Satellite monitoring of seawater intrusion and soil salinization dynamics

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Globally, 833 million hectares of land, representing 8.7% of the Earth's terrestrial surface, are at risk of salinization, mainly in arid and coastal zones.[1] This process is driven by the interaction between natural seawater intrusion (e.g., tides and storm surges), global warming, and human activities, such as excessive groundwater extraction, leading to persistent salt accumulation and land degradation.

Recently, seawater intrusion has attracted growing attention due to its disruption of the freshwater-saltwater interface.[1] Saline water intrudes into terrestrial ecosystems through surface and subsurface pathways, and subsequent evaporation leaves salt residues that exacerbate soil salinization. Intrusion intensity has increased in coastal areas of Southeast Asia, the Mediterranean, the North of Europe, and the United States driven by climate-induced sea level rise and groundwater overextraction.[1] In 2024, intrusion frequency across China rose markedly due to extreme weather and astro-

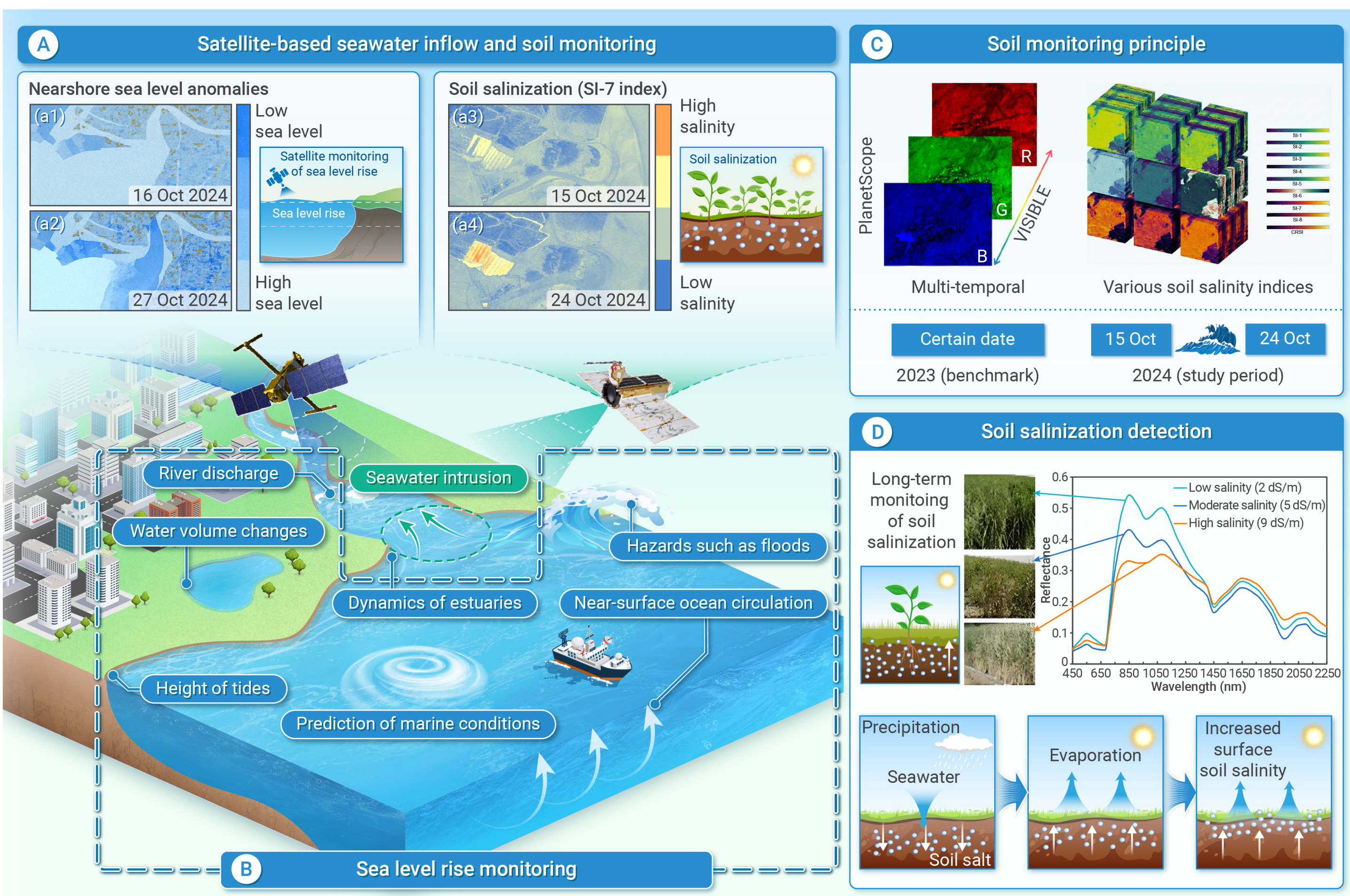

Figure 1. Seawater intrusion monitoring from the perspective of satellite remote sensing (A) Satellite-based seawater inflow monitoring, showing a sea level rise of 1.8 m in October 2024, derived through the integrated use of SWOT KaRIn elevation data and Sentinel-2A multispectral observations. (B) Sea level rise monitoring, demonstrating how SWOT's KaRIn detects sub-meter sea surface changes before and after intrusion events to identify landward-moving seawater fronts. (C) Soil Monitoring principle, illustrating how multi-spectral sensors capture soil moisture, surface crusting, and early salinity signals induced by seawater intrusion. (D) Soil salinization detection, showing the responses of salinity increase and vegetation stress post-intrusion, highlighting intrusion-driven changes.

nomical high-tide events.[2] The events struck regions including Hebei, Liaoning, and Guangxi, affecting over 3,400 people and triggering direct economic losses of over 72 million CNY. These impacts extend beyond ecological damage to disrupt economic and social systems, thereby introducing systemic risks.

