a specific focus on the impact of irrigation events and subsequent evaporation. The analysis evaluates their ability to capture the dynamic interactions between wetting fronts, heat capacity, conductivity, and evaporative cooling.

## Materials and Methods

Soil heat transport was described by the one-dimensional heat conduction-convection equation (Eq. 1):

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2} \pm S \quad (1)$$

where  $T$  is temperature ( $^{\circ}\text{C}$ ),  $t$  time (d),  $z$  depth (m),  $\alpha$  the thermal diffusivity ( $\text{m}^2 \text{d}^{-1}$ ) ( $\alpha = \lambda / (C_p)$ ), where  $\lambda$  is thermal conductivity and  $S$  represents heat sinks or sources (e.g. latent heat consumption during evaporation).

HYDRUS-1D was configured to solve the coupled water and heat flow equations numerically using an implicit method. The van Genuchten-Mualem model was used for soil hydraulic properties (Mualem, 1976; van Genuchten, 1980), with parameters for a loamy soil taken from the RETC database. Heat transport included both conduction and convection. To simplify



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system complexity, the following assumptions were made (Rezaei et al., 2017): (1) In the one-dimensional model (used for sensitivity analysis), only vertical water movement was considered; (2) Upper boundary conditions were spatially uniform; (3) Free drainage was assumed at the lower boundary and (4) Soil profile was treated as vertically continuous and homogenous.

SWAP (Soil–Water–Atmosphere–Plant) integrates soil water flow, heat transport, and crop processes, solving Richards' equation simultaneously with Fourier's law for soil heat transfer. The equations are solved explicitly by the model. The model was run with modules for soil water flow and heat transport activated. The upper boundary condition was defined by daily meteorological data, and the lower boundary was set to free drainage. The model solved the surface energy balance to partition incoming radiation.

R-based analytical model as a simplified approach was implemented using the analytical solution to the heat conduction equation under sinusoidal surface forcing (Eq. 2):

$$T_{(z,t)} = T_{ave} + A_{(0)} \exp(-z/D) \sin \left[ \omega(t - t_0) - \frac{z}{D} \right] \quad (2)$$

where  $T_{ave}$  is average surface temperature,  $A(0)$  is amplitude at the surface,  $\omega$  is angular frequency ( $\omega=2\pi/P$ , with  $P$  the daily cycle), and  $D = \sqrt{\frac{2\alpha}{\omega}}$  is the damping depth.

To account for the cooling effect of soil water evaporation, the latent heat flux (LE) was translated into an equivalent soil temperature reduction:

$$\Delta T(^{\circ}K) \approx \frac{LE \left( \frac{J}{m^2} \right)}{C_{layer} \left( \frac{J}{m^2 \cdot K} \right)} \quad (3)$$

where  $C_{layer}$  is the volumetric heat capacity of the soil layer. This formulation allowed direct comparison of temperature dynamics with and without irrigation-induced evaporative cooling.

### Model conceptual, Input data and assumptions

A two-month summer period was simulated with a constant daily air temperature cycle (minimum: 30 °C, maximum: 45 °C). Other meteorological parameters were simplified: relative humidity was set to 5%, and sunshine duration to 14 hours per day. Three irrigation events of 20 mm each were applied on days 5, 15, and 25. The soil profile was initialized at a uniform water content of  $0.20 \text{ cm}^3 \text{ cm}^{-3}$ . Model outputs for soil water content and temperature at depths of 31, 62, and 92 cm were compared. Model performance was qualitatively assessed by comparing the temporal patterns of soil temperature and moisture in response to irrigation. The Root Mean Square Error (RMSE) between model outputs at key depths was calculated for a quantitative inter-comparison.

### Results and Discussion

The three models exhibited distinct behaviors in simulating the coupled dynamics of soil water and heat transport, reflecting their underlying mathematical frameworks and conceptual approaches.



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### *Analytical Solution: Strengths and Limitations for Thermal Profiling*

The custom R script implementing the analytical solution (Equation 2), produced smooth, sinusoidal temperature waves propagating with depth with depth into the soil profile (Figures 1 & 2). This approach effectively illustrated key physical principles, such as the exponential damping of the temperature amplitude and the increasing time lag with depth. The method is particularly valuable for theoretical explorations, such as estimating the damping depth for a given thermal diffusivity and period.

However, a major limitation is the assumption of constant thermal properties ( $\alpha, C_v, \lambda$ ). In reality, these properties vary strongly dependent on soil water content. As a result, the R implementation could not reproduce the cooling effect of irrigation, since it does not update thermal diffusivity in response to dynamic changes in moisture. While this makes the approach unsuitable for simulating managed agricultural systems where water content fluctuates substantially, it remains a useful tool for analyzing soil temperature propagation under relatively stable moisture conditions.

