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Geospatial analysis of soil moisture variability and its implications for irrigation management using GIS

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Abstract

Soil moisture variability across space and time critically influences crop water availability, irrigation scheduling, and water-use efficiency, especially in regions with variable rainfall and heterogeneous soils. This review synthesises research on the use of geospatial tools—primarily Geographic Information Systems (GIS) and remote sensing—to quantify spatial and temporal patterns of soil moisture. We examine methods including interpolation of in situ measurements, satellite-derived microwave and multispectral data, and hybrid models combining soil, topographic, and climatic variables. We discuss the strengths and limitations of each approach, highlight recent advances in multi-sensor fusion and machine-learning estimation, and demonstrate how resulting soil moisture maps inform precision irrigation planning. Drawing on case studies from around the world and India, we outline how GIS-based soil-moisture analysis supports efficient water management, drought mitigation, and sustainable agriculture. The review concludes by identifying knowledge gaps and proposing directions for integrating soil moisture geospatial data into operational irrigation decision support systems.

Keywords: Soil moisture, GIS, remote sensing, irrigation management, interpolation

1. Introduction

Soil moisture (SM) refers to the water contained within the pore spaces of soil. It controls water availability for plants, influences evapotranspiration and runoff, affects nutrient movement, and modulates hydrological and ecological processes. In agricultural regions, variability in soil moisture—across both space and time—poses significant challenges for efficient water allocation, irrigation scheduling, and yield optimisation.

Traditional irrigation planning often assumes uniform soil-water conditions across a field or region. But soils vary in texture, structure, depth; topography influences water retention and drainage; rainfall and climate are heterogeneous; land use and vegetation cover change dynamically. Ignoring this variability leads to over-irrigation in some areas (wasting water and causing waterlogging) and under-irrigation in others (stressing crops) ^[1, 2].

Geospatial tools—primarily Geographic Information Systems (GIS) and remote sensing (RS)—enable mapping, monitoring, and analysis of soil moisture variation over large areas and over time. Advances in sensor technology (microwave, multispectral, thermal), data assimilation, and spatial-statistical modelling enable high-resolution soil-moisture estimates beyond the limited coverage of ground sensors ^[2, 3].

This review examines the current state of geospatial analysis of soil moisture variability, the methods employed, the observed spatio-temporal patterns, and their applications in irrigation management. Special attention is given to studies in India and similar agroclimatic regions, highlighting potential for precision irrigation, drought preparedness, and sustainable water use.

2. Importance of Soil Moisture in Agriculture and Irrigation

- **Water availability for crops:** Soil moisture determines the water accessible to plant roots. Adequate soil moisture ensures sustained plant growth; deficits stress crops, reducing yield. In irrigated and rain-fed agriculture alike, timely knowledge of soil moisture enables well-timed irrigation to match crop water demand ^[3, 4].

- **Soil health and nutrient dynamics:** Soil water is essential for dissolution, movement and uptake of nutrients. It influences soil microbial activity, nutrient cycling, soil temperature, and the chemical and biological processes necessary for soil fertility [4, 5].
- **Environmental and hydrological balance:** Soil moisture regulates infiltration, surface runoff, groundwater recharge, evapotranspiration, and runoff generation. These processes influence flood risk, drought resilience, and water resource sustainability. For water-scarce or monsoon-driven climates (like many parts of India), managing soil moisture is vital for drought and flood mitigation [5, 6].
- **Efficient irrigation and water conservation:** With increasing water scarcity and pressure on freshwater resources, efficient irrigation becomes critical. Mapping soil moisture variability helps tailor irrigation —applying water where and when needed —minimising waste and ensuring equitable distribution across heterogeneous lands.
- **Climate resilience and sustainable farming:** In regions with variable or uncertain rainfall (e.g., monsoon variability), soil moisture analysis aids forecasting and planning —helps anticipate drought, schedule irrigation or rainfall-recharge, plan cropping patterns — ultimately supporting resilient agriculture under changing climate patterns [4, 6].

Given these roles, having accurate spatial and temporal soil moisture information is foundational for modern irrigation management, water resource planning, and sustainable agriculture.

