Scottish International Conference on

Multidisciplinary research and Innovation (SICMRI 2026)

REMOTE SENSING AND GIS-BASED ASSESSMENT OF SOIL SALINITY IN IRRIGATED LANDS: SCIENTIFIC AND METHODOLOGICAL FOUNDATIONS

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Abstract

Soil salinity is a major land-degradation concern in irrigated agricultural systems, particularly in arid and semi-arid regions where high evaporation, inappropriate irrigation practices, shallow groundwater, and inadequate drainage can contribute to salt accumulation. This thesis examines the scientific and methodological foundations of assessing soil salinity through remote sensing and geographic information systems (GIS). It discusses the potential of Sentinel-2 and Landsat satellite imagery, spectral information, field-based electrical conductivity measurements, and spatial analysis for identifying salinity patterns and supporting agricultural land management. Particular attention is given to the limitations of satellite-based assessment, including the influence of soil moisture, vegetation cover, soil texture, and seasonal conditions on spectral responses. The thesis proposes an integrated assessment framework in which remotely sensed information is calibrated and validated using field and laboratory measurements. The study is based on a review of scientific literature and methodological synthesis; it does not claim original field measurements or experimentally derived results.

Keywords: soil salinity, irrigated lands, remote sensing, geographic information systems, GIS, Sentinel-2, Landsat, electrical conductivity, spatial analysis, land degradation.

1. Introduction

Irrigated agriculture plays an essential role in food production and rural economic development, particularly in regions where precipitation is insufficient to meet crop water requirements. However, the long-term productivity of irrigated land depends on maintaining appropriate soil and water conditions. Soil salinity is among the major challenges affecting irrigated agricultural systems because excessive concentrations of soluble salts can interfere with plant water uptake, restrict crop development, and reduce the productive capacity of agricultural land.

Salinity development is influenced by several interacting factors, including climate, irrigation-water quality, groundwater depth, soil characteristics, drainage efficiency, and agricultural management practices. In arid and semi-arid environments, high evaporation rates may facilitate the accumulation of salts near the soil surface, particularly where drainage is insufficient. Consequently, identifying the spatial distribution and temporal dynamics of salinity is important for developing effective land-management and soil-conservation strategies.

Conventional soil-salinity assessment relies on field sampling and laboratory analysis. Measurements of soil electrical conductivity provide important information about soluble salts and are widely used in salinity investigations. Nevertheless, field sampling alone may be time-consuming and expensive when large agricultural areas must be assessed repeatedly. Moreover, point-based measurements may not fully represent the spatial variability of soil conditions unless the sampling design adequately captures differences across the landscape.

Remote sensing offers complementary capabilities by providing repeated observations over extensive geographical areas. Satellite imagery enables researchers to examine spatial patterns, compare

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observations collected at different times, and identify locations requiring further field investigation. When combined with GIS, remotely sensed data can be integrated with soil maps, irrigation infrastructure, topographic information, and laboratory measurements.

Wang et al. (2024) reviewed advances in the quantitative assessment of soil salinity using remote sensing and machine-learning algorithms. Their review highlights the potential of integrating spectral information and computational models while emphasizing that model performance depends on environmental conditions, data quality, and methodological choices [1].

Despite these advances, satellite imagery does not measure soil salt concentration directly under all conditions. Spectral responses can be affected by soil moisture, texture, surface crusting, vegetation cover, and seasonal changes. Therefore, reliable assessment requires a methodological framework that combines remote sensing with field observations and appropriate validation procedures.

Research aim

The aim of this thesis is to examine the scientific and methodological foundations of assessing soil salinity in irrigated lands using remote sensing and GIS and to identify practical approaches for improving the reliability of spatial assessment.

Research objectives

1. To examine the principal environmental and agricultural factors contributing to soil salinity in irrigated areas.
2. To evaluate the potential applications of Sentinel-2 and Landsat imagery in salinity assessment.
3. To describe a methodological framework for integrating satellite observations with field and laboratory measurements.
4. To explain the role of GIS in spatial analysis, salinity mapping, and agricultural land management.
5. To identify the main limitations and future prospects of remote-sensing-based soil-salinity assessment.