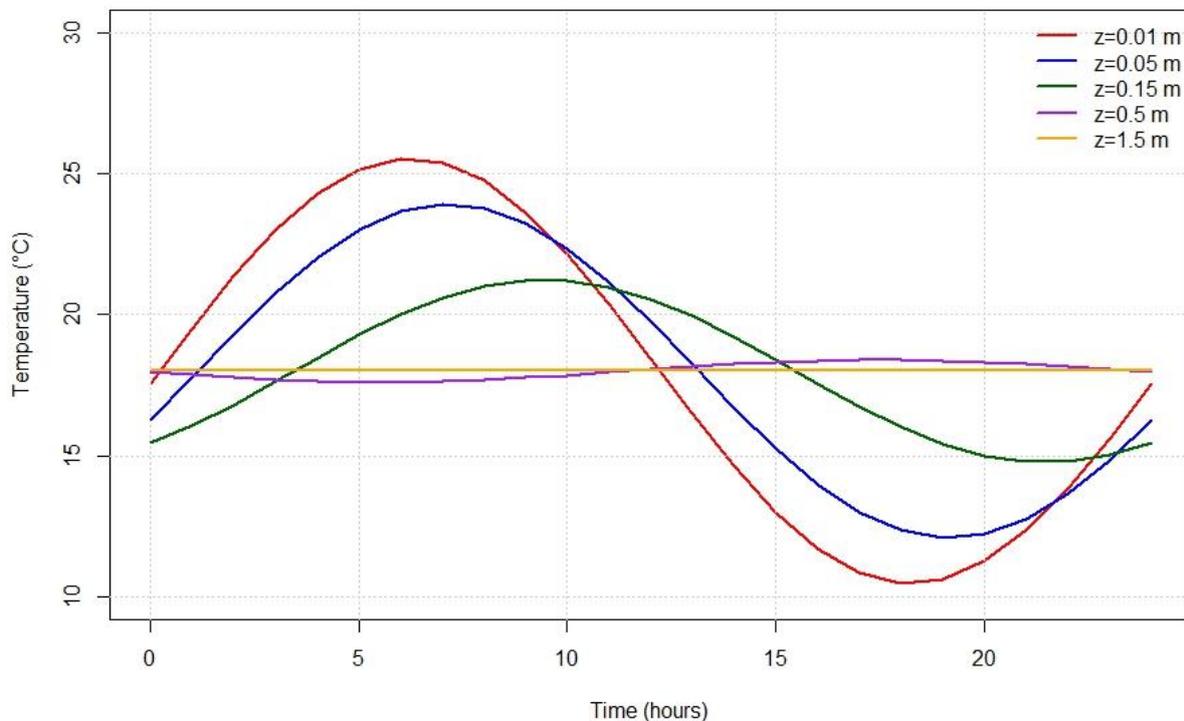


Figure 1- Simulation of soil temperature variation by time as predicted by equation (2) and R script