3. Methods for Soil Moisture Estimation and Geospatial Analysis

There are three broad approaches to estimating and mapping soil moisture: ground-based measurements, remote sensing, and GIS-based spatial interpolation and modelling.

3.1 Ground-based methods

Ground-based methods include gravimetric sampling, in-situ sensors (e.g., dielectric sensors, moisture probes), and automated observation stations. The gravimetric method involves collecting soil samples and measuring mass before and after drying to calculate volumetric moisture content. These methods provide accurate point-scale measurements, often considered the “ground truth” [6, 7].

Recent developments include low-cost sensor networks using microprocessors and IoT technologies. For example, a system developed at a research institution in India used a Raspberry Pi-based sensor network to measure soil moisture and temperature,

demonstrating a high correlation ($r \approx 0.9$) with standard gravimetric observations. arXiv
However, ground methods have limited spatial coverage; scaling to fields, districts, or watersheds requires interpolation or combination with spatial methods [7, 8].

3.2 Remote sensing approaches

Remote sensing enables large-area monitoring. Sensors on satellites or drones measure reflectance (optical, multispectral, thermal) or microwave backscatter—data that can be correlated with soil moisture.

A recent comprehensive review (2016– 2024) of remote-sensing-based soil moisture estimation identified satellite data as the dominant method (used in ~ 73% of studies) [8, 9].

Microwave sensors (passive or active SAR) are particularly valuable because they can sense soil moisture independent of cloud cover and are sensitive to soil dielectric properties. Active radar (e.g., SAR) is increasingly used to estimate soil moisture, potentially at high spatial resolution. For instance, a 2025 study using satellite-based SAR (Sentinel-1) tested soil moisture prediction for wheat fields, using backscatter coefficients and vegetation-correcting indices, and was validated against ground measurements collected via a portable probe at 5 cm depth [9, 10].

3.3 GIS-based interpolation, modelling, and hybrid approaches

GIS provides a framework for integrating datasets—soil texture, topography (elevation, slope), land cover, rainfall or climate data—with soil moisture observations or remote sensing outputs, enabling spatial interpolation, modelling, and mapping.

Interpolation techniques like Inverse Distance Weighting (IDW), Spline, Ordinary Kriging, and Kriging with External Drift (KED) have been widely used. A comparative study over an area in India (about 1,535 km²) using 82 field-measured soil moisture points found that KED (incorporating soil organic carbon as an auxiliary variable) produced the lowest error (RMSE $\approx$ 8.7%) among methods [10, 11].

Hybrid models may include soil and topographic variables—e.g., the Soil Moisture Proxy Model (SMPM), which combines soil properties, slope, aspect, drainage patterns, and land use to estimate potential soil moisture across a watershed.

Semi-distributed hydrological models incorporating remote sensing and GIS (e.g., DPHM-RS) integrate processes such as interception, evapotranspiration, soil moisture, runoff, and routing to simulate water fluxes across basins.

These methods allow estimation of soil moisture at locations without direct measurements, generation of continuous soil moisture maps, and analysis of spatial patterns in relation to terrain, soil type, rainfall, and land use [12, 13].

Table 1: Soil Moisture Estimation Techniques and Their Accuracy

Technique	Method	Accuracy	Applications
Ground-based Gravimetric	Soil sample analysis	High (point scale)	Field-level moisture assessment, calibration of models
In-situ Sensors	Dielectric sensors, Probes	Moderate to High (depends on sensor type)	Real-time monitoring, small-scale irrigation control
Remote Sensing (SAR)	Microwave remote sensing	Moderate to High (depends on conditions)	Large-area mapping, cloud-independent monitoring
GIS-based Kriging/IDW	Spatial interpolation	High (with sufficient data)	Spatial mapping, site-specific irrigation management
Remote Sensing (Multispectral)	Optical imagery	Moderate	Vegetation moisture assessment, large-scale monitoring

4. Spatio-Temporal Variability of Soil Moisture: Patterns and Drivers

Soil moisture varies significantly across space and time.

