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Leveraging Remote Sensing and Geospatial Technologies in Soil and Water Resources Mapping and Characterization: A Review

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ABSTRACT

Soil and groundwater, important natural resources, are essential for sustaining ecosystem health and maintaining agricultural production. However, both resources are under severe threat due to increasing demand for human consumption, agricultural operations and industrial activities. This situation warrants accurate monitoring and mapping to ensure their sustainable use. Since conventional methods are expensive and cumbersome, there is a need for innovative alternative approaches. The integration of remote sensing, Geographical information systems (GIS) and advanced geospatial technologies offers effective solutions for mapping and monitoring soil and groundwater. These tools provide accurate, cost-effective methods for estimating soil properties, detecting land degradation processes such as soil salinization and identifying potential groundwater zones. High-resolution satellite imagery, combined with machine learning, enables digital soil mapping, improving assessments of soil variability and land suitability. The adoption of these advanced technologies has revolutionized soil and groundwater assessment. Digital soil mapping enhances understanding of land resources, while remote sensing and GIS facilitate environmental conservation and sustainable agriculture. This article systematically underscores the role of these technologies in soil and groundwater management, highlighting their importance in resource sustainability.

Key words: Digital soil mapping, Geospatial technology, Groundwater mapping, Remote Sensing, Spatial variability.

Soil and groundwater, both finite and invaluable natural resources, play fundamental roles in supporting ecosystems, regulating water cycles and sustaining agricultural productivity. However, the growing global demand for raw materials, food and energy, has intensified pressure on land, resulting in resource depletion, soil degradation and groundwater depletion (Cronin, 2009). Prasad (2004) emphasized that soil degradation in India threatens food security, urging urgent measures to protect soil health and here soil survey and soil classification help in better understanding of their characteristics, constraints and potential. Effective management of these resources is essential to maintain environmental sustainability, particularly in the face of climate change and land degradation. Soil, as the foundation of all production systems, exhibits significant spatial variability of variety of soil properties depending on spatial locations. Understanding its characteristics, spatial distribution and quality is crucial for ecosystem balance (Gessler, 1996). In this regard, soil survey is a potential tool which provides a systematic and scientific understanding of different soil types, their characteristics and distribution, enabling predictions about their potential uses (Mandal and Sharma, 2005). These surveys also classify soils and offer valuable insights that enhance natural resource management.

Groundwater a vital source of irrigation and human consumption, also require careful management. In regions, where irrigation is crucial, groundwater depletion poses a significant challenge. Additionally, issues such as soil salinization and pollution from solid waste further degrade soil health, necessitating monitoring and remediation efforts. Traditional methods of assessing soil and groundwater quality, although valuable, are time consuming, labour intensive and expensive (Laake, 2000). These conventional techniques are limited in their ability to capture spatial variability of soil properties and groundwater dynamics across large areas.

Recent advancements in geospatial technologies, particularly geographical information system (GIS), remote sensing (RS) and also digital soil mapping (DSM), have revolutionized how soil and ground water are characterized, monitored and managed. These technologies allow for more efficient, precise and comprehensive approaches to natural resources management by integrating high resolution satellite imageries, with machine learning, geostatistics and advanced modelling techniques (Shrestha, 2006). The integration of RS and GIS not only

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accelerates soil and groundwater mapping processes but also enhances the detail and accuracy of the data, reducing time and cost involved (Karla *et al.,* 2010). Such advancements offer significant potential to address growing challenges related to land degradation, soil salinization and ground water depletion, while promoting sustainable resource use.

In this review article, we explore the role of advanced geospatial techniques in soil survey, RS and GIS in soil resource mapping and characterization, groundwater mapping and discuss the application in addressing the pressing issues of land degradation, resource depletion and environmental sustainability.

RS and GIS in terrain characterization

Traditionally, landform mapping relied on aerial photograph interpretation (Dent and Young, 1981). With remote sensing, more accurate resource mapping is possible (Karale *et al.,* 1988). Satellite data and GIS enable spatial analysis, aiding in erosion risk assessment, watershed characterization and soil conservation. Drainage morphometry offers insights into land resource distribution (Strahler, 1964). Topographical variations significantly influence soil variability, necessitating geomorphological understanding and field surveys (McBratney *et al.,* 2000; Velmurugan and Carlos, 2009). Satellite imagery and topographic maps help delineate physiographic variations like slope and land-cover (Speight, 1990). High-resolution satellite data improve geographic unit inventories. IRS-ID LISS-III data enhances geomorphological delineation by integrating lithology, drainage and contour information. Soil-landform units exhibit homogeneity in parent material, influencing soil-geomorphic processes (Wilson and Gallant, 2000; Hengl and Reuter, 2008). Digital Elevation Models (DEMs) enhance slope classification for soil surveys (Hammer *et al.,* 1995). DEM-derived terrain attributes effectively delineate soil boundaries (McBratney *et al.,* 2003). Integrating high-resolution satellite data, GIS and field validation improves terrain characterization and soil inventory in a toposequence (Reddy *et al.,* 2012).