However, accurately characterizing the spatial extent, dynamics, and post-event impacts of seawater intrusion, especially for soil salinization at regional scales, remains challenging. Traditional monitoring relies mainly on sparse wells or point-based surveys, which are spatially discontinuous and temporally infrequent, limiting their ability to resolve rapid, event-driven intrusion processes across heterogeneous coastal landscapes. Consequently, the position of intrusion fronts and their terrestrial legacies are often poorly understood.

Satellite remote sensing provides a pathway to overcome these limitations by spatially continuous, physically based observations. This study integrates coastal hydrodynamic signals with land-surface soil salinity indicators to develop a satellite-based framework for tracking seawater intrusion and its impacts on soil salinization, as summarized in Figure 1.

INTEGRATED SATELLITE OBSERVATIONS FOR COASTAL MONITORING

The Surface Water and Ocean Topography (SWOT) mission can map ocean surface elevation anomalies, and optical sensors such as Sentinel-2 and Landsat 8/9 derive soil salinization extent and severity from spectral indices. Optical satellite methods perform well in arid regions, achieving up to 90% accuracy in quantifying surface salt accumulation and distinguishing salinity types based on visible and near-infrared (VNIR) spectral data. SWOT provides transformative capabilities for monitoring seawater intrusion and its impact (Figure 1A). Specifically, it enables (1) intrusion front detection through sea surface height anomalies that pinpoint inland-moving seawater boundaries; (2) hydrodynamic analysis via continuous measurements that elucidate tidal forcing and saltwater-groundwater interactions; and (3) all-weather, large-scale coverage using radar interferometry for high-resolution monitoring across extensive coastal regions.

SWOT OBSERVATIONS OF SEAWATER INTRUSION DYNAMICS

Sea level rise is a primary driver of seawater intrusion and soil salinization in coastal zones. Frequent inundation by saline water stresses salt marsh vegetation, reducing the coverage of Suaeda salsa communities, benthic faunal density, and biodiversity. As intrusion events become more frequent, sediment re-suspension reshaped tidal channel fractal structures and pushed saline-freshwater interfaces landward. This leads to the exceedance of critical salinity thresholds in *Suaeda salsa* habitats, suppressing seedling survival and degrading wetland carbon sequestration. In the saline wetland core of the Liaohe Delta, this triggers a self-reinforcing cycle of habitat fragmentation and ecosystem decline. Collectively, these impacts drive vegetation loss, shallow groundwater salinization, and the expansion of saline soils.

