

# Spatiotemporal Monitoring of Salinity Intrusion in the Mekong Delta using Sentinel-2 imagery and Google Earth Engine (2020–2024)

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**Abstract**— Salinity intrusion is one of the most critical environmental challenges affecting the Mekong Delta, Vietnam, threatening agricultural productivity, freshwater availability, and the long-term sustainability of coastal livelihoods. This study investigated the spatial and temporal dynamics of salinity intrusion across the Mekong Delta during 2020–2024 using Sentinel-2 satellite imagery processed within the Google Earth Engine platform. Annual dry-season composites were generated from Sentinel-2 Level-2A imagery acquired between January and April. Cloud and shadow pixels were removed using the Scene Classification Layer, while water bodies were excluded using the Modified Normalized Difference Water Index (MNDWI). A Salinity Index (SI), derived from Sentinel-2 bands B3 and B11, was applied to classify saline, brackish, and freshwater zones. The resulting annual maps revealed a persistent coastal–inland salinity gradient, with the strongest salinity influence concentrated in coastal provinces including Ca Mau, Bac Lieu, Soc Trang, Tra Vinh, and Kien Giang. Saline areas increased from 41,022 ha in 2020 to a peak of 73,024 ha in 2022, whereas brackish areas expanded from 145,189 ha in 2020 to 348,225 ha in 2023. Freshwater areas increased from 365,613 ha in 2020 to 439,513 ha in 2021 but subsequently declined to 213,420 ha in 2024. These results demonstrate the usefulness of multi-temporal remote sensing and cloud-based geospatial analysis for regional salinity monitoring and support environmental planning and water-resource management in the Mekong Delta.

**Keywords**— Salinity intrusion; Mekong Delta; Sentinel-2; Google Earth Engine; salinity index; remote sensing.

## I. INTRODUCTION

The Mekong Delta is one of the most important agricultural regions in Southeast Asia; however, it is increasingly exposed to dry-season salinity intrusion. In the Vietnamese Mekong Delta, salinity intrusion has become a major environmental and socio-economic concern because it threatens freshwater availability, damages agricultural systems, and contributes to land-use instability in coastal and estuarine zones. Recent studies have identified climate change and sea-level rise, upstream hydropower development, riverbed sand mining, and groundwater extraction as major drivers intensifying salinity intrusion in the delta (Eslami et al., 2021; Kaveney et al., 2023; Loc & Park, 2025).

The dry-season salinity problem in the Mekong Delta is especially serious because reduced upstream discharge, tidal forcing, and coastal water-level dynamics can allow saline water to move further inland. Field observations and integrated coastal–inland modelling have shown that salinity intrusion in the delta is highly sensitive not only to freshwater discharge, but also to ocean surge, tides, and anthropogenic riverbed

incision, highlighting the complexity of the phenomenon and the need for regionally consistent monitoring tools (Eslami et al., 2021). At the same time, agricultural reviews report that inland dry-season salinity intrusion has already caused substantial impacts on rice production and has accelerated the search for alternative cropping systems in affected areas (Kaveney et al., 2023).

Remote sensing provides an effective complementary approach for monitoring salinity-affected environments because it enables repeated, spatially consistent observations across large geographic areas. Compared with conventional field-based monitoring, satellite observations allow more comprehensive regional assessments of environmental dynamics. However, methodological choices, spatial scale effects, and validation constraints remain important challenges in operational applications of satellite-based salinity monitoring (Tamiminia et al., 2020).

Among currently available Earth-observation systems, Sentinel-2 is particularly suitable for environmental monitoring because it provides high-resolution multispectral imagery covering visible, near-infrared, and shortwave-infrared wavelengths. The mission includes 13 spectral bands with spatial resolutions ranging from 10 to 60 m, enabling detailed monitoring of terrestrial surface conditions and land-cover dynamics (Drusch et al., 2012). In addition, Sentinel-2 Level-2A products provide bottom-of-atmosphere reflectance and include scene classification information that supports cloud and shadow masking in preprocessing workflows (European Space Agency, n.d.; Copernicus Data Space Ecosystem, n.d.).

Google Earth Engine further enhances regional remote-sensing applications by providing cloud-based access to extensive satellite data archives and high-performance geospatial processing capabilities. The platform enables large-scale environmental analysis through integrated datasets, parallel computing infrastructure, and flexible programming interfaces. Previous studies have described Earth Engine as a planetary-scale geospatial analysis platform widely used for multi-temporal environmental monitoring (Gorelick et al., 2017; Tamiminia et al., 2020; Google for Developers, n.d.).

