Advanced Techniques for Characterizing Soil Hydrological and Transmission Properties

Yashasvi Sood[1*], Dr. Narender K. Sankhyan[2], Dr. Lav Bhushan[3], Anamika Karmani[1], Pritika Nalwa[1] and Aayushi[1]

[1]*M.Sc. Research Scholar, Department of Soil Science, CSK HPKV, Palampur, HP, India-176062*
[2]*Head cum Principal Scientist, Department of Soil Science, CSK HPKV, Palampur, HP, India-176062*
[3]*Subject Matter Specialist, Department of Soil Science, CSK HPKV, Palampur, HP, India-176062*

Corresponding Author
Yashasvi Sood
Email: soodyashasvi560@gmail.com

OPEN ACCESS

Keywords

Soil hydrological and transmission properties, Advanced techniques

How to cite this article:

Sood, Y., Sankhyan, N. K., Bhushan, L., Karmani, A., Nalwa, P. and Aayushi. 2025. Advanced Techniques for Characterizing Soil Hydrological and Transmission Properties. *Vigyan Varta* 6 (5): 110-114.

ABSTRACT

Soil hydrological and transmission properties describe how water interacts with soil, including absorption, retention and movement of water in soil. These properties impact drainage and nutrient availability to plants. Understanding and characterizing these properties is essential for efficient water management, nutrient management in agriculture, environmental conservation, civil engineering, hydrology and water resource management. Various techniques are used for measuring these properties including traditional as well as advanced methods. Traditional methods are labour intensive, time consuming, limited to small scale or laboratory conditions and are unable to provide continuous or real time data. Thus, replacing or supplementing them with advanced techniques is recommended. Several advanced techniques like remote sensing, tracer techniques, spectroscopic techniques, digital and computational methods, synthetic aperture radar, cosmic ray neutron sensors are used to quantify soil hydrological and transmission properties. These techniques allows accurate and precise measurement, they are non-invasive resulting in minimal soil disturbances, and helps in faster and real-time data collection.

INTRODUCTION

Soil hydrological and transmission properties describe how water interacts with soil, including absorption, retention and movement of water in soil. Various soil hydrological and transmission properties include permeability, infiltration rate, water holding capacity, hydraulic conductivity, maximum water retentive capacity, field capacity, wilting point, capillary rise, drainage and evapotranspiration. Various physical (texture, structure, porosity, bulk density, particle density, temperature, slope and topography), chemical (salinity, sodicity, organic matter content, cation exchange capacity), biological (presence of microbes, plant roots, earthworms and burrowing organisms) factors affect these properties of soil. Traditional methods to characterize these properties are direct and indirect methods. Direct methods include gravimetric method, calcium carbide method, and alcohol burning method. Indirect methods include nuclear techniques (neutron moisture meter, gamma ray scanner), electrical resistance methods. Single ring and double ring infiltrometer to measure infiltration rate, lysimeter, open pan evaporimeter to measure evapotranspiration. These methods have certain limitations as they are time cosuming, lack precision, limited to laboratory conditions, inaccurate and lack automation thus are not able to provide real-time and continuous data. They often rely on manual data collection and observation. These methods are not typically integrated with automated sensors or data loggers for real-time feedback. The absence of automation prevents continuous data streaming. To overcome these limitations modern techniques have emerged that are more accurate, precise, les labour intensive, non-invasive and provide real-time and continuous data.

Advanced techniques

Advanced techniques leverage advancements in sensor technology, data acquisition and computational modelling to provide more accurate, continuous and large-scale measurements of soil hydrological and transmission properties. These techniques not only overcome the scale limitations of traditional methods but also enhance the understanding of complex soil water processes by integrating high frequency large scale, multidimensional data. As a result, they are increasingly used in field such as agriculture hydrology and water management.

Remote sensing and geophysical methods

These methods include ground penetrating radar, soil moisture sensors and electrical resistivity tomography.

