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The GEOSPACE framework: a component-based modular approach to soil-plant-atmosphere continuum modeling

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ABSTRACT: The soil-plant-atmosphere continuum (SPAC) encompasses complex, interconnected processes that govern water, energy, and matter exchange. Traditional modeling approaches struggle with the diversity of physical formulations and rapid evolution of SPAC science. We present GEOSPACE (v1.2.9), a component-based framework leveraging object-oriented programming (OOP) principles to enable flexible, extensible SPAC modeling. The framework comprises three main components: WHETGEO (soil water flow using Richards' equation), GEOET (evapotranspiration (ET) with multiple model options), and BrokerGEO (coupling component). Key innovations include bidirectional feedback between infiltration and evapotranspiration, multiple stress factor formulations, and a software architecture that allows model extensions without modifying existing validated code. Validation using the "Spike II" lysimeter experiment demonstrates excellent mass balance closure and reveals that neglecting ET-infiltration coupling overestimates groundwater recharge. The open-source framework adheres to FAIR principles and provides a foundation for reproducible, transparent SPAC research.

Keywords: Soil-plant-atmosphere-continuum; Richards' equation; Lysimeter experiments; Object Oriented Programming; FAIR principles

1 INTRODUCTION

The SPAC system integrates heat transfer, evapotranspiration (ET), precipitation, water absorption, soil water flow, and gas exchange (Fischer et al, 2020; Blyth et al., 2021). Current debates surrounding soil-root interactions, plant hydraulics, water stress formulations, and atmospheric coupling necessitate modeling frameworks capable of accommodating diverse physical formulations and evolving research findings (Manoli et al., 2017; Carminati et al., 2020, D'Amato 2024).

Traditional physically-based models (PBM) and land surface models (LSM/SVAT) often employ monolithic architectures that complicate modification and extension (Fatichi et al., 2016). Component-based modeling approaches offer superior flexibility by dividing software into self-contained, independent components interconnected through supporting frameworks (Moore et al., 2017, David et al., 2013).

We present GEOSPACE (GEOframe Soil-Plant-Atmosphere Continuum Estimator), particularly its one-dimensional implementation GEOSPACE-1D (v1.2.9), which integrates Modeling by Components (MBC) with object-oriented programming (OOP) principles. Rather than creating a single SPAC model, GEOSPACE establishes a system enabling creation of multiple models adapted to specific user needs.

2 METHODS

2.1 System Architecture

GEOSPACE-1D comprises three primary components operating in a cyclic feedback loop (Fig. 1):

WHETGEO (Water Heat and Transport in GEOframe) solves the conservative form of the Richards-Richardson equation using the Newton-Casulli-Zanolli algorithm (Casulli and Zanolli, 2010).

GEOET (GEOframe EvapoTranspiration) implements multiple ET models: Priestley-Taylor (PT), Penman-Monteith FAO (PM-FAO), and the Prospero model (Bottazzi, 2021). The Prospero model extends the Schymanski and Or (2017) approach, solving coupled energy budget and vapor transport equations (D'Amato and Rigon, 2025). GEOET also incorporates stress factor estimation using Jarvis (1976) and Medlyn et al. (2021) formulations.

BrokerGEO couples WHETGEO and GEOET by partitioning global evapotranspiration across soil control volumes using three methods: average-weighted, size-weighted, and root-density-weighted. This partitioning employs root functioning models to distribute transpiration demand realistically. Details can be found in (D'Amato, 2024 and D'Amato et al., 2025).

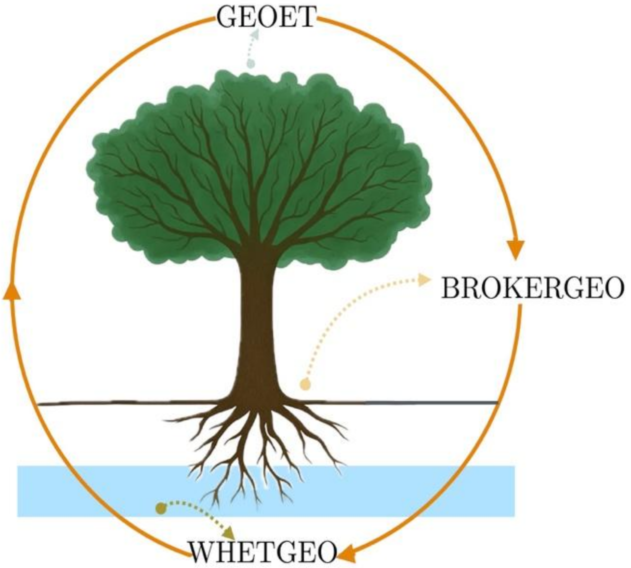

Figure 1. GEOSPACE-1D operational cycle showing bidirectional feedback between soil water flow (WHETGEO) treating with soil, evapotranspiration computation (GEOET) treating with canopy, and flux partitioning (BrokerGEO), treating with roots. The cyclic path includes: (1) WHETGEO computes soil water potential (ψ) for each control volume; (2) GEOET-StressFactor determines reduction in ET based on ψ and environmental variables; (3) Global stress factor (G_w) and actual ET (AET) computed; (4) BrokerGEO partitions AET across control volumes using root distribution; (5) WHETGEO recalculates ψ based on water extraction; (6) Iteration continues until the end of the simulation