Accordingly, the aim of this study is to develop a multi-temporal, cloud-based remote-sensing workflow for monitoring salinity-related surface patterns in the Mekong Delta and to quantify the spatial and temporal dynamics of saline, brackish, and freshwater zones from 2020 to 2024. The study contributes a regionally consistent assessment framework that can support

environmental analysis and practical decision-making in land and water management.

II. MATERIALS AND METHODS

A. Study area

The study was conducted in the Mekong Delta, Vietnam, a low-lying deltaic region in the downstream part of the Mekong River system. The area includes 13 provincial-level administrative units and is characterized by dense river and canal networks, strong land–water interactions, and high sensitivity to coastal salinity intrusion, especially during the dry season. The study area was defined as the entire Mekong Delta, with analysis organized at the provincial scale for spatial comparison and area statistics. The geographic extent and province layout are shown in Fig. 1.

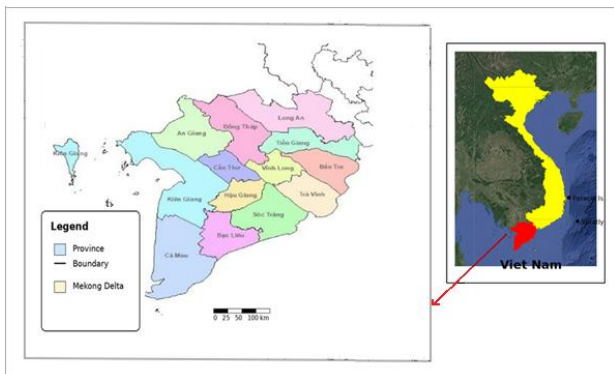


Fig. 1. Study area and provincial administrative units of the Mekong Delta.

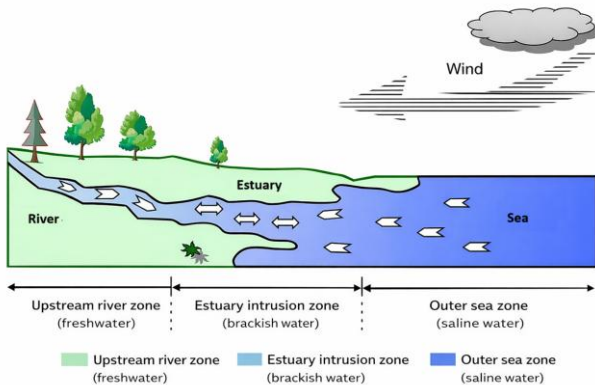


Fig. 2. Conceptual mechanism of salinity intrusion from the sea through estuaries and river channels.

B. Data sources

This study used Sentinel-2 MSI Level-2A imagery accessed and processed in Google Earth Engine. The Sentinel-2 mission offers high-resolution multispectral imagery with 13 spectral bands and spatial resolutions between 10 and 60 m, together with a five-day revisit interval under full mission configuration (Drusch et al., 2012). Level-2A data are bottom-of-atmosphere reflectance products and are suitable for surface-based spectral analysis (European Space Agency, n.d.). The main datasets and ancillary layers are summarized in Table 1.

Sentinel-2 Level-2A imagery was selected for the 2020–2024 period, and the primary bands used for salinity-related

analysis were B3 (green) and B11 (SWIR1). Additional spectral bands, including B2, B4, B8, and B12, were used during preprocessing and mask generation. The images were filtered to the dry season, from 1 January to 30 April of each year, in order to capture the period when salinity intrusion is typically most pronounced in the Mekong Delta. The spectral bands and derived indices used in the workflow are listed in Table 2.

Provincial administrative boundaries were used to clip the study area and summarize class areas by province. The provincial boundary layer was obtained from the FAO Global Administrative Unit Layers (GAUL) dataset (Food and Agriculture Organization of the United Nations, 2015).

TABLE 1. Datasets and ancillary layers used in the study.

Dataset	Source	Spatial / temporal characteristics	Purpose in this study
Sentinel-2 MSI Level-2A	ESA / Copernicus via Google Earth Engine	13 spectral bands; 10-60 m; dry-season composites (Jan-Apr) for 2020-2024	Salinity index calculation, cloud masking, annual mapping
Scene Classification Layer (SCL)	Sentinel-2 Level-2A	Per-pixel land/cloud/shadow classes	Cloud-shadow masking and support for land-mask generation
FAO/GAUL administrative boundaries	FAO GAUL 2015	Provincial boundary polygons for the 13 Mekong Delta provinces	Study-area clipping and province-level area statistics

TABLE 2. Spectral bands and derived indices used in the workflow.