The SWOT satellite, equipped with the Ka-band Radar Interferometer (KaRIn), offers approximately 100 m spatial resolution and up to four revisits per month, enabling precise monitoring of sea surface height.[3] Between October 10 and 30, 2024, SWOT captured a rapid water level rise of 1.8 m at the Liaohe estuary, driven by astronomical tides, sustained southeasterly winds, and prior heavy rainfall (Figure 1A). This seawater intrusion event rapidly altered hydrodynamic conditions in tidal channels, triggering shifts in sediment transport and depositional patterns that amplified lateral erosion. Collectively, these observations demonstrate the capability of SWOT Altimeter to detect coastal sea level anomalies and provide early warnings for coastal ecosystem risks (Figure 1B).

MULTI-SPECTRAL DETECTION OF SOIL SALINIZATION

SWOT provides critical hydrodynamic context for salinization monitoring by quantifying the seawater intrusion extent and persistence. These observations help identify infiltration-prone zones and guide interpretation of surface salinity signals captured by multi-spectral sensors (Figure 1A). Furthermore, remote sensing-derived spectral indices can reveal subtle surface features associated with salt accumulation. This capability makes them essential tools for mapping soil salinization.[4]

In sparsely vegetated areas, multi-spectral indices enable direct estimation of surface salinity by correlating reflectance especially in the shortwave infrared (SWIR) range with ground-measured salt concentrations. In densely vegetated zones, salinity-induced physiological stress alters canopy reflectance in the VNIR spectrum, particularly in red-edge (700-750 nm) and near-infrared bands, enabling indirect inference of subsurface salinity.[5] This positions vegetation as a natural biosensor for salinization. However, large-scale application remains challenging, primarily due to the lack of reliable *in situ* calibration data and the high cost of field sampling. These constraints limit spatial validation and hinder robust model generalization. To overcome this limitation, we derived various salinity indices: canopy response salinity index (CRSI) and soil salinity index-7 and -8 (SI-7 and SI-8) from 3 m PlanetScope data (Figure 1C). These specific indices were selected after extensive testing of dozens of spectral indices. Comparative analysis of pre- and post-intrusion index anomalies against baseline variations revealed the exceptional sensitivity of these indices in detecting seawater intrusion events. This sensitivity enables spatially explicit quantification of intrusion-driven soil salinity dynamics across coastal wetlands (Figure 1D).

CONCLUSION

By coupling offshore hydrodynamic forcing with onshore ecological response, satellite-based monitoring provides the essential data to quantify coastal degradation driven by seawater intrusion. The integration of SWOT radar interferometry with multi-spectral indicators enables the coupling of transient sea-level anomalies with rapid soil salinization. This synergistic approach overcomes the spatial fragmentation of traditional monitoring and provides a scalable lens to map the terrestrial legacy of seawater intrusion. Moving forward, the priority lies in transitioning from passive monitoring to predictive intelligence. Overcoming the sensitivity limitations of traditional indices requires leveraging emerging small-satellite constellations where the synergy of multispectral and thermal infrared data can detect pre-visual physiological markers of salt stress. This observational frontier must be anchored by coupled hydrodynamic-atmospheric models that resolve the complex interactions between tidal forcing, storm surges, and bathymetry. Integrating these disparate data streams into operational frameworks will enable real-time decision support and ensure the resilience of coastal ecosystems against global climate change.

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AUTHOR CONTRIBUTIONS

J. W., N. X., Q. L, and H. L. designed research; J. W., L. H., and J. Y. performed research and. analyzed data; J. W., L. H., J. Y., and N. X. wrote the paper. All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.