Research methods

The thesis uses a literature-review and methodological-synthesis approach. The principal methods include scientific literature analysis, comparative assessment of remote-sensing approaches, examination of spectral indicators, and synthesis of procedures for spatial data integration and validation. No original field experiment or newly measured dataset is claimed.

2. Main Body

2.1. Soil Salinization in Irrigated Agricultural Systems

Soil salinization occurs when soluble salts accumulate in the soil to levels that adversely affect soil properties and plant growth. In irrigated agricultural systems, salinity is commonly associated with the interaction of climatic conditions, irrigation practices, groundwater dynamics, soil characteristics, and drainage performance. These factors may vary considerably within a single agricultural district, producing substantial spatial differences in salinity severity.

In arid and semi-arid environments, evaporation can concentrate dissolved salts in the soil solution. When groundwater containing dissolved salts approaches the root zone, capillary movement may transport salts upward. If drainage and leaching are insufficient, salts can accumulate over time.

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Irrigation water quality and the suitability of irrigation management practices also influence the salinity balance of agricultural soils.

The consequences of salinity extend beyond the presence of visible salt deposits. Elevated concentrations of soluble salts can reduce the ability of plants to absorb water, even where soil moisture appears adequate. Certain ions may also cause specific toxicity or nutrient imbalances. The extent of these effects depends on crop tolerance, salt composition, soil properties, and the stage of plant development.

From a monitoring perspective, soil salinity should therefore be considered a spatially variable environmental process rather than a uniform property of an entire field. Field measurements provide essential information about actual soil conditions, while satellite imagery offers a means of identifying spatial patterns and directing additional sampling.

Wang et al. [1] emphasize the growing role of remote sensing and machine learning in the quantitative assessment of soil salinity. Their review also identifies continuing challenges associated with differences in environmental conditions, sampling strategies, model development, and validation. These findings support the use of integrated assessment frameworks rather than reliance on a single spectral indicator.

2.2. Satellite Data Sources for Soil Salinity Assessment

Satellite remote sensing provides repeated observations of the Earth's surface at different spatial, spectral, and temporal resolutions. For irrigated agricultural areas, Sentinel-2 and Landsat are particularly relevant because they provide multispectral imagery suitable for investigating soil surfaces and vegetation conditions.

Sentinel-2 imagery. The Sentinel-2 mission provides multispectral observations that can support agricultural monitoring, vegetation analysis, and the examination of exposed soil surfaces. Its relatively detailed spatial information is useful for distinguishing spatial variation within agricultural landscapes. The availability of multiple spectral bands also enables the calculation of vegetation indices and selected salinity-related indicators.

Landsat imagery. Landsat provides a long historical record of multispectral observations. This makes it useful for examining changes in agricultural landscapes over extended periods, provided that differences in sensors, processing methods, acquisition dates, and spatial resolution are appropriately considered.

The selection of satellite data should reflect the research objective. If the purpose is to map salinity-related patterns at a particular time, image quality and the availability of suitable field observations are central considerations. If the objective is to investigate temporal change, consistency between observation dates and the comparability of the selected images become especially important.

Gerardo and de Lima [2] investigated Sentinel-2 imagery for assessing soil salinity in irrigated rice fields in Portugal. Their study combined vegetation indices, which capture the indirect effects of salinity on crop growth, with indicators derived from visible, near-infrared, and shortwave-infrared bands. This research illustrates the value of combining different spectral approaches rather than treating a single index as a definitive measure of soil salinity.

2.3. Spectral Characteristics and Salinity-Related Indicators

Remote sensing-based soil salinity assessment relies on the relationship between surface characteristics and reflected electromagnetic radiation. Salt-affected soils may exhibit distinctive spectral

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responses under certain conditions, particularly where salts are visible on the soil surface. However, these responses are not unique to salinity and may overlap with those associated with soil texture, moisture, organic matter, surface roughness, and other factors.

For this reason, spectral indicators should be interpreted within the environmental context of the study area. Three broad categories of information are particularly relevant:

1. Directly observed surface characteristics: spectral responses from exposed soil, including potential salt crusts.
2. Vegetation-related indicators: changes in vegetation reflectance that may indirectly reflect the effects of salinity on plant growth.
3. Environmental covariates: factors such as topography, soil properties, groundwater conditions, and temperature that can help explain spatial patterns.