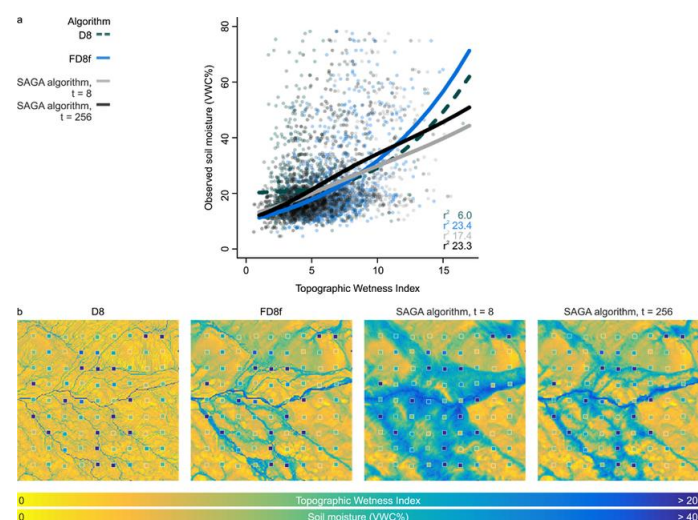
Understanding these patterns—and their drivers—is essential for designing effective irrigation strategies and drought/flood management.

4.1 Spatial variability: soil, topography, land use

- **Soil texture and structure:** Soil moisture retention depends heavily on soil texture, organic matter content, porosity, and bulk density. For example, a 2025 study in East Kazakhstan found that heavy soils (loam, silt-loam, clay-loam) consistently maintained higher soil moisture than light-textured soils (sands) across different years [13, 14].
- **Topography and drainage characteristics:** Terrain influences water accumulation and drainage. Indices like the Topographic Wetness Index (TWI) combine slope and upslope contributing area to identify zones likely to accumulate moisture [14, 15].

For example, in watershed-scale analyses, areas in depressions, gentle slopes, or flow-path convergence often show higher soil moisture potential than ridges and convex slopes, where runoff and drainage reduce retention. The SMPM applied in a semi-arid watershed in Mesa Verde (USA) demonstrated how topographic and soil variables together highlight zones with higher water-holding potential, offering guidance for water management and dryland agriculture [15, 16].

- **Land use and vegetation cover:** Vegetation influences evapotranspiration, shading, and interception of rainfall; land cover changes alter infiltration and evaporation. Areas under dense vegetation may exhibit different soil moisture dynamics than bare land or cropland. Seasonal crops, crop rotations, and cropping intensity also affect spatial soil moisture distribution [16, 17].
- **Heterogeneous field-scale variability:** Even within a single field, moisture can vary depending on micro-topography, soil heterogeneity, irrigation method, and previous water application. A 2023 study in a corn-soybean production field, using a 55 m × 55 m grid (44 sampling points) and moisture sensors at multiple depths (31, 61, 76 cm), documented substantial spatial and temporal variation. The authors used interpolation (IDW) to map soil water tension (SWT) across the field to support site-specific irrigation management [17, 18].



TWI highlights natural moisture accumulation zones, strengthening interpretation of terrain-driven soil moisture variation (Source; Riihimäki, Henri & Kemppinen, J. & Kopecký, Martin & Luoto, Miska. (2021). Topographic Wetness Index as a Proxy for Soil Moisture: The Importance of Flow-Routing Algorithm and Grid Resolution. *Water Resources Research*. 57. 10.1029/2021WR029871.)

4.2 Temporal variability: seasons, rainfall, drought, irrigation

- **Seasonal variation and rainfall dependence:** In monsoon-driven climates (like much of India), soil moisture strongly follows rainfall patterns. A long-term geospatial study over India (1991–2010) using satellite-derived soil moisture revealed distinct spatial patterns: in the early monsoon (June), many northern and central regions showed low soil moisture with high interannual variability; by July, moisture increased broadly and variability decreased, reflecting monsoon progression [18, 19].

The study used statistical measures (e.g., coefficient of variation and correlation with rainfall) and identified areas that consistently experienced moisture deficits — a valuable approach for drought-risk mapping.