RS and GIS in soil resource mapping and characterization

Soil is a vital resource requiring efficient management for sustainable agriculture. Soil mapping spatially defines soil types (Abuzar and Ryan, 2001) and high-resolution satellite data enables detailed assessment of soil distribution and challenges. Advances in technology have improved soil mapping methods (Borse *et al.,* 2018; Ingle *et al.,* 2019; Kuchanwar *et al.,* 2021). Spatial databases aid planning and development assessments using repeated satellite coverage. Satellite imagery reduces soil mapping time by 60-80% compared to manual methods (Liengsakul *et al.,* 1993). Ingle *et al.* (2018) used geostatistics and GIS-based kriging to assess soil fertility, revealing high spatial variability in organic carbon and potassium levels for site-specific management. Mondal *et al.* (2020) assessed spatial variability of available phosphorus under three landuses using geostatistics, revealing highest variability in poplar-wheat system and strong spatial dependence using nugget-sill ratio of semi-variogram. They also assessed spatial variability of Soil Organic Carbon (SOC) under three landuses (berseem, rice-wheat and poplar-wheat) using geostatistics and found highest SOC in poplar-wheat and also identified Gaussian, spherical, exponential models as best fitting semi-variogram models in respective landuse systems (Mondal *et al.,* 2021). Researchers highlight the effectiveness of satellite data Indian Remote Sensing (IRS-P6) (Velmurugan and Carlos, 2009) and IRS-P6, Linear Imaging Self-Scanning Sensor (LISS-IV) (Hiese *et al.,* 2011, Reddy *et al.,* 2012) for large-scale soil mapping. Panchromatic (PAN) merged satellite data provide detailed soil inventories (Walia *et al.,* 2010). RS and GIS are powerful tools for soil characterization (Srivastava and Saxena, 2004; Reddy *et al.,* 2008; Pareta and Pareta, 2012). GIS-based soil information supports developmental projects and agricultural research (Ramakrishnan and Guruswamy, 2009). Improved soil mapping enhances land-use planning, aiding farmers in sustainable land management (Scull *et al.,* 2003).

Role of RS and GIS in soil survey

RS and GIS have revolutionized soil surveys by providing high-precision mapping tools and detailed spatial analysis. Traditional methods are labour-intensive, whereas RS and GIS enable efficient soil characterization. High-resolution imagery, such as PAN and LISS III, is invaluable for updating cadastral maps, aiding local land management (Barnes and Eckl, 1996). Satellite images facilitate soil series delineation, improving planning and resource allocation (Karale *et al.,* 1988). RS allows large-area coverage with high spatial resolution, supporting soil-landscape relationship studies. Physiographic mapping combines topographic maps with satellite imagery, using spectral variations for classification (Velmurugan and Carlos, 2009). Global Positioning System (GPS) integration enhances soil surveys by providing precise location data, minimizing errors and improving field verification (Stombaugh *et al.,* 2002). High-resolution GPS data refines soil profile mapping and supports accurate classification (Longley *et al.,* 1999; Panhalkar, 2011).

Post-survey, GIS organizes soil databases, enabling spatial analysis and overlay with thematic layers such as landuse and hydrology (Burrough and McDonnell, 1998). GIS tools assist in land capability classification, soil resource mapping and land degradation assessment (Ekanayake and Dayawansa, 2003). Integrating RS, GPS and GIS enhances soil mapping precision and supports sustainable land management.

Prasad (2021) emphasized the significance of geospatial technologies, noting that multi-spectral and multi-temporal RS data improve accuracy, cost-effectiveness and efficiency in soil surveys. These tools

are essential for addressing soil variability, land degradation and resource management challenges.

