

# Geospatial Assessment and Reclamation Dynamics of Salt-Affected Soils in Uttar Pradesh

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## 1. Introduction

### 1.1 Background and Significance

Soil salinity and sodicity are major land degradation processes that threaten agricultural sustainability, soil health, and food security. Salt-affected soils modify physicochemical properties, disrupt plant-water relations, and reduce nutrient availability, thereby constraining crop productivity. In India, these soils occupy nearly 6.7 million hectares and are unevenly distributed, with large concentrations in the Indo-Gangetic plains. Uttar Pradesh contains a significant share, dominated by sodic and saline-sodic soils characterized by high pH and elevated exchangeable sodium percentage. Excess sodium induces clay dispersion, structural degradation, and reduced hydraulic conductivity, severely limiting infiltration and crop establishment [1].

### 1.2 Overview of Agriculture in Uttar Pradesh

Uttar Pradesh is central to India's food security, contributing substantially to the production of rice, wheat, sugarcane, and pulses. Fertile alluvial soils and extensive irrigation networks have supported highly intensive systems, particularly the rice-wheat rotation. However, prolonged irrigation, poor drainage, canal seepage, and marginal-quality groundwater have accelerated secondary salinization and waterlogging. Canal command areas, especially within the Sharda Sahayak system, exhibit strong interactions between shallow groundwater tables and sodicity development. These hydro-edaphic processes have intensified soil degradation, reduced crop productivity, and heightened production risks for farming communities across affected regions [2].

### 1.3 Problem Statement

Despite the availability of established reclamation technologies, including gypsum amendments, subsurface drainage, and salt-tolerant cultivars, extensive cultivated areas in Uttar Pradesh remain affected by salinity and sodicity. A major limitation arises from inconsistencies among datasets, diagnostic thresholds, and mapping approaches, which constrain reliable state-scale assessment and inter-study comparability [3]. Additionally, many investigations remain localized, restricting the development of integrated, spatially explicit frameworks required for regional planning, resource prioritization, and long-term monitoring. These challenges highlight the need for harmonized geospatial diagnostics and multi-scale analyses linking soil properties, degradation drivers, and reclamation outcomes. This study contributes by integrating multi-source geospatial datasets with field-validated soil diagnostics to establish a scalable framework for regional salinity assessment.

## 1.4 Objectives of the Study

This study aims to:

- Assess the extent and spatial distribution of salt-affected soils in Uttar Pradesh using geospatial datasets and secondary sources.
- Characterize the dominant physicochemical properties of problem soils across major agro-climatic zones.
- Examine key natural and anthropogenic drivers contributing to soil salinity and sodicity.
- Evaluate reclamation strategies and derive management implications from documented case studies.

## 1.5 Scope and Limitations

The analysis focuses on salt-affected agricultural landscapes of Uttar Pradesh, particularly the Indo-Gangetic plains and major canal command areas. The study primarily utilizes secondary datasets integrated with geospatial techniques and targeted validation. Although satellite-based assessments enhance spatial coverage, uncertainties related to spectral variability and classification thresholds are recognized. The findings provide regional-scale insights relevant for land management and policy planning.

This paper is structured into six sections covering the study background, literature synthesis, study area description, methodology, case-based insights, and concluding implications.

## 2. Literature Review

### 2.1 Concept and Types of Salt-Affected Soils

Soil salinity refers to the accumulation of soluble salts in the root zone, mainly chlorides and sulphates of sodium, calcium, and magnesium, while sodicity denotes excessive exchangeable sodium on the soil exchange complex [4]. Saline soils are defined by  $EC_e > 4 \text{ dS m}^{-1}$ ,  $ESP < 15$ , and  $pH < 8.5$ , where crop limitations arise primarily from osmotic stress. Sodic soils, characterized by  $ESP > 15$  and high pH, are dominated by structural degradation processes, including clay dispersion, poor aggregation, and reduced infiltration. Saline-sodic soils exhibit both high  $EC_e$  and  $ESP$ ; without calcium amendments, leaching often converts them into strongly sodic soils [5]. In irrigated Indo-Gangetic regions, sodic soils are more widespread due to groundwater quality, bicarbonate-rich irrigation waters, and drainage constraints.