Band / index	Sentinel-2 expression	Primary interpretation	Role in workflow
B3 (Green)	0.56 μm, 10 m	Visible green reflectance	Used in SI and water discrimination
B11 (SWIR1)	1.61 μm, 20 m	Sensitive to moisture and salt-related surface response	Used in SI and land-surface salinity contrast
MNDWI	(B3 - B11) / (B3 + B11)	Open-water enhancement	Support land-mask and water exclusion
SI	(B11 - B3) / (B11 + B3)	Normalized salinity-related spectral contrast	Classify saline, brackish, and freshwater conditions

C. Image preprocessing

All satellite data preprocessing and image aggregation were conducted within Google Earth Engine, a cloud-based geospatial analysis platform designed to support large-scale remote-sensing applications. Image collections were filtered by spatial extent and acquisition date using the functions filterBounds() and filterDate(). For each year, the selected images were aggregated into annual median composites to reduce the influence of residual cloud contamination, noise, and anomalous reflectance values.

Cloud and shadow masking were conducted using the Scene Classification Layer (SCL) associated with Sentinel-2 Level-2A products. Cloud shadows, medium-probability cloud, high-probability cloud, and cirrus pixels were excluded during preprocessing. To restrict the salinity analysis to terrestrial

surfaces, open-water bodies were removed prior to SI calculation. This step combined MNDWI-based water extraction with Scene Classification Layer information to exclude seawater, major rivers, canals, and other open-water pixels from the analysis domain. The Modified Normalized Difference Water Index (MNDWI) is widely used to highlight open-water features while minimizing spectral interference from built-up land, vegetation, and soil surfaces (Xu, 2006). Key preprocessing steps are illustrated in Figure 3.

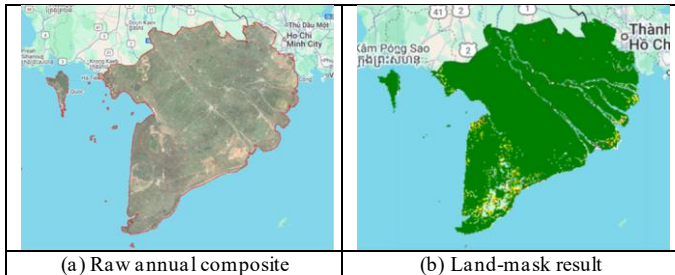


Fig. 3. Preprocessing steps used to build cloud-free, land-only annual composites for salinity analysis.

#### D. Salinity Index (SI) calculation

After image preprocessing, a Salinity Index (SI) was calculated from Sentinel-2 spectral data to characterize salinity-related surface conditions across the Mekong Delta. The SI was derived from the green band (B3) and the shortwave infrared band (B11) of Sentinel-2 Level-2A imagery. Saline-affected surfaces tend to show relatively higher reflectance in the SWIR region and lower reflectance in the green band, which supports the use of a normalized contrast between these two bands.

$$SI = \frac{B11 - B3}{B11 + B3}$$

This formulation is spectrally consistent with the use of a normalized difference index and is the inverse-sign counterpart of the Modified Normalized Difference Water Index (MNDWI), which is defined as  $(Green - SWIR) / (Green + SWIR)$  for water extraction. In the present study, water bodies were removed before SI analysis; therefore, the reversed sign formulation was adopted so that increasingly positive values indicate stronger SWIR dominance and, consequently, stronger salinity-related surface influence. SI values in the study area were generally distributed within an approximate range of -0.3 to 0.3, consistent with the expected behavior of a normalized difference index.

#### E. Salinity classification and area statistics

Based on the SI values, the Mekong Delta was classified into three salinity-related surface classes: saline, brackish, and freshwater. The classification was conducted after land masking and the resulting annual maps were used for temporal comparison and provincial area statistics. The operational thresholds used in this classification are presented in Table 3.

The threshold at  $SI = 0.00$  was selected as the natural transition point of the normalized difference formulation, where reflectance in the green and SWIR1 bands is balanced. Because the SI values observed in the study were mostly distributed between approximately -0.3 and 0.3, the threshold of 0.10 was adopted to distinguish weakly positive transitional conditions

from more distinctly saline spectral responses. These thresholds should be interpreted as study-specific operational thresholds rather than universal salinity standards and can be refined in future work through calibration against field-measured salinity or electrical conductivity (ECe) observations.