A comprehensive review by Gojiya et al. [3] discusses remote sensing and GIS applications in soil salinity analysis, including spectral indices, vegetation indicators, regression approaches, neural networks, and satellite data. The review highlights that the suitability of a particular method depends on the study context and the extent of vegetation cover.

The Normalized Difference Vegetation Index (NDVI), for example, can help identify differences in vegetation condition that may be associated with salinity. However, NDVI does not measure soil salinity directly. A low value may also result from water stress, nutrient deficiency, crop maturity, sparse vegetation, or exposed soil. Consequently, vegetation indices should be treated as supporting indicators rather than independent measurements of soil salt concentration.

2.4. Field Measurements and Laboratory Validation

Field observations are essential for evaluating whether satellite-derived patterns correspond to actual soil salinity conditions. A robust assessment framework combines remote sensing with soil sampling and laboratory measurements.

The electrical conductivity of soil extracts is widely used to characterize soluble salts. The method of measurement must be reported clearly because electrical conductivity values depend on the soil-to-water ratio, extraction procedure, sample preparation, and measurement conditions. Electrical conductivity measured in a saturated soil-paste extract is commonly denoted as ECe, while other procedures may produce values that are not directly interchangeable with ECe.

A field sampling plan should account for spatial variation in soil type, topography, irrigation conditions, and land use. Sampling only easily accessible locations may produce biased results if the selected points do not represent the full range of conditions in the study area.

A suitable validation procedure includes the following steps:

- Select sampling locations that represent the major environmental and soil conditions within the study area.
- Record the geographical coordinates and relevant site characteristics of each sample.
- Collect and analyze soil samples using a consistent, documented laboratory procedure.
- Match field measurements with satellite observations that are temporally appropriate for the research objective.
- Reserve independent samples for evaluating model performance rather than using every sample to develop the model.

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The temporal relationship between field sampling and satellite acquisition is important. Soil moisture, irrigation, rainfall, and surface conditions may change rapidly, so measurements collected substantially later than the satellite observation may not accurately represent the conditions present when the image was acquired.

Field validation also helps distinguish between a map that shows general spectral patterns and a map that provides defensible quantitative estimates of soil salinity. Without independent validation, the accuracy of a salinity map should not be assumed.

2.5. GIS-Based Spatial Analysis and Mapping

Geographic information systems provide a framework for integrating remote sensing observations with field measurements and other spatial datasets. GIS enables researchers to organize, analyze, visualize, and compare information collected from different sources.

A GIS-based soil salinity assessment may incorporate:

- satellite-derived spectral indicators;
- laboratory measurements of soil electrical conductivity;
- soil type and soil-property maps;
- elevation and terrain information;
- groundwater and drainage information, where available;
- irrigation infrastructure and agricultural field boundaries.

Before these datasets are combined, their coordinate systems, spatial resolution, acquisition dates, and data quality should be checked. Differences in spatial resolution can affect the results of analysis, particularly where small agricultural fields or narrow drainage features are involved.

GIS can also be used to produce thematic maps that distinguish areas with different estimated salinity levels. The classification thresholds should be based on an explicitly stated scientific or management criterion, and the uncertainty of the underlying estimates should be acknowledged.

Temporal GIS analysis can help compare maps from different years or seasons. Such comparisons may identify locations where salinity-related indicators have changed, although changes in imagery, crop cover, moisture, or processing methods must be ruled out before interpreting these differences as actual soil salinization or reclamation.

The principal value of GIS is therefore not simply the production of maps. It is the integration of heterogeneous evidence into a spatial framework that supports interpretation, further field investigation, and agricultural land-management decisions.

2.6. Machine Learning for Quantitative Soil Salinity Mapping

Machine-learning methods can be used to model relationships between field-measured soil salinity and satellite-derived or environmental variables. Depending on the research objective and available data, methods such as Random Forest, support vector regression, and gradient-boosting algorithms may be considered.

A typical modelling workflow includes data preparation, selection of explanatory variables, model training, validation, and spatial prediction. Potential explanatory variables may include reflectance values from selected spectral bands, salinity-related indices, vegetation indicators, terrain characteristics, and other environmental information.

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The suitability of a model depends on the quality and representativeness of the training data. A complex algorithm cannot compensate for inaccurate laboratory measurements, insufficient sampling, or strong differences between the sampled locations and the areas where predictions are made.