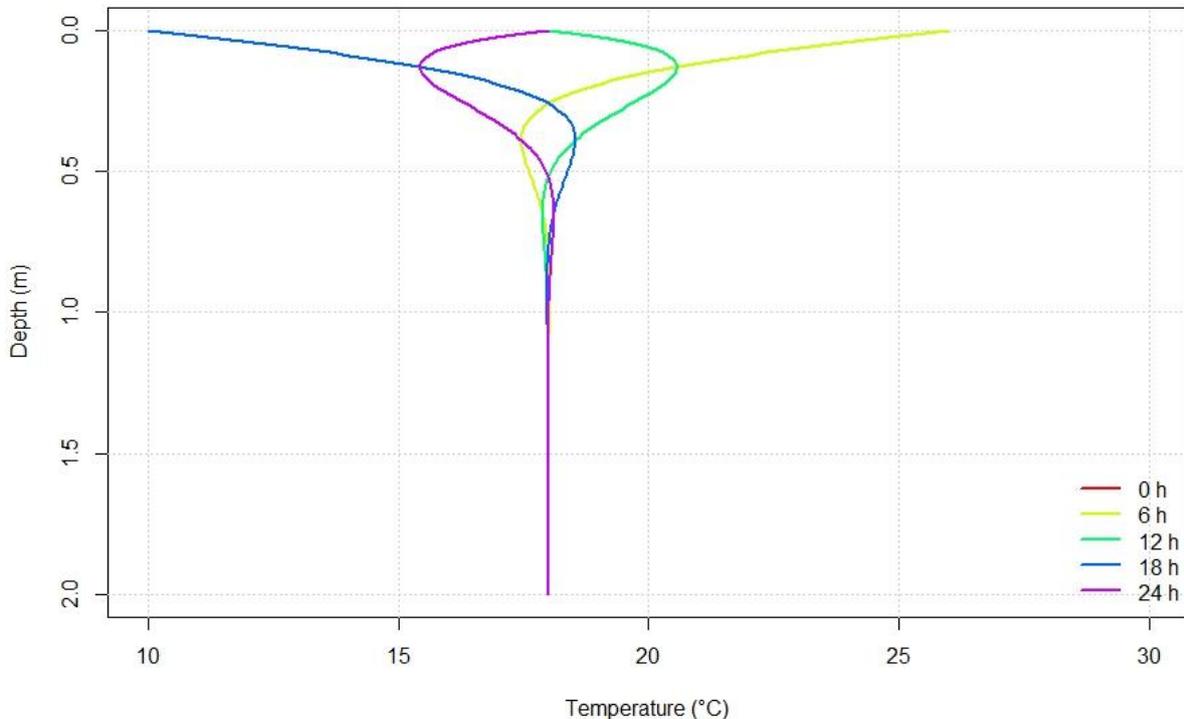


Figure 2- Simulation of soil temperature variation by soil depth as predicted by equation (2) and R script

### *Divergent Responses of Soil Moisture to Irrigation*

The simulation of soil water content revealed fundamental differences in how HYDRUS-1D and SWAP handle water flow (Figure 3). HYDRUS-1D predicted sharp, immediate increases in water content following irrigation events, with similarly rapid declines due to evaporation (Figure 5). This response is characteristic of its precise numerical solution to the Richards equation for variably saturated flow, which accurately captures the rapid propagation of wetting fronts in a one-dimensional profile.

In contrast, SWAP simulated a more gradual and dampened response to irrigation (Figure 3). The increase in water content was less abrupt, and the subsequent drying phase was more extended. This behavior aligns with SWAP's design as a field-scale model, which often incorporates conceptualizations for soil heterogeneity and root water uptake that can smooth out rapid hydrological pulses. The first soil layer, initialized at a lower water content, showed the most significant relative increase, correctly reflecting its higher capacity to store incoming water before transmitting it to deeper layers.

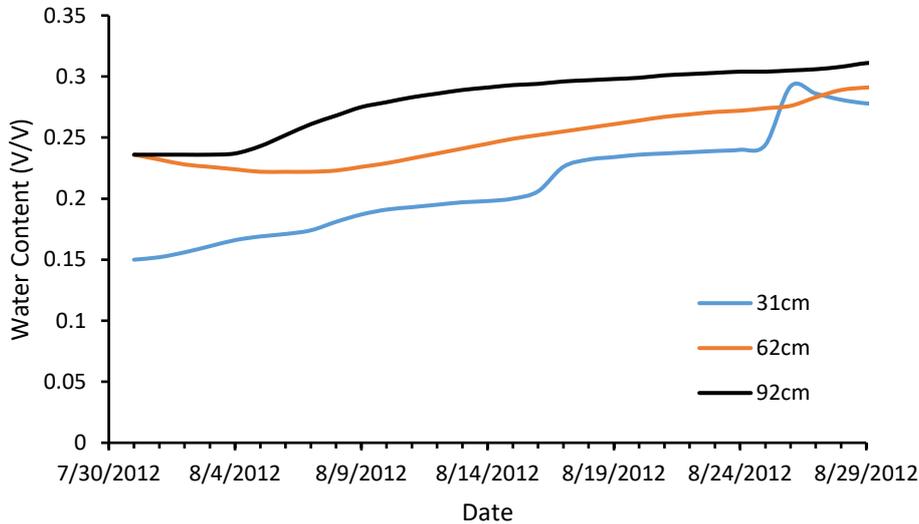


Figure 3- Simulation of soil water content at different depths and dates in SWAP output