TABLE 3. Operational SI thresholds used for salinity classification.

Class	SI range	Interpretation
Freshwater	$SI < 0.00$	Green reflectance greater than SWIR1 reflectance
Brackish	$0.00 \leq SI < 0.10$	Transition zone between freshwater and saline conditions
Saline	$SI \geq 0.10$	More distinct salinity-related spectral response

#### F. Analytical workflow

The analytical workflow consisted of six main steps: (1) selection of dry-season Sentinel-2 Level-2A imagery for 2020–2024; (2) filtering by study boundary and date; (3) cloud and shadow masking using SCL; (4) generation of annual median composites; (5) removal of water pixels using MNDWI and SCL; and (6) computation of SI followed by classification into saline, brackish, and freshwater zones and summary of area statistics. The complete processing sequence is summarized in Figure 4.

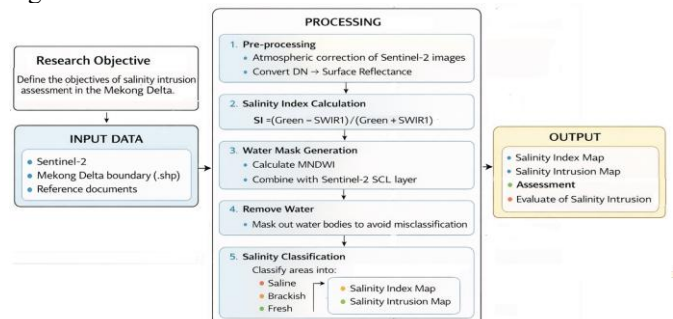


Fig. 4. Analytical workflow for Sentinel-2 preprocessing, SI calculation, classification, and area statistics.

### III. RESULTS

#### A. Spatial distribution of SI during 2020–2024

The annual SI maps revealed a persistent coastal–inland gradient of salinity-related surface conditions across the Mekong Delta. Throughout the study period, SI values were generally distributed between approximately -0.3 and 0.3, with higher values concentrated in coastal and estuarine areas and lower values dominating inland and upstream parts of the delta. This pattern indicates a clear spatial contrast between marine-influenced coastal zones and freshwater-dominated inland zones. The full set of annual SI maps is presented in Figure 5.

In 2020, high SI values were concentrated mainly in the southern and southeastern coastal parts of the delta, especially in Ca Mau, Bac Lieu, Soc Trang, and Tra Vinh. In contrast, inland provinces such as An Giang, Dong Thap, and Long An showed low SI values, indicating limited salinity influence on land surfaces in those areas.

In 2021, the general spatial pattern remained similar, but areas with medium to high SI values expanded slightly relative to 2020. High SI values still followed the coastline and river

mouths, while the inland core of the delta remained dominated by low SI values.

In 2022, the SI maps showed a clearer increase in medium and high SI values, particularly in the southwestern coastal sector, including the Ca Mau Peninsula and coastal Kien Giang. Compared with earlier years, the salinity-affected footprint widened, and transitional areas with intermediate SI values became more visible in inland locations.

In 2023, the SI pattern remained highly differentiated in space. High SI values continued to occur in coastal zones and near major estuaries, whereas the central delta was still characterized mainly by low SI values. A notable feature of 2023 was the appearance of medium-SI belts along the main river system, suggesting inland propagation of salinity along river corridors under reduced freshwater flow conditions.

In 2024, salinity conditions remained pronounced across the coastal fringe. High SI values were still observed in Ca Mau, Bac Lieu, Soc Trang, and Tra Vinh, while scattered medium-SI patches also appeared farther inland, implying an increasing risk of localized salinity intrusion beyond the immediate coastal belt.

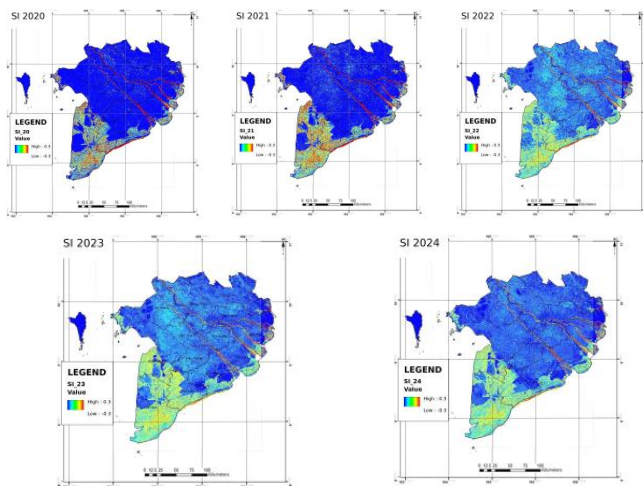


Fig. 5. Annual SI maps for the Mekong Delta from 2020 to 2024.