Wang et al. [1] reviewed studies published between 2016 and 2023 and reported that Landsat was frequently used in remote sensing-based soil salinity research. Their review also found that prediction performance varied among environmental settings and that the addition of more explanatory variables did not necessarily improve model accuracy. These findings highlight the importance of selecting variables based on scientific reasoning and evaluating models with independent data.

For quantitative modelling, common evaluation metrics include the coefficient of determination (\(R^2\)), root mean square error (RMSE), and mean absolute error (MAE).

$$RMSE=\sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i-\hat{y}_i)^2}$$

$$MAE=\frac{1}{n}\sum_{i=1}^{n}|y_i-\hat{y}_i|$$

Here, \(y_i\) represents the observed soil salinity value, \(\hat{y}_i\) represents the predicted value, and \(n\) is the number of validation observations.

RMSE gives greater weight to larger prediction errors, while MAE represents the average absolute difference between observed and predicted values. Both metrics should be reported in units consistent with the target variable. The \(R^2\) statistic describes the proportion of variation explained by a model under the evaluation framework used, but it should not be interpreted as a complete measure of prediction quality.

These metrics should only be reported as empirical findings when actual observations and predictions are available. In a literature-based thesis such as this one, they are presented as recommended evaluation procedures rather than as results obtained from a new experiment.

2.7. Methodological Limitations and Future Prospects

Despite substantial advances, remote sensing-based soil salinity assessment faces several methodological challenges.

First, vegetation cover can obscure the spectral response of the soil surface. During periods of dense crop growth, satellite observations may predominantly reflect vegetation rather than the underlying soil. In such situations, vegetation indicators may provide indirect evidence of salinity-related stress, but this relationship can be influenced by many other factors.

Second, soil moisture and recent irrigation can alter surface reflectance. Comparisons between images acquired under different moisture conditions may therefore produce apparent changes that do not correspond to changes in salt concentration.

Third, salinity varies with soil depth. Surface observations cannot automatically establish the salinity conditions of the entire crop root zone. This limitation is particularly important where salts accumulate below the visible surface or where groundwater contributes to the salinity of deeper soil layers.

Fourth, model transferability remains a concern. A model developed in one region may perform poorly elsewhere because of differences in soil composition, climate, crop type, management practices, or satellite acquisition conditions. Independent validation is therefore essential before applying a model to a new location.

Future research can address these challenges by integrating multispectral imagery with field measurements, soil information, groundwater observations, and additional remote sensing data where

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appropriate. Time-series analysis may help distinguish seasonal crop development from persistent salinity-related patterns. Machine-learning models may improve spatial prediction when supported by representative field data and transparent validation procedures.

For irrigated agricultural regions, including those in Uzbekistan, this integrated approach could support more systematic soil monitoring and help identify areas requiring detailed investigation. Nevertheless, the suitability of any specific method should be established using local environmental conditions and field evidence rather than assumed from results obtained elsewhere.

3. Conclusion

Remote sensing and geographic information systems offer complementary capabilities for assessing soil salinity in irrigated agricultural lands. Sentinel-2 and Landsat imagery can provide repeated observations over extensive areas, while GIS supports the integration of spectral data, soil measurements, and environmental information into spatially explicit assessments.

The literature indicates that reliable salinity mapping requires more than the selection of a satellite sensor or spectral index. The results depend on image quality, soil and vegetation conditions, representative field sampling, appropriate modelling, and independent validation. Vegetation indices may reveal indirect effects of salinity on crop growth, whereas exposed-soil indicators may provide information about surface conditions. Neither approach should be interpreted as a universal substitute for laboratory measurements.

An integrated workflow combining satellite imagery, field-based electrical conductivity measurements, GIS analysis, and appropriately validated statistical or machine-learning models provides a scientifically defensible basis for assessing soil salinity. Such a framework can support the identification of areas requiring additional investigation, the monitoring of spatial changes, and the planning of agricultural land-management interventions.

Future research should prioritize locally validated methods, transparent reporting of uncertainty, and the integration of surface observations with information about the crop root zone. These priorities are particularly relevant to irrigated agriculture in arid and semi-arid environments, where sustainable soil management is essential for maintaining long-term agricultural productivity.

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