### 2.2 Global Status of Salt-Affected Soils

Soil salinization is a major global land degradation process affecting agricultural productivity and ecosystem stability. Approximately 1.3-1.4 billion hectares worldwide are impacted by salinity and sodicity, including large areas of cropland. Salt-affected soils are most prevalent in arid and semi-arid regions where evapotranspiration exceeds precipitation. Significant affected zones occur in Australia, Central Asia, and the Middle East, northern China, and the Americas [6]. Climate change, freshwater scarcity, and irrigation intensification are expected to accelerate salinity expansion, estimated at nearly 2 million hectares annually.

### 2.3 Soil Salinity in India

India hosts one of the world's largest extents of salt-affected soils, estimated at about 6.7 million hectares, distributed across both coastal and inland regions. Sodic soils constitute a dominant share, with Gujarat, Uttar Pradesh, Rajasthan, Maharashtra, and West Bengal accounting for most affected areas. Salinity

development is closely associated with irrigation practices, groundwater quality, canal seepage, and inadequate drainage. Although significant areas have been reclaimed through gypsum amendments, salt-tolerant cultivars, and improved water management, large tracts remain degraded [7]. Recent assessments highlight the need for updated spatial inventories and integrated soil-water monitoring frameworks [8].

## 2.4 Previous Studies on Soil Salinity in Uttar Pradesh

Numerous studies have examined salinity and sodicity dynamics across Uttar Pradesh's Indo-Gangetic canal commands, identifying strong interactions among irrigation, shallow groundwater, and inadequate drainage. Spatial analyses in the Sharda Sahayak system reveal extensive waterlogging and sodicity driven by hydrological controls on salt accumulation. Empirical findings link soil organic carbon with key sodicity indicators (pH, ESP, SAR), indicating progressive degradation. Modelling of ESP-SAR relationships has strengthened predictive monitoring. Institutional studies confirm.

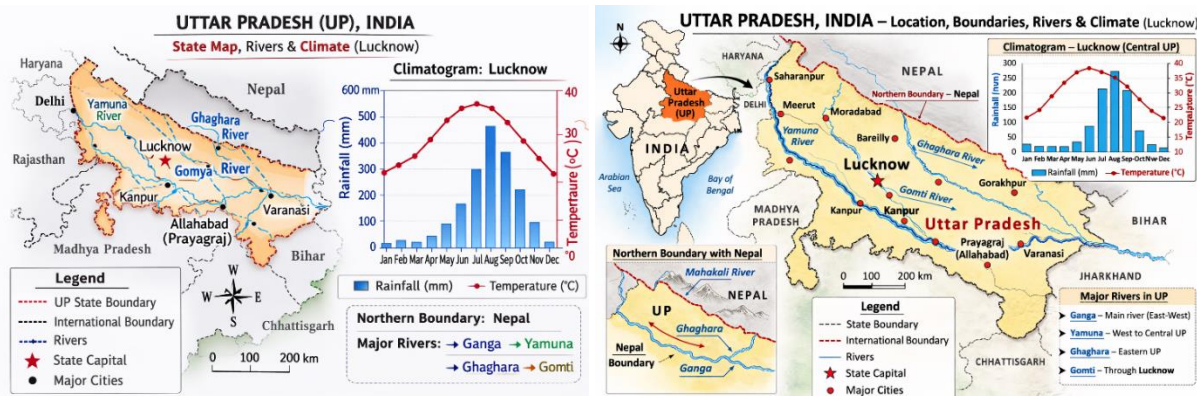
## 2.5 Knowledge Gaps Identified

Despite considerable research progress, important gaps remain in understanding salinity dynamics at broader spatial scales. Many studies are localized and vary in sampling depth, diagnostic thresholds, and temporal coverage, restricting the development of consistent state-wide assessments [11]. Differences in mapping approaches and spectral interpretations further complicate comparability. Limited integration of remote sensing with systematic ground validation may lead to uncertainty in estimating salt-affected extents. Additionally, investigations linking biophysical salinity indicators with socio-economic factors, technology adoption, and reclamation sustainability remain limited [12]. These limitations underscore the need for harmonized geospatial diagnostics and integrated monitoring frameworks.