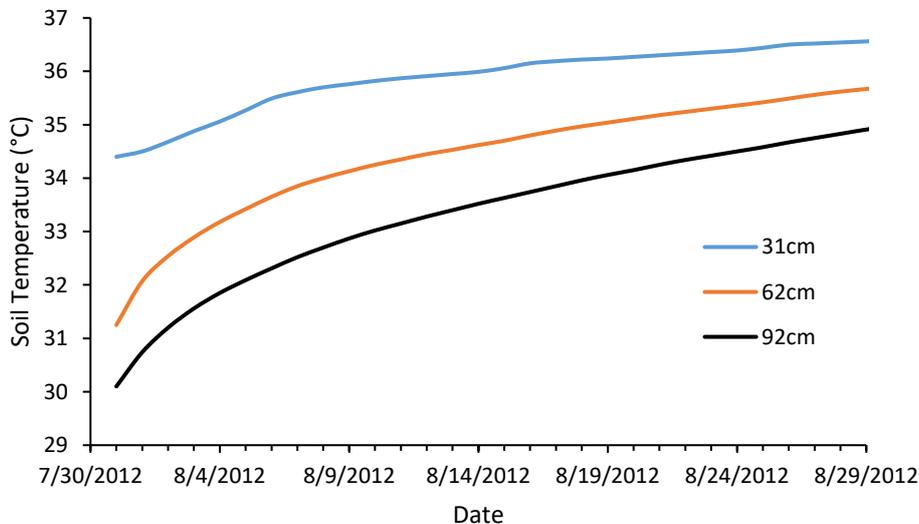


Figure 4- Simulation of soil temperature at different depths and dates in SWAP output

### *Model-Specific Simulation of Irrigation-Induced Thermal Dynamics*

The impact of irrigation on soil temperature was a key differentiator among the models.

SWAP demonstrated a moderate thermal response. Instead of a sharp temperature drop, the primary effect was a dampening of the diurnal temperature amplitude following irrigation (Figure 4). This is consistent with its strength in modeling the surface energy balance. The increase in soil moisture enhances the thermal conductivity and heat capacity, facilitating a greater conductive heat flux into the soil during the day and out of it at night, thereby reducing



the peak temperatures and raising the minimum temperatures. This finding is supported by Zhao et al. (2025), who reported good agreement between SWAP-simulated and measured soil temperatures, noting its effectiveness in capturing seasonal trends. However, the model's relatively low sensitivity to the short-term irrigation pulse, as observed here, may be linked to its numerical scheme or its integrated crop-soil-atmosphere approach, which can buffer rapid changes. The RMSE of approximately 2.5 °C reported by Balashov et al. (2014) for SWAP temperature predictions underscores the level of uncertainty inherent in such integrated models under field conditions.

HYDRUS-1D provided a more detailed, process-based representation of the short-term thermal effects. It distinctly captured the rapid cooling of the soil profile immediately following irrigation (Figure 6). This cooling is a direct result of two coupled processes: (1) the consumption of latent heat during surface evaporation, and (2) the increased volumetric heat capacity of the wetted soil, requiring more energy to raise its temperature. The effect was most pronounced in the surface layers and diminished within hours to a day, as the surface dried and energy inputs dominated again. This aligns with the findings of Zhao et al. (2022), who using HYDRUS-2D, reported that irrigation delayed the transmission of air temperature fluctuations into the soil. Furthermore, our results corroborate the principle discussed by Chen et al. (2025), who observed that irrigation can alter subsurface temperatures by enhancing hydrothermal coefficients, a process that HYDRUS-1D's coupled equations are specifically designed to simulate. The model's ability to use sub-daily time steps was crucial for resolving these fast processes, which would be averaged out in models operating on a daily time step.

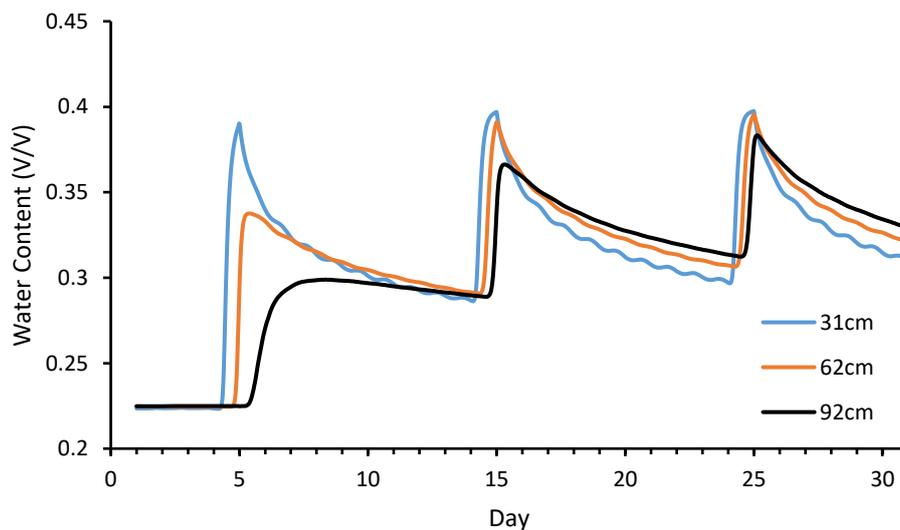


Figure 5- Simulation of soil water content at different depths and dates in Hydrus-1D output