2.2 *Software Engineering Design*

GEOSPACE employs advanced OOP patterns including:

- *Programming to interfaces: Core functionalities implemented as abstract objects rather than concrete classes;*
- *Factory pattern: Runtime selection of implementations without code modification;*
- *Singleton pattern: Data classes instantiated once and updated each time step.*

This architecture adheres to the open-closed principle, open to extension, closed to modification. Adding new ET models or stress formulations requires only creating new classes extending existing interfaces, without modifying validated code. The framework integrates with OMS3 (Object Modeling System v3), providing component-based architecture, workflow recording for reproducibility, and services for calibration and parallelization (David et al., 2013).

The numerical core of GEOSPACE-1D is in Java, with Python used for pre/post-processing. The design adheres with FAIR (Findable, Accessible, Interoperable, Reusable) principles to ensure transparent, reproducible workflows.

Typical GEOSPACE-1D simulations (200–300 control volumes, hourly resolution, annual period) complete in about 30 s on a standard desktop computer, demonstrating high computational efficiency while maintaining full coupling between soil and canopy processes.

3 RESULTS

3.1 *Baseline simulation*

We validated GEOSPACE-1D using the 'Spike II' experiment dataset (Nehemi et al., 2020) a two-month lysimeter study with a willow tree. Configuration details are presented in Table 1.

Table 1. Parameters values used in simulation.

Parameter	**Value**
Soil Column depth	2.5 m
Control volumes	250
Time step	Hourly
Canopy height	3.5 m
LAI range	2.5 – 4.0
Root depth	2 m constant
ET model	Prospero + PM-FAO
Stress factor Transpiration	Root density weighted
Stress factor Evaporation	Average weighted
Transpiration splitter	Root water weighted
Evaporation splitter	Average water weighted

3.2 *Mass balance and coupling effects*

The simulation achieved excellent mass balance closure with errors 10^{-9} m, demonstrating numerical robustness despite complex coupled processes including surface ponding, infiltration fronts, and stress-limited transpiration. Comparison of coupled (baseline) versus uncoupled (infiltration-only) simulations revealed dramatic differences: the baseline (coupled) bottom flux was 181 mm while the uncoupled bottom flux was 602 mm, resulting in an overestimation of 235% of groundwater recharge when neglecting ET.

3.3 *Stress factor dynamics*

Water stress evolved dynamically throughout the simulation, with stress factors varying from 0.4 to 1.0 across the root zone depending on recent precipitation events and atmospheric demand. The root-density-weighted representative stress factor showed strong correlation with atmospheric vapor pressure deficit ($r^2 = 0.73$), indicating proper representation of atmosphere-plant-soil feedback mechanisms.