## 3. Study Area: Uttar Pradesh

### 3.1 Geographical Location and Climate

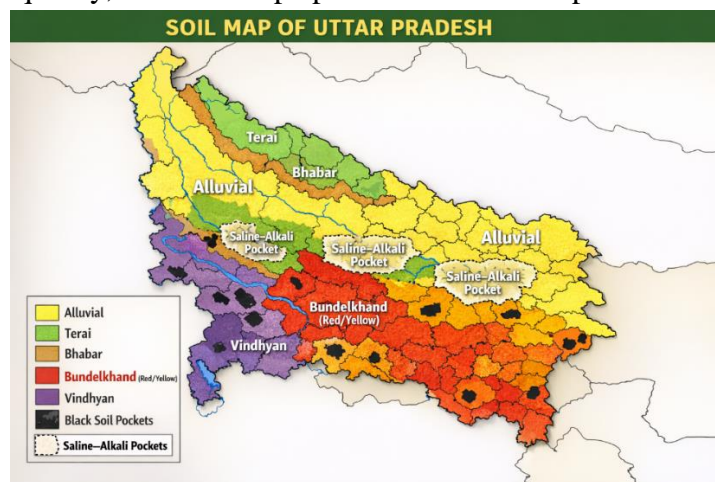
Uttar Pradesh is situated in northern India between latitudes 23°52'N and 30°24'N and longitudes 77°03'E and 84°39'E, covering about 240-243 thousand km<sup>2</sup> [13]. The state largely forms part of the Indo-Gangetic alluvial plain shaped by the Ganga, Yamuna, and their tributaries, while the Vindhyan highlands and Bundelkhand plateau mark its southern boundary. The climate is tropical monsoon with hot summers, a southwest monsoon season, and cool winters. Annual rainfall ranges from 800 to 1,200 mm, showing a pronounced east-west gradient [14]. Climatic variability strongly influences soil moisture dynamics, leaching processes, groundwater behaviour, and salinity risks.



**Figure 1.** Geographic overview of Uttar Pradesh showing boundaries, neighboring regions, major rivers and Lucknow’s climatogram.

### 3.2 Major Soil Types of Uttar Pradesh

Alluvial soils dominate Uttar Pradesh, covering nearly 70-80% of the state’s geographical area. Formed from fluvial deposits, these soils range from sandy loam to clay loam textures and are generally fertile, supporting intensive agriculture. However, saline-alkali (usar/reh) soil inclusions are widespread, particularly in poorly drained and canal-irrigated regions [15]. Other major soil groups include coarse-textured Bhabar soils, fine-textured Terai soils prone to waterlogging, and red-yellow soils of Bundelkhand and Vindhyan zones. The distribution of problem soils is largely controlled by hydrological conditions, groundwater quality, and landscape position rather than parent material alone [16].



**Figure 2.** Thematic soil map of Uttar Pradesh showing the distribution of major soil groups and saline-alkali pockets.

### 3.3 Irrigation Practices and Canal Networks

Uttar Pradesh has one of India’s largest irrigated areas, sustained by extensive canal networks, tube wells, and groundwater systems. Major canals, including the Upper Ganga, Lower Ganga, Sharda Sahayak, and Yamuna systems, support intensive agriculture across the plains. Despite productivity gains, prolonged canal irrigation and inadequate drainage have contributed to rising groundwater tables, waterlogging, and secondary salinization. Canal seepage and the use of marginal-quality groundwater further accelerate sodicity development, particularly in low-relief regions. The Sharda Sahayak Canal Command is among the most salinity-prone areas, characterized by shallow water tables and poor drainage [17].