- **Drought and moisture persistence:** Periods of delayed or poor rainfall produce soil moisture deficits. Geospatial time-series mapping helps identify persistent dry zones, enabling analysis of drought frequency. In the 20-year Indian soil moisture dataset, some regions experienced 4–6 years of drought in June, highlighting the vulnerability [20, 21].
- **Irrigation events and water application:** In irrigated agriculture, artificial water application alters soil moisture independently of rainfall. Integration of soil moisture maps with irrigation data enables assessment of irrigation effectiveness, detection of over- or under-irrigation, and guidance for future scheduling. Sensor-based field studies show that spatially distributed moisture measurements and interpolation can support precision irrigation by matching water supply to localised field moisture conditions.
- **Sub-seasonal and interannual dynamics:** Soil moisture can fluctuate within a cropping season (before/after rainfall, irrigation, evapotranspiration), and across years depending on rainfall variability, land use change, or management practices.

5. Applications for Irrigation Management and Water Resource Planning

Geospatial analysis of soil moisture has direct and practical applications in irrigation planning, efficiency improvement, drought and flood risk management, and policy-level water resource planning [22, 23].

5.1 Precision irrigation and site-specific water management

By mapping spatial variability at the field or watershed scale, GIS-based moisture maps can guide where to apply water, how much, and when. This reduces over-irrigation (water waste and salinity risk) and under-irrigation (crop stress), thereby improving water-use efficiency. Field-level sensor networks combined with interpolation methods (e.g., IDW, Kriging) support micro-zone-based irrigation scheduling.

For instance, in fields under pivot or drip irrigation, moisture sensors plus GIS interpolation help detect zones with lower moisture retention, allowing targeted water application rather than blanket irrigation [24, 25].

5.2 Drought risk assessment and water scarcity management

Long-term geospatial soil moisture datasets enable drought mapping, vulnerability assessment, drought frequency analysis,

and early warning. In monsoon-dependent regions, identifying zones with recurring soil moisture deficits helps allocate irrigation resources, plan drought-resilient cropping patterns, and design water-saving strategies.

5.3 Watershed and basin-level water management, planning of water harvesting structures

At larger scales, GIS-based soil moisture and topographic analysis help identify zones likely to collect and retain water, suitable for water-harvesting infrastructure (e.g., small check dams, recharge ponds), rainwater harvesting, and groundwater recharge. Hybrid hydrological models that integrate soil moisture, rainfall, evapotranspiration, runoff, and land cover (e.g., DPHM-RS) support basin-scale water balance estimation and decision-making [26, 27].

5.4 Agricultural planning and crop water demand mapping
By overlaying soil moisture maps with soil type, land use, crop distribution, and climatic data, planners and farmers can estimate the spatial distribution of irrigation demand. GIS-based demand maps facilitate optimised water allocation, reduce water delivery inequality, and support judicious water management at the district or regional level [28, 29].

5.5 Monitoring and evaluating irrigation system performance, waterlogging, and salinity risk
GIS-based soil moisture observations allow detection of zones of over-irrigation, poor drainage, waterlogging, or salinity buildup. Over time, such monitoring helps evaluate the performance of irrigation infrastructure, drainage design, and remedial measures. Also helpful in diagnosing inefficiencies or inequalities in water delivery systems.

Table 2: Geospatial Methods for Irrigation Planning and Water Resource Management

Geospatial Method	Strengths	Applications	Limitations
GIS-based soil moisture mapping	Large-area coverage, continuous monitoring	Precision irrigation, drought management, water resource planning	Requires reliable ground-truth data, potential model uncertainty
Satellite-based SAR imagery	Independent of cloud cover, high resolution	Mapping soil moisture across heterogeneous terrains	Limited depth penetration, influenced by surface roughness
Remote Sensing (Optical)	High temporal frequency, easy access	Irrigation scheduling, crop water demand estimation	Affected by vegetation cover, surface conditions
Hydrological models (e.g., DPHM-RS)	Integrates multiple data sources	Watershed management, irrigation infrastructure planning	Requires extensive input data, model calibration
Ground-based sensor networks	Real-time, accurate data	Micro-zone irrigation, water deficit detection	Expensive, limited spatial coverage

6. Case Studies (with Emphasis on Indian Context)

6.1 Interpolation-based soil moisture mapping: Example from Varanasi, India

In a study over about 1,535 km² around Varanasi, 82 soil-moisture field measurements were taken. Four spatial interpolation techniques — Inverse Distance Weighting (IDW), Spline, Ordinary Kriging, and Kriging with External Drift (KED) — were compared. KED (with soil organic carbon as auxiliary variable) produced the lowest error (RMSE ~ 8.69%), outperforming other approaches. This demonstrates that combining soil property data (beyond moisture) with spatial interpolation in GIS improves estimation accuracy [30, 31]. This approach provides a practical method for district-level soil moisture mapping, thereby enabling irrigation planning based on actual spatial variation rather than coarse assumptions.