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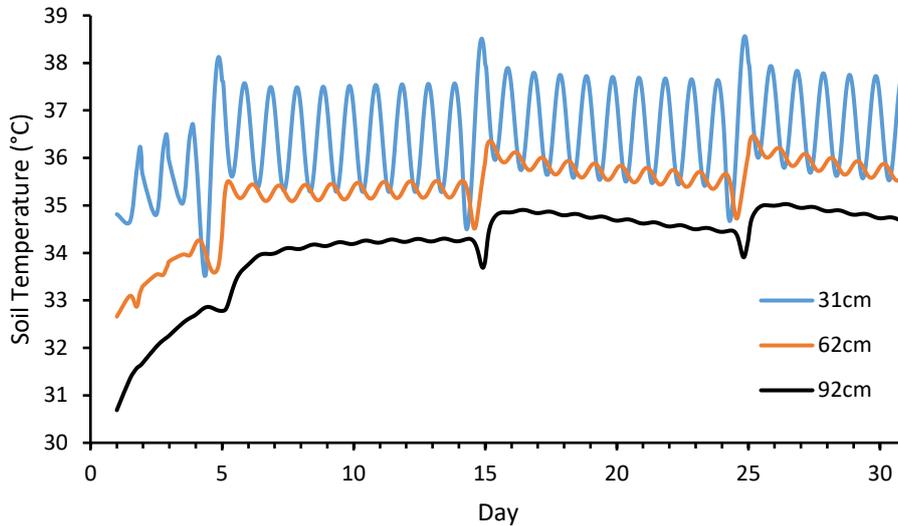


Figure 6- Simulation of soil temperature at different depths and dates in Hydrus-1D output

### *Quantifying the Evaporative Cooling Effect*

The analysis analytical custom function highlighted the critical importance of scale and soil layer definition when accounting for latent heat flux. The results demonstrated that evaporative cooling is a highly surface-localized phenomenon. For a 5 mm evaporation event:

- When applied to an unrealistically thin layer (1 cm), the calculated cooling exceeded 300 °C, indicating model breakdown of the lumped-capacity assumption as the layer's water content was completely depleted.
- For a more representative surface layer (10 cm), the calculated temperature reduction was a significant 52 °C.
- When distributed over a deeper layer (30 cm), the cooling effect was diluted to a more moderate 17 °C.

This exercise underscores a key challenge: translating an energy flux into a temperature change requires an assumption about the volume of soil participating in the energy exchange. The results further illustrate that thin-layer assumptions can yield physically unrealistic outcomes, particularly when water availability is limited. Comprehensive process-based models like HYDRUS-1D avoid this issue by solving the heat flow equation directly, where the cooling effect is naturally distributed according to the soil's thermal properties and the evaporation source depth. The recent analysis confirms that the incorporation of latent heat effects is non-trivial and highly sensitive to model conceptualization, highlighting the importance of coupling thermal dynamics with soil water processes.



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## Conclusion

This comparative analysis demonstrates that the selection of a model for simulating coupled soil heat and water transport must be aligned with the specific research objectives. HYDRUS-1D excels in revealing the detailed, short-term physics of the system, particularly the immediate impacts of irrigation and evaporation on soil temperature. Its high temporal resolution and rigorous coupling of water and heat flow make it ideal for process-level investigation. SWAP provides an integrated, system-level perspective that is valuable for assessing seasonal water and energy balances at the field scale. Its representation of the surface energy balance effectively captures the moderating influence of soil moisture on diurnal temperature fluctuations, though it may be less sensitive to abrupt irrigation events. The Analytical R Model serves as an excellent educational and theoretical tool for understanding the principles of heat conduction in a homogeneous soil but is inadequate for scenarios involving dynamic changes in soil water content. The primary limitation of uncoupled or simplified models is the treatment of soil thermal properties as static. The strong dependency of heat capacity and conductivity on soil moisture is a fundamental driver of the interactions observed in this study. Future work should use high-resolution models like HYDRUS-1D to improve parameterizations of soil thermal properties. These can then be integrated into large-scale land surface models to enhance accuracy under dynamic hydrological conditions.

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