Practical utility of RS data for micro-level planning

Geo-spatial technology is crucial for sustainable watershed management, aiding in resource mapping, monitoring and prioritization (Khan *et al.,* 2001; Gosain and Rao, 2004; Borse *et al.,* 2018; Ingle *et al.,* 2019; Kuchanwar *et al.,* 2021). RS and GIS techniques help analyze watershed morphometry (Agarwal, 1998; Biswas *et al.,* 1999) and support land-use planning. PAN merged with LISS III and IV data has been widely used for watershed characterization (Singh, 2009; Vittala *et al.,* 2010; Das *et al.,* 2012; Shanwad *et al.,* 2012). Cartosat-1 stereo data aids in DEM construction for watershed demarcation and mapping (Kumar *et al.,* 2008; Mohamed and Murthy, 2008; Sharma *et al.,* 2010; Pareta and Pareta, 2012). Summary of different satellites used in micro-level planning is listed in Table 1.

Soil suitability mapping

Soil suitability is essential for maximizing the use of available land resources to support sustainable agricultural production (Hanna *et al.,* 2000; Ekanayake and Dayawansa, 2003). The advent of high-resolution satellite imagery, coupled with GIS-based terrain analysis, has significantly expanded and improved the efficiency of soil suitability mapping. This method focuses on soil characteristics, climate, landuse and topography, with the assumption that these factors vary continuously across space (Lagacherie and McBratney, 2007). Recently, soil suitability for millets in Banka district has been done by Vimal *et al.* (2024). Karthika *et al.* (2024) used Sentinel-2 data in characterization of soil resources for sorghum suitability in Mahbubnagar, Telangana and reported that only 1.51% area was highly suitable and 33.99% area was marginally suitable due to soil limitations. The spatial data can be easily visualized and analysed within a GIS framework. Singha and Swain (2016) reviewed land suitability analysis methods, highlighting the effectiveness of integrating GIS, remote sensing, fuzzy logic and Analytic Hierarchy Process (AHP) for optimizing agricultural landuse planning. Several researchers have created soil suitability maps using multi-criteria evaluation techniques, along with Quick Bird (60 cm) and LISS-IV imagery (Ceballos-Silva and Lopez-Blanco, 2003), while (Ingle *et al.,* 2021, 2024) employed IRS-P6 LISS-III, LISS-IV satellite data for land suitability assessments of watershed for cotton depicted in Fig 1.

RS in digital soil mapping

Understanding the spatial variation of soil properties is crucial for effective soil management (Mondal *et al.,* 2024). High-resolution soil mapping is essential, as conventional methods fail to capture soil variability and require extensive sampling, making them costly and time-consuming. Digital Soil Mapping (DSM) addresses these limitations by integrating remote sensing data with statistical,

Table 1: Summary of different satellites used at micro level planning.

Satellites	Resolution (m)	Study area	Purpose	References
Sentinal-2 data	10	Mahabubnagar Rural Mandal, Mahabubnagar District, Telangana	Characterization of soil resources for sorghum suitability	Karthika *et al.* (2024)
Cartosat merged IRS-P6 LISS-III, LISS-IV	5.8	Bareli Watershed, Dhanora Block, (M.P.)	Land resources inventory	Ingle *et al.* (2019)
IRS-P6 LISS-IV	5.8	Ridhora watershed, Katol tahsil, (Maharashtra)	Soil resources inventory	Kuchanwar *et al.* (2021)
IRS-P6, LISS-III, LISS-IV	5.8	Barela village, (M.P.)	Soil resources inventory	Borse *et al.* (2018)
IRS-P6, LISS-III	23.2	Katol block, (Maharashtra)	Soil fertility assessment	Kuchanwar *et al.* (2022)
IRS-P6 LISS IV	5.8	Borgaon Manju watershed (Maharashtra)	Soil resource inventory	Reddy *et al.* (2012)
Resourcesat-1+ Cartosat-1	2.5	Mohammadabad village (Andhra Pradesh)	Soil fertility assessment	Wadodkar and Ravishankar (2011)
IKONOS	1 (PAN); 4 (NIR)	Experimental plot (Jalandhar)	Soil mapping	Raj and Koshal (2012)
WorldView-2	0.46 (PAN); 1.84 (NIR)	Nawalparasi district (Nepal)	Precision agriculture	Barala (2010)
IKONOS	1 (PAN); 4 (NIR)	Bhopalpur village (Uttar Pradesh)	Village mapping	Praveen *et al.* (2010)
Cartosat-1	2.5	Sheo tehsil (Rajasthan)	Demarcation of watershed	Tomar and Singh (2012)
IRS-P6, LISS III, LISS IV	5.8	Bandu watershed (West Bengal)	Watershed prioritization	Das *et al.* (2012)
PAN+LISS III	5.8	Pavagada Taluk, (Karnataka)	Resource management	Vittala *et al.* (2010)

geostatistical, Machine Learning (ML) and Deep Learning (DL) models to predict soil properties at unsampled locations (Hengl *et al.,* 2014; Ma *et al.,* 2019).