6.2 Satellite-based soil moisture for crop irrigation: 2024 Study on Wheat Fields in India

A 2025 study used Sentinel-1 SAR imagery to predict soil moisture in wheat fields during critical phenological stages (tillering, flowering, grain filling) — dates: 19 Feb, 9 Mar, 14 Apr — when soil water availability is crucial for yield. Ground-truth data were collected using a portable moisture probe at a depth of 5 cm. Backscatter coefficients (VV, VH) and radar-vegetation index (RVI) were used as predictors [32, 33]. This demonstrates the feasibility of satellite-based soil moisture estimation for guiding irrigation during key crop stages, offering a scalable, remote method for crop water management.

6.3 Long-term soil moisture spatio-temporal mapping across India (1991– 2010)

A study using ESA-satellite-derived surface soil moisture over

India (daily data) for 20 years (1991– 2010) analysed interannual variability, correlation with rainfall, and drought frequency. Monthly mean images (e.g., June and July) showed significant spatial variability: many northern and central states had low moisture in early monsoon (June) with high year-to-year variability; by July, moisture increased with less variability. Regions like Uttar Pradesh, East Rajasthan, Punjab, Haryana, Bihar, Gujarat, and parts of Chhattisgarh and Jharkhand showed low mean moisture and high coefficient of variation (CV) [34, 35]. Drought frequency mapping (years when soil moisture fell less than 90% of normal) identified significant drought-prone areas. In June, about 32% of pixels experienced 4– 6 years of drought; in July, 25% of pixels did [36, 37]. These maps can inform regional irrigation planning, drought mitigation, reservoir and groundwater recharge strategies.

6.4 Watershed-scale soil moisture potential mapping in semi-arid region (USA) — implications for water harvesting and dryland agriculture

Although not in India, the watershed-scale application of the Soil Moisture Proxy Model (SMPM) in a semi-arid watershed in Mesa Verde (Colorado, USA) illustrates how combining soil, slope, aspect, drainage, and land cover data in GIS can identify zones with higher water retention potential [38, 39]. This has direct relevance for arid and semi-arid regions worldwide, including many parts of India where dryland farming or water harvesting is critical. Such identification enables targeted placement of rainwater-harvesting structures, selection of crops suited to local moisture conditions, and optimised land management for sustainable agriculture [40, 41].

Table 3: Case Study Locations and Soil Moisture Mapping Approaches

Study Location	Soil Moisture Mapping Method	Techniques Used	Key Findings
Varanasi, India	GIS-based interpolation	Kriging, IDW	Identified moisture variations, improved irrigation planning
Himalayan Region, India	Remote Sensing (SAR)	Sentinel-1 imagery	High accuracy in soil moisture prediction during monsoon season
Mesa Verde, USA	Hybrid Model (GIS + Remote Sensing)	DPHM-RS, Soil moisture proxy model	Zones identified for water retention potential, guiding water harvesting
Lower Mahanadi Basin, India	Remote Sensing + GIS	MODIS LULC, SoilGrids	SOC improvement in forested zones, bulk density decrease in agricultural land

7. Challenges, Limitations, and Future Directions

7.1 Data limitations: spatial resolution, sensor depth, calibration

- **Sensor limitations:** Satellite-based remote sensing (especially microwave/SAR) often captures only near-surface (e.g., upper few centimetres) soil moisture. For crop root-zone planning (20–60 cm or deeper), surface moisture may not represent actual plant-available water. Many crops draw water from deeper layers; reliance solely on surface data may misguide irrigation. This limitation is widely acknowledged [42, 43].
- **Spatial resolution constraints:** Coarse-resolution satellite products may miss small-scale variability; interpolation and modelling require sufficient ground-truth points, which are often lacking.
- **Vegetation and surface conditions interference:** Vegetation cover, crop residues, surface roughness, and land cover changes influence remote-sensed reflectance or backscatter, complicating soil moisture retrieval. The presence of crops during the growing season makes estimation harder. Recent reviews note that vegetation interference, limited penetration depth, and calibration requirements remain significant challenges [44, 45].
- **Sparse in-situ data:** Many regions, especially in developing countries, lack dense soil moisture monitoring networks. Without in-situ data, validation of remote-sensing or model outputs remains uncertain. Studies often rely on limited or sporadic ground measurements [46, 47].