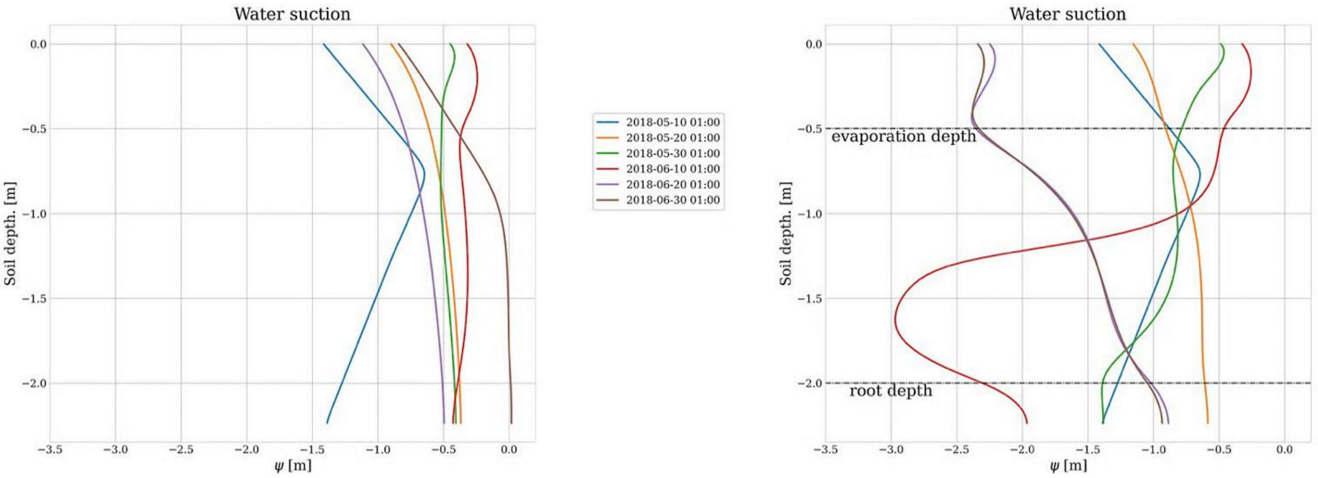

Figure 2. Water suction dynamics comparison: Water suction profiles at selected time steps from infiltration simulations without (left) and with (right) evapotranspiration (ET) flux

Evaporation (E) and transpiration (T) rates showed distinct temporal patterns, with transpiration dominating during mid-day periods (peak ~ 1.5 mm/h) while evaporation remained relatively constant (~0.1-0.2 mm/h), properly reflecting the different driving processes and stress sensitivities.

4 DISCUSSION

4.1 Key Innovations

Bidirectional Feedback: Unlike traditional approaches treating ET as a boundary condition, GEOSPACE achieves full coupling where soil moisture influences ET and vice versa through the sink term $S(z)$. This bidirectional feedback is essential for accurate representation of SPAC dynamics, as demonstrated by the 234% difference in predicted recharge and illustrated in Fig. 2, which compares infiltration simulations with and without ET flux.

Multiple Formulations: The framework enables direct comparison of different physical formulations (e.g., Jarvis vs. Medlyn stomatal models, different stress aggregation methods, and other models) under identical conditions, facilitating model evaluation and hypothesis testing. This capability is crucial given ongoing scientific debates about optimal process representations.

4.2 Practical Applications

GEOSPACE-1D (v1.2.9) is a one-dimensional model suited for plot-scale use, but it can be extended to hillslope or catchment scales by linking multiple soil columns through lateral flow. A 2D version is under development, with the soil module completed and the BrokerGEO coupling being extended to a bidimensional grid.

GEOSPACE serves multiple user communities:

Hydrologists can use the framework to assess how vegetation dynamics affect infiltration, groundwater recharge, and watershed water budgets. Neglecting vegetation effects can severely bias hydrologic predictions, particularly in water-limited environments or for long-term simulations.

Agricultural scientists benefit from multiple ET model options (PT, PM-FAO, Prospero) allowing selection based on data availability and desired process resolution. The FAO-standard PM model facilitates comparison with established agricultural practices, while Prospero enables detailed investigation of crop water stress responses.

Geotechnical engineers can use GEOSPACE outputs such as pore-pressure dynamics, suction, and water content to infer effective stresses and evaluate slope or foundation stability. The framework can also be extended to incorporate full hydro-mechanical coupling for advanced stress analyses.

Ecosystem researchers can leverage the detailed energy budget and stress factor outputs to understand plant responses to water limitation and explore eco-hydrological feedback. The framework's ability to output leaf temperatures, vapor pressure deficits, and sunlit/shaded canopy fractions supports plant physiological studies.

5 CONCLUSIONS

GEOSPACE demonstrates that component-based architecture and advanced software engineering enhance both scientific flexibility and computational reliability in SPAC modeling. The framework successfully implements proper bidirectional coupling between infiltration and evapotranspiration, provides multiple physics formulations allowing users to select appropriate complexity for their applications, and enables seamless integration of new research through its extensible OOP design.

Future development will extend the framework to 2D/3D applications, integrate full plant hydraulics and carbon cycle models, and incorporate emerging understanding of rhizosphere processes. The modular architecture ensures these additions without altering validated components.

GEOSPACE is freely available as open-source software (GPL 3.0) with complete documentation, tutorials, and example applications at https://github.com/geoframecomponents/GEOSPACE-1D. We invite community contributions and collaborations to further develop this evolving framework for SPAC research.

To our knowledge, no existing SVAT or LSM framework combines similar modularity and runtime physics selection (Blyth et al., 2021), while its OMS3 workflow recording and Jupyter-based documentation strongly support FAIR principles in computational hydrology (Wilkinson et al., 2016).

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7 DATA AVAILABILITY

Simulation data are available on Zenodo (https://doi.org/10.5281/zenodo.14269885). Input data from the Spike II experiment are available at https://doi.org/10.5281/zenodo.4037240.

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