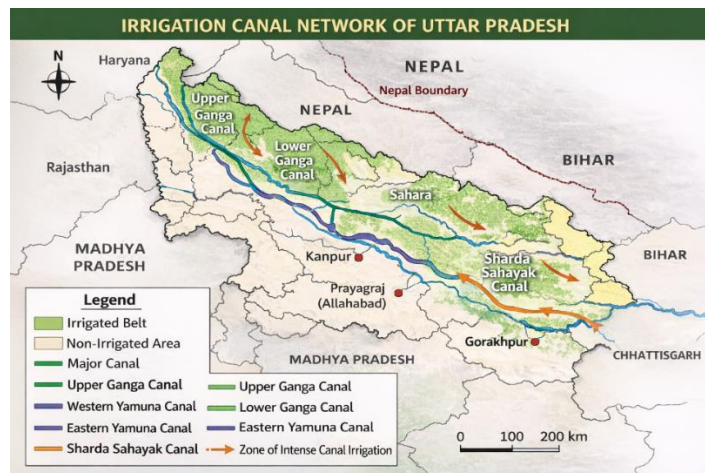


Figure 3. Irrigation canal network of Uttar Pradesh.

### 3.4 Regions Prone to Salinity and Waterlogging

Salt-affected soils in Uttar Pradesh are estimated at about 1.37 million hectares, primarily concentrated in the Indo-Gangetic alluvial plains under canal irrigation and high water-table conditions. Districts including Rae Bareli, Unnao, Hardoi, Prayagraj, and Pratapgarh exhibit extensive sodic and saline-sodic soils linked to poor drainage and prolonged irrigation. In western and central regions, excessive irrigation has produced localized salinity and alkalinity patches (usar lands) [18], while Terai and eastern areas frequently face waterlogging due to heavy rainfall and low relief. These hydro-edaphic conditions constrain crop productivity and complicate reclamation efforts, particularly under shallow groundwater tables [19].

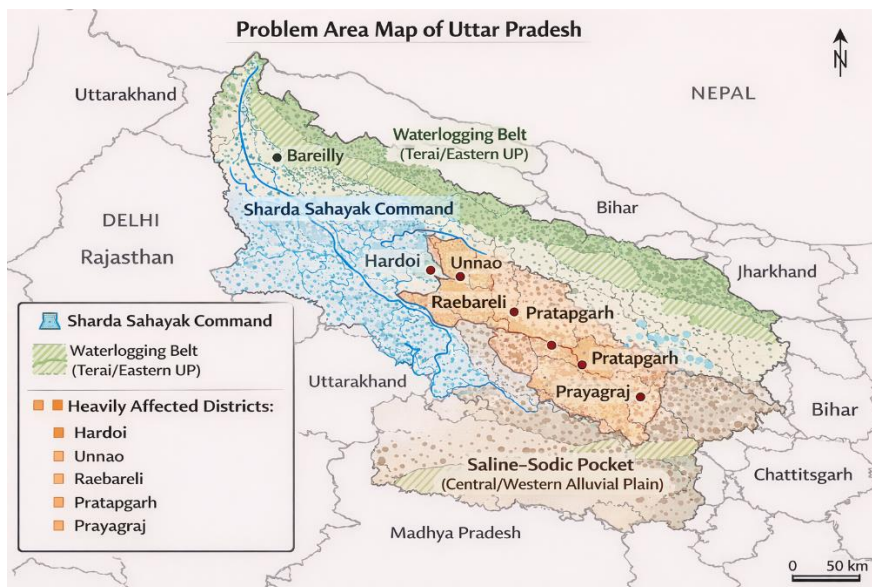


Figure 4. Problem area map of Uttar Pradesh showing major zones affected by waterlogging and saline-sodic soils.

## 4. Materials and Methods

This study employed an integrated framework combining secondary datasets, field validation, laboratory analysis, and geospatial modelling to assess soil salinity and sodicity across selected regions of Uttar Pradesh.