**B. Spatial distribution of saline, brackish, and freshwater zones**

The salinity classification maps indicated that freshwater remained the dominant class in much of the inland and upstream Mekong Delta, whereas saline and brackish zones were concentrated mainly in coastal provinces. Across the study period, the most persistent saline and brackish areas were observed in Ca Mau, Bac Lieu, Soc Trang, Tra Vinh, and Ben Tre, while inland provinces such as An Giang, Dong Thap, Can Tho, and part of Long An were predominantly freshwater. The corresponding annual classification maps are shown in Figure 6.

In 2020, freshwater dominated the inland and upper delta, while saline and brackish zones were clearly expressed along the coast and major estuarine areas. The brackish class formed a transition belt between freshwater inland areas and more saline coastal surfaces.

In 2021, the spatial structure remained broadly similar to 2020, with freshwater still predominant inland and saline/brackish classes concentrated in coastal provinces. Coastal provinces remained the main centers of saline influence, while brackish zones formed transition corridors.

By 2022, the quantitative results show a marked intensification of salinity-related conditions at the regional scale. Saline and brackish areas increased strongly, especially in coastal provinces, while the tabulated area statistics indicate a sharp reduction in freshwater area. The dominant interpretation for 2022 is that the salinity transition advanced inland rather than retreated.

In 2023, brackish and saline areas expanded again, especially around the Ca Mau Peninsula and the coastal sectors of Bac Lieu and Soc Trang. The brackish class appeared denser and extended farther inland than in the previous year, while freshwater areas were still present in upstream provinces but showed contraction near the brackish interface.

In 2024, the classification maps indicated the strongest overall salinity intrusion pattern of the study period in spatial terms. Saline and brackish zones expanded substantially in coastal provinces, and the freshwater-brackish boundary shifted farther inland, narrowing freshwater areas in parts of the central delta.

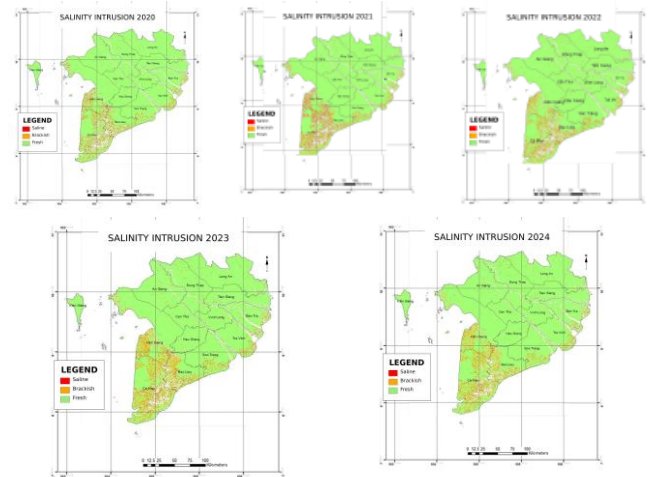


Fig. 6. Annual classification maps showing saline, brackish, and freshwater zones from 2020 to 2024.

**C. Interannual area changes in saline, brackish, and freshwater zones**

TABLE 4. Total area of saline, brackish, and freshwater zones in the Mekong Delta during 2020-2024.

Year	Saline area (ha)	Brackish area (ha)	Freshwater area (ha)
2020	41,022	145,189	365,613
2021	43,718	185,195	439,513
2022	73,024	299,955	234,001
2023	45,220	348,225	231,702
2024	35,646	291,947	213,420

The class-area statistics show clear interannual variability in salinity conditions across the Mekong Delta. Total saline area increased from 41,022 ha in 2020 to 43,718 ha in 2021, then rose sharply to 73,024 ha in 2022, before declining to 45,220 ha

in 2023 and 35,646 ha in 2024. Thus, the saline class reached its maximum extent in 2022 and its minimum extent in 2024. Annual class totals are summarized in Table 4 and visualized in Figure 7.

The brackish area expanded much more strongly over the study period. It increased from 145,189 ha in 2020 to 185,195 ha in 2021, then surged to 299,955 ha in 2022 and reached a peak of 348,225 ha in 2023. Although it declined slightly in 2024 to 291,947 ha, it still remained far above the 2020 and 2021 levels. This indicates that the brackish class was the most dynamic and expansive transition zone during the study period.