7.2 Temporal and dynamic complexity

Soil moisture dynamics are influenced by rainfall, evapotranspiration, irrigation, land use change, groundwater uptake, and soil processes. Capturing this complexity requires frequent observations and integration of multiple datasets (climate, land cover, soil properties). Many studies focus on snapshots (single dates) or short periods; long-term continuous monitoring at high spatial resolution remains difficult [48, 49].

7.3 Model and interpolation challenges

Spatial interpolation assumes spatial autocorrelation — that nearby points have similar moisture. Where soil, topography, or land use change abruptly, interpolation may yield misleading estimates. Hybrid models combining soil/topographic variables mitigate some issues, but require detailed ancillary data (soil maps, DEMs, land cover), which may be missing or outdated in many regions.

7.4 Integrating soil moisture data into operational irrigation decision-support systems (DSS)

Despite numerous studies, operational systems that integrate geospatial soil moisture maps into everyday irrigation planning remain limited. Challenges include data availability, temporal frequency, user capacity (farmers, water managers),

infrastructure, and institutional uptake.

7.5 Future directions and research opportunities

- **Multi-sensor fusion and machine learning:** Recent trends show growing use of multi-sensor data (microwave, optical, thermal) combined with machine/deep learning for improved soil moisture estimation. These methods may better account for vegetation, soil heterogeneity, and surface conditions.
- **Root-zone moisture estimation:** Research should focus on combining surface observations with soil hydraulic models, in-situ deep sensors, and data assimilation to estimate moisture in the root zone (not just surface). Approaches such as simultaneous estimation of hydraulic parameters and soil moisture distribution using remote sensing and modelling show promise [49, 50].
- **High-resolution, frequent monitoring:** Use of UAVs/drones, dense sensor networks, and smartphone-enabled data collection (IoT) can fill spatial and temporal gaps, especially for smallholder farms.
- **Locally calibrated models for diverse soil and agro-climatic zones (especially in India):** India's agroecological diversity demands region-specific calibration and validation. The systematic establishment of ground observation networks, soil mapping, integration of climatic data, and local field studies will improve reliability.
- **Operational decision-support systems for farmers and water managers:** Development of GIS-based DSS integrating soil moisture, crop calendar, climate forecasts, irrigation infrastructure, water availability and demand, to translate geospatial insights into actionable irrigation schedules [51, 52].

8. Conclusion

Soil moisture variability—across space and time—is a critical factor for efficient water use, sustainable agriculture, drought and flood risk management, and long-term water resource planning. Geospatial tools, primarily GIS and remote sensing, enable mapping and monitoring of soil moisture at scales and resolutions not feasible with ground-based measurements alone. A range of methods — from simple interpolation of in-situ measurements to satellite-based microwave sensing to hybrid models incorporating soil, topography, climate, and land cover data — have been successfully applied globally and in India [53, 54].

Empirical evidence demonstrates that soil moisture distribution is highly heterogeneous even within small areas or single fields, driven by soil texture, topography, land use, and temporal factors such as rainfall and irrigation. GIS-based soil moisture mapping supports precision irrigation, targeted water application, drought and water-stress assessment, watershed-level planning, and water-harvesting design. In India, interpolation-based mapping (e.g., in Varanasi), satellite-based

monitoring (wheat-wheat cropping regions), and long-term moisture trend analysis highlight significant potential.

However, challenges persist: remote sensing often provides only surface moisture; temporal frequency and spatial resolution remain limited; vegetation, surface conditions, and the lack of dense in-situ networks complicate reliable estimation; and the integration of data into operational irrigation scheduling frameworks remains limited^[55].

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