- Ground penetrating radar uses high frequency electromagnetic waves to penetrate the ground and detect variations in soil composition, moisture content. Transmitted waves when reflected back are detected by receiving antenna. Travel time and amplitude of the reflected signals are recorded and processed to create an image of the subsurface.

- Soil moisture sensors measure the water content or water potential in the soil by detecting changes in soil's electrical, dielectric or pressure properties. Since water has distinct physical, electrical characteristics compared to soil minerals and air, these differences can be exploited to estimate the amount of water present in soil.

- Electrical resistivity tomography is widely used to map soil hydrological properties and transmission properties. These maps helps in understanding infiltration, soil moisture distribution. By analyzing variations in soil resistivity, it provides valuable insights by generating 2D, 3D images of the subsurface.

Tracer techniques

Tracer techniques include dye tracing and isotopic tracers.

- Dye tracing is widely used technique in soil hydrology to study water movement, infiltration patterns, preferential flow paths and solute transport within the soil. It involves applying a coloured dye solution to the soil. Most commonly used dyes are brilliant blue FCF, rhodamine WT. the dye pattern reveals the flow pathways, percolation depth and water distribution.

- Isotopic tracers allow to trace percolation, infiltration rate, root water uptake. This method uses isotopes like Oxygen-18 (^{18}O), Deuterium (^{2}H or D) that provides detailed insights into soil processes without disturbing the natural soil environment.

Digital and computational methods

These methods include various soil hydrological models and machine learning algorithms.

- Hydrological models- A **hydrological model** is a mathematical or computational tool that simulates the movement, distribution, and quality of water through the hydrological cycle Various hydrological models used to characterize soil hydrological and transmission properties include hihydrosoil v2.0 given by futurewater, hydrus model given by Jirka Simunek, SWAP model given by R.A. Feddes, P. Kabat, J. Halbertsma and rainfall runoff models like CROPWAT given by FAO and SWAT given by USDA. Hihydro soil v2.0 is an advanced computational model designed to simulate soil hydrological properties. It integrates digital soil mapping, remote sensing, and field sensor data with numerical simulation techniques to estimate key parameters such as hydraulic conductivity, soil moisture distribution and water infiltration. The **hydrus model** is a **numerical simulation software** used to model the **movement of water, heat, and solutes** in **variably saturated porous media** (such as soil). It solves the **Richards equation** for water flow and the **advection-dispersion equation** for solute transport under a wide range of boundary conditions and soil properties. The various outputs estimated using this model are Water content and flux, Cumulative infiltration, drainage & run off by processing data and applying numerical solution of governing equations like Richard equation for water flow. By using various inputs like Soil properties like texture, organic matter content, Climate data, root water uptake parameter. SWAP stands for soil water atmosphere plant. The SWAP model is a one-dimensional physically-based, agro-hydrological model. It is designed to simulate water flow, solute transport and plant growth in a soil–water atmosphere–plant environment. SWAP model is used to determine water content at different depths, amount of water lost through deep percolation, biomass production, harvest index and total water loss from soil and plant surfaces by processing and integrating the data by using the inputs like soil hydraulic properties (water retention curve, hydraulic conductivity), crop characteristics (root depth, crop growth stage, water uptake rate), meteorological data (rainfall, temperature, solar radiation, wind speed). **Rainfall-runoff models** are mathematical models used to simulate and predict how **rainfall** translates into **runoff** in a particular area. The various outputs assessed using this model are streamflow, runoff volume, peak discharge, infiltration rate.

- Machine learning algorithms (MLA's) - They are computational model inspired by the structure and function of the human brain, designed to recognize patterns and learn from data by mimicking the way biological neurons work. Soil-water interactions are highly nonlinear, which ANNs handle well. MLA's learn patterns directly from data without needing explicit physical equations. They can incorporate diverse data sources like satellite data, soil surveys, and field measurements and can work effectively even with incomplete data and thus are used to predict soil hydraulic conductivity, soil water retention and infiltration rate.