## 4.1 Data Sources

The analysis relied primarily on secondary data obtained from established institutional repositories. Soil resource information and salinity inventories were compiled from ICAR-CSSRI reports, NBSS&LUP soil maps, and published literature. Groundwater quality parameters were derived from Central Ground Water Board (CGWB) datasets and related hydrogeological assessments [20]. Satellite imagery comprised multi-temporal Sentinel-2 Level-2A and Landsat-8/9 datasets (2024-2025), selected to represent dry-season conditions conducive to salinity detection. Ancillary spatial layers included district boundaries, canal networks, and land use/land cover (LULC) datasets sourced from national geospatial portals [21].

## 4.2 Sampling Design and Site Selection

To support remote sensing interpretation, targeted field validation was conducted across representative salinity hotspots in western, central, and Bundelkhand regions of Uttar Pradesh. Sampling locations were selected using stratified purposive sampling within previously identified salt-affected mapping units [22]. A total of 45 soil sampling sites were investigated. Geographic coordinates were recorded for spatial referencing, ensuring consistency with GIS-based analyses. Sampling depth intervals were defined to capture vertical variability in salinity and sodicity dynamics.

## 4.3 Soil Sampling and Laboratory Analysis

Soil samples were collected at three depth intervals: 0-15 cm, 15-30 cm, and 30-60 cm, following standard ICAR-CSSRI protocols [23]. Composite samples were prepared to minimize local heterogeneity.

Laboratory analyses focused on key diagnostic indicators of salinity and sodicity:

- Soil reaction (pH)
- Electrical conductivity of saturation extract (EC<sub>e</sub>)
- Exchangeable sodium percentage (ESP)
- Sodium adsorption ratio (SAR)

Exchangeable cations (Ca<sup>2+</sup>, Mg<sup>2+</sup>, Na<sup>+</sup>, K<sup>+</sup>) were determined using ammonium acetate extraction, while soil organic carbon (SOC) was measured via Walkley-Black oxidation. Physical parameters, including soil texture and bulk density, were evaluated to interpret structural constraints.

## 4.4 Salinity Indicators and Diagnostic Criteria

Salinity and sodicity classifications followed widely accepted thresholds [24]:

- Saline soils: EC<sub>e</sub> > 4 dS m<sup>-1</sup>, ESP < 15
- Sodic soils: ESP > 15, pH > 8.5
- Saline-sodic soils: EC<sub>e</sub> > 4 dS m<sup>-1</sup>, ESP > 15

These criteria facilitated integration of field observations with remotely sensed salinity indices.

## 4.5 GIS and Remote Sensing Analysis

Geospatial analyses were conducted using GIS-based spatial modelling techniques. Sentinel-2 imagery (10 m resolution) was atmospherically corrected and processed for salinity-sensitive spectral indices [25], including:

- Normalized Difference Salinity Index (NDSI)
- Soil Salinity Index (SSI)

- Vegetation Soil Salinity Index (VSSI)

Supervised classification using the Random Forest algorithm was applied to delineate salt-affected zones. Training datasets were derived from field validation points and existing salinity inventories. Classification accuracy was evaluated using confusion matrix metrics, yielding kappa coefficients consistent with acceptable land degradation mapping standards.

#### 4.6 Statistical and Modelling Approaches

Descriptive statistics were employed to summarize soil physicochemical variability. Correlation analyses assessed relationships among E<sub>Ce</sub>, ESP, SAR, and pH. Machine learning-based regression modelling (Random Forest Regression) was implemented to examine predictive relationships among salinity indicators and environmental covariates [26]. Cross-validation techniques were applied to evaluate model robustness. Spatial patterns of salinity distribution were further examined using spatial autocorrelation measures, enabling interpretation of clustering tendencies across districts.

### 5. Case Studies from Uttar Pradesh:

Documented reclamation efforts across Uttar Pradesh provide valuable insights into the biophysical effectiveness, socio-economic outcomes, and operational challenges associated with management of salt-affected soils. Among these, the Uttar Pradesh Sodic Lands Reclamation Projects (UPSLRPs), implemented through multiple phases, represent one of the most extensive landscape-scale interventions targeting sodic soils in the Indo-Gangetic plains [27].