DSM utilizes the SCORPAN (S= Soil, C= Climate, O= Organisms, R= Relief, P= Parent material, A= Age, N= Spatial location) framework, incorporating soil samples and environmental variables to improve prediction accuracy (Batjes *et al.,* 2020). Techniques like regression kriging enhance interpolation (Wang *et al.,* 2022), while ML models outperform geostatistics in capturing non-linear relationships (Taghizadeh-Mehrjardi *et al.,* 2021). DL, with its multilayer neural networks, excels in large-scale mapping by extracting complex patterns from remote sensing data (Behrens *et al.,* 2018; Padarian *et al.,* 2019). Prediction uncertainty is evaluated using prediction intervals (Wadoux *et al.,* 2020).

DSM is widely used to map soil properties such as moisture (Das *et al.,* 2023; Mondal *et al.,* 2024), pH (Pahlavan-Rad and Akbarimoghaddam, 2018), electrical conductivity (Ranjbar and Jalali, 2016) and organic carbon (Mponela *et al.,* 2020). Global-scale digital maps like the Global-Soil-Map aid in soil characterization (Arrouays *et al.,* 2014; Poggio *et al.,* 2021). In India, national and regional DSM initiatives have mapped soil texture, pH, SOC and micronutrients, supporting site-specific nutrient management and sustainable agriculture (Dharumarajan *et al.,* 2017; Santra *et al.,* 2017; Reddy *et al.,* 2021; Dasgupta *et al.,* 2023).

RS in soil salinity mapping

Soil salinity is a major land degradation issue, especially in arid, semi-arid and sub-humid regions (Dehni and Lunis, 2012). It results from natural processes like mineral weathering and seawater intrusion, but human activities, particularly poor irrigation practices, exacerbate the problem (El-Rawy *et al.,* 2024). Climate change is expected to intensify soil salinity, further threatening agriculture (Lekka *et al.,* 2024).

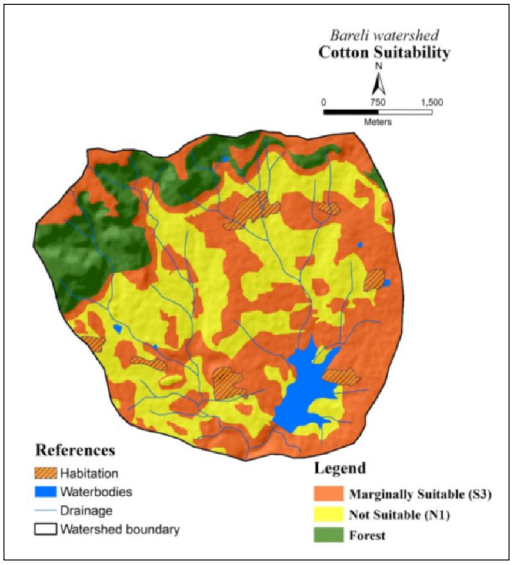


Fig 1: Land suitability map for cotton cultivation.

Traditional soil salinity assessment methods are costly and time-consuming (El-Rawy *et al.,* 2024), necessitating advanced geospatial technologies. Earth observation (EO) and RS provide efficient, large-scale soil salinity mapping (Dehni and Lunis, 2012). Satellite sensors like Landsat Thematic Mapper (TM), Enhanced Thematic Mapper (ETM), Operational Land Imager (OLI) and IRS LISS-III integrate with GIS for accurate mapping. Spectral indices such as the Salinity Index (SI) and Normalized Difference Salinity Index (NDSI) are commonly used for soil salinity classification. Recent advancements in ML and DL enable digital soil salinity mapping by incorporating topographic and hyperspectral RS data. Google Earth Engine (GEE) is increasingly used for soil salinity analytics, with studies demonstrating the effectiveness of ML models like random forest and support vector machine (Aksoy *et al.,* 2022). Artificial Neural Network (ANN) models help analyze soil-water-salt dynamics (Zickus *et al.,* 2002; Rahouma and Aly, 2020), while Convolution Neural Network (CNN)-based DL models enhance soil salinity mapping (El-Rawy *et al.,* 2024). Integrating geospatial technology with ML and DL facilitates efficient, large-scale soil salinity monitoring, supporting sustainable agricultural management.