Spectroscopic techniques

Spectroscopic techniques have emerged as powerful tools for characterizing soil hydrological and transmission properties. These methods utilize electromagnetic radiation to analyze soil properties in a non-destructive and rapid manner. Techniques such as visible-near infrared (Vis-NIR), mid-infrared (MIR), Raman spectroscopy, and hyperspectral reflectance spectroscopy are commonly employed.t These methods rely on the interaction of electromagnetic radiation with soil constituents, where specific wavelengths are absorbed depending on the chemical bonds and physical characteristics present.

Large scale techniques

These methods includes synthetic aperture radar and cosmic ray neutron sensors.

- Synthetic aperture radar- Synthetic Aperture Radar (SAR) is a type of active remote sensing technology that uses microwave radar signals to create high-resolution images of the Earth's surface, regardless of weather conditions or lighting (day or night). SAR is widely used in soil science and hydrology for monitoring soil moisture, surface roughness, and land cover changes.
- Cosmic ray neutron sensors- A **Cosmic Ray Neutron Sensor (CRNS)** is a device used to measure **soil moisture** by detecting **neutrons** produced when **cosmic rays** from outer space interact with the Earth's atmosphere and surface.

Various researchers have conducted several studies on characterizing soil hydrological and transmission properties. For instance, Pravukalyan and Rama (2016) at IARI New Delhi used hydrus-2D model for simulating soil water dynamics in drip-irrigated citrus. The study revealed that observed and simulated (using hydrus model) water content was nearly equal and hydrus-2D can be used to simulate the water distribution with very good accuracy.

Babei *et al*. (2021) evaluated soil water content and water uptake by corn plant roots (Single cross 260) under different soil moisture and water salinity stresses using the agro hydrological Soil–Water–Atmosphere–Plant (SWAP) model. Study indicated that the SWAP model can be used as a powerful tool to simulate field water cycle and evaluate irrigation practices.

Simons *et al*. (2020) prepared global map of water content at pF 4.2 (permanent wilting point) using HiHydroSoil v2.0. The map was accurate in predicting the water content at permanent wilting point for different regions.

Advantages of advanced techniques

- **Increased accuracy and precision:** Modern soil measurement devices use high-quality sensors that measure small variations in soil properties with minimal interference. Automated systems reduce human error. Machine learning models combine data from multiple sources (e.g., satellite, field sensors, weather data) to improve predictive accuracy.

- **Non-invasive and minimal soil disturbance:** Non-invasive methods measure soil properties **through the soil surface** or from aboveground, allowing minimum soil disturbance as there is least soil sampling. Some techniques like SAR, CRNS measure soil moisture without even touching the soil. Modern methods use electromagnetic and acoustic signals to probe soil properties without inserting sensors into the soil.

- **High-throughput capability:** Modern methods for characterizing soil hydrological and transmission properties have significantly improved in their ability to cover **large areas** and handle **high volumes of data** quickly and efficiently. This shift is driven by advancements in **remote sensing, automation, sensor technology**, and **data processing** that allow researchers to measure soil properties over broad geographic areas and at fine temporal resolutions — all while maintaining high accuracy and precision.

- **Faster and real time data collection**

CONCLUSION

Advance techniques allow for large-scale soil property predictions, improving applications in precision agriculture, water resource management and climate resilience planning. They provide real-time, accurate and reliable information. The advancement of modern techniques for characterizing soil hydrological and transmission properties has significantly improved our ability to understand and predict soil-water interactions and these can be widely adopted to predict various soil properties.

REFERENCES

Babaei MA, Biglouei MH, Pirmoradian N and Mohammadi AR. 2021. Optimizing agricultural water use through simulation of soil water content and water uptake under soil moisture and irrigation water salinity stresses: case study of corn roots using SWAP model. *Environmental Resources Research* 9(1): 99-106

Pravukalyan P and Rama KS. 2016. Using hydrus-2D model for simulating soil water dynamics in drip-irrigated citrus. *Poljoprivredna tehnika* 41(1): 59-68

Simons G, Koster, R and Droogers P. 2020. Hihydrosoil v2. 0-high resolution soil maps of global hydraulic properties. *Future Works. https://www. futurewater. eu/projects/hihydrosoil.*