#### 5.1 Reclamation Outcomes and Biophysical Improvements

Large-scale reclamation initiatives under UPSLR phases have demonstrated that integrated interventions - combining gypsum application, land levelling, drainage management, and salt-tolerant cropping systems - can substantially improve soil properties and restore agricultural productivity. Field observations and institutional reports indicate consistent reductions in soil pH and ESP following reclamation. Severely sodic soils (pH > 9.5-10.5; ESP > 50%) have been reported to stabilize within agronomically viable ranges (pH ≈ 8.0-8.5; ESP < 20%) over multi-year treatment periods [28]. These physicochemical improvements correspond with enhanced soil aggregation, infiltration capacity, and root-zone conditions. Crop productivity gains represent a key indicator of reclamation success. Previously unproductive lands have shown marked increases in rice and wheat yields following amendment-based restoration [29]. Such responses underscore the reversibility of sodicity-induced constraints under appropriate soil and water management regimes.

#### 5.2 District-Level Experiences and Management Insights

Case evidence from central Uttar Pradesh underscores the critical role of hydrological controls in reclamation sustainability. Areas with shallow groundwater tables and poor drainage show elevated risks of salinity rebound when corrective measures are inadequately maintained. In districts such as Unnao, Rae Bareli, and Hardoi, successful reclamation has been associated with subsurface drainage, conjunctive water use, and improved field-level water management [30]. Enhanced hydraulic conductivity and reduced surface water stagnation have contributed to soil stabilization. Participatory mechanisms, including water user groups and farmer cooperatives, further support long-term outcomes by enabling collective infrastructure maintenance and drainage management [31].

### 5.3 Socio-Economic Implications of Reclamation

Beyond soil restoration, reclamation programmes have produced measurable socio-economic benefits. Yield stabilization, cropping intensification, and diversification opportunities have enhanced farm income and reduced production risks. Economic assessments suggest that amendment-based reclamation generates positive long-term returns despite initial investment requirements [32]. Improved soil productivity increases land value and supports livelihood resilience in previously marginal agricultural zones. However, cost barriers remain a persistent constraint. Gypsum procurement, drainage installation, and land modification practices often exceed the financial capacity of smallholder farmers [33]. Access to subsidies, credit mechanisms, and technical support significantly influences adoption patterns.

### 5.4 Adoption Constraints and Operational Challenges

Despite demonstrated technical feasibility, reclamation adoption remains spatially uneven. Key constraints include high upfront costs, limited farmer awareness, variability in irrigation water quality, and climatic uncertainties. Erratic rainfall patterns complicate leaching efficiency, while high-intensity precipitation events may damage bunding and drainage structures [34]. Inadequate extension services further limit dissemination of site-specific reclamation protocols. Seed availability for salt-tolerant cultivars represents another operational bottleneck. Sustained productivity gains depend on alignment between soil amendments and appropriate crop genotypes [35].

## 6. Conclusion and Recommendations

Soil salinity and sodicity remain major constraints to agricultural sustainability in Uttar Pradesh, particularly in canal-irrigated Indo-Gangetic regions where degradation is closely linked to hydrological processes, irrigation practices, and groundwater dynamics. The dominance of sodic and saline-sodic soils highlights the role of exchangeable sodium in causing structural degradation, reduced infiltration, and declining soil productivity, indicating that salinity management is fundamentally a soil-water interaction challenge. Evidence from reclamation programmes shows that sodicity-induced limitations are largely reversible through integrated strategies involving gypsum amendments, drainage management, and salt-tolerant cropping systems, although adoption variability and infrastructural constraints affect long-term outcomes. Geospatial techniques provide effective tools for salinity diagnostics and monitoring. Sustainable management therefore requires targeted reclamation planning, improved drainage, conjunctive water use, wider dissemination of tolerant cultivars, and strengthened institutional support.

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