RS in detection, monitoring and mapping of dumping/waste disposal sites

Accurate identification and mapping of illegal dumping sites are essential to mitigate environmental hazards triggered by climate change (Fraternali *et al.,* 2024). Poorly managed sites emit greenhouse gases, degrade air quality and cause leachate contamination, threatening ecosystems and human health (Alberti *et al.,* 2022). Traditional on-site inspections are costly and time-consuming, but RS offers a cost-effective solution for monitoring landfill sites (Fraternali *et al.,* 2024).

Drone-based RS enables detailed local-scale mapping, while satellite RS provides large-area coverage. EO satellites, such as Sentinel and Landsat, capture multispectral and hyperspectral imagery, offering high spatial and temporal resolution for landfill monitoring (Jutz and MilagroPerez, 2018). Landsat-8 and Landsat-9 with OLI and Thermal Infrared Sensors (TIRS) and Sentinel-1's microwave data, are widely used for detecting land-cover changes, stressed vegetation and surface temperatures (Gill *et al.,* 2019). India's IRS series and European Space Agency's (ESA's) Sentinel-2 provide free high-resolution optical data for large-scale monitoring. Meanwhile, World View and GeoEye-1 offer very high-resolution images suited for small-scale urban waste sites (Fraternali *et al.,* 2024).

RS-derived indices like Normalized Difference Vegetation Index (NDVI) and Soil Adjusted Vegetation Index (SAVI) detect poor vegetation health linked to landfill presence, while Land Surface Temperature (LST) is used for identifying heat anomalies in dumping areas (Cadau *et al.,* 2013). Multi-factor analysis integrates geospatial data to assess environmental impacts (Abou El-Magd *et al.,* 2022).

Techniques like feature extraction, object classification and computer vision enhance landfill site detection and mapping (Seror and Portnov, 2018; Nazari *et al.,* 2020).

RS and geospatial technology in groundwater mapping

Groundwater, constituting 26% of Earth's freshwater, is vital for drinking, agriculture and industry (Arulbalaji *et al.,* 2019). Its significance is higher in arid, semi-arid and mountainous regions with scarce surface water (Algaydi *et al.,* 2019). Groundwater meets 40% of agricultural, 30% of industrial and half of the drinking water needs globally (Famiglietti, 2014). However, traditional assessment methods are costly, time-consuming and fail to capture key sub-surface dynamics (Kumar and Krishna, 2018; Acharya *et al.,* 2019). Geospatial technologies, particularly RS and GIS, provide cost-effective solutions for mapping groundwater potential and scarcity zones (Rampheri *et al.,* 2023; Bennett, 2025). RS offers critical hydrological data like soil moisture, vegetation conditions and land surface displacement (Hilbich *et al.,* 2022). Satellite and drone-based RS enhance groundwater storage assessment (Adams *et al.,* 2022), aiding in delineating groundwater zones and monitoring fluctuations (Ni *et al.,* 2018; Akhter *et al.,* 2021; Sreekanth *et al.,* 2023). In India, integrating geospatial and geophysical techniques with RS data identified groundwater potential in Dehradun using the Weighted Index Overlay method and 2D Electrical Resistivity Tomography (Gyeltshen *et al.,* 2020). RS-derived elevation models further aid in groundwater storage analysis (Massoud *et al.,* 2021). Multispectral and hyperspectral RS helps assess land surface and soil spectral properties influencing groundwater occurrence (Kumar *et al.,* 2022). While RS supports large-scale monitoring, limitations like sensor resolution and atmospheric variability necessitate refined methodologies to improve accuracy in groundwater mapping.

CONCLUSION

The integration of GIS and remote sensing along with other advanced geospatial technology has made revolution in sustainable management of soil and groundwater by providing precise, scalable and cost-effective solutions. These advanced geospatial techniques provide critical insights into soil variability, salinity levels and groundwater availability, enabling sustainable resource management practices. The use of high-resolution satellite data coupled with machine learning techniques, significantly improves the efficiency and accuracy of soil and groundwater mapping and their sustainable management. Thus, such innovative technological approaches make it easier to address environmental challenges such as soil degradation and water scarcity. Since global demands for these two important natural resources continue to grow, these advanced technologies will definitely play a vital role in ensuring their sustainable uses as well as their preservation for future generations.

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Conflict of interest

The authors declare no conflict of interest.

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