By contrast, the freshwater area increased from 365,613 ha in 2020 to 439,513 ha in 2021, but then declined sharply to 234,001 ha in 2022 and continued to decrease to 231,702 ha in 2023 and 213,420 ha in 2024. Therefore, the freshwater class was largest in 2021 and smallest in 2024, showing a substantial contraction in the latter part of the study period.

Overall, the regional area statistics indicate three key temporal features: (1) a saline-area peak in 2022, (2) a brackish-area peak in 2023, and (3) a continuous freshwater decline after 2021. These three features together suggest not only saline expansion in selected years, but also a broader inland shift of the freshwater–salinity transition zone.

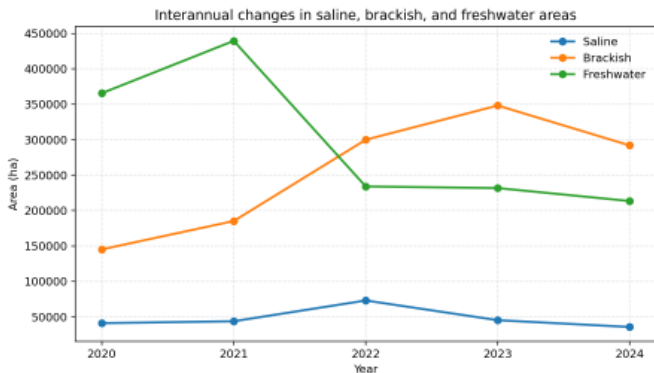


Fig. 7. Interannual changes in saline, brackish, and freshwater areas in the Mekong Delta, 2020–2024.

**D. Provincial hotspots and spatial concentration of salinity-related classes**

Provincial statistics confirm that salinity-related classes were concentrated primarily in coastal provinces. In terms of the saline class, Ca Mau consistently recorded the largest saline area across the study period, rising from 12,311.47 ha in 2020 to 23,413.02 ha in 2022, then remaining high at 16,397.19 ha in 2023 and 14,152.63 ha in 2024. Bac Lieu also represented a major saline hotspot, with 9,543.08 ha in 2020, 17,516.05 ha in 2022, and 11,210.38 ha in 2024. Kien Giang showed a particularly strong saline increase in 2022, reaching 11,639.14 ha before declining again in later years. Province-level patterns for 2024 are summarized in Table 5.

For the brackish class, Ca Mau and Kien Giang were the most prominent hotspots. Ca Mau increased from 59,478.99 ha in 2020 to 121,333.82 ha in 2022 and 139,908.96 ha in 2023, before remaining very high at 121,152.38 ha in 2024. Kien Giang increased from 27,375.22 ha in 2020 to 56,694.23 ha in 2022 and 74,051.62 ha in 2023, then stayed high at 63,746.02

ha in 2024. Bac Lieu also recorded persistently large brackish extents, rising from 24,869.93 ha in 2020 to 68,959.24 ha in 2023.

By contrast, inland provinces generally maintained larger freshwater areas and much lower saline extents. For example, An Giang retained freshwater areas of 11,490.06 ha in 2020, 11,813.91 ha in 2021, 9,684.96 ha in 2022, 10,286.84 ha in 2023, and 9,570.91 ha in 2024, while its saline area remained relatively low. Dong Thap showed a similar pattern, with freshwater consistently exceeding saline area in every year.

Taken together, the province-level results identify Ca Mau, Bac Lieu, and Kien Giang as the most persistent salinity hotspots, while An Giang, Dong Thap, and Can Tho remained predominantly freshwater-oriented despite signs of increasing transitional influence in some years. The cumulative hotspot ranking is summarized in Table 6 and Figure 8.

TABLE 5. Province-level area statistics for saline, brackish, and freshwater classes in 2024.

Province	Saline (ha)	Brackish (ha)	Freshwater (ha)
An Giang	485	2,566	9,571
Bac Lieu	11,210	52,269	22,696
Ben Tre	1070	10,728	27,175
Ca Mau	14,153	121,152	52,356
Can Tho City	136	1,070	3,967
Dong Thap	520	3,978	14,376
Hau Giang	154	874	1,266
Kien Giang	2,944	63,746	16,554
Long An	693	4,843	6,210
Soc Trang	2,665	14,960	19,485
Tien Giang	386	2,447	13,312
Tra Vinh	992	12,156	17,571
Vinh Long	237	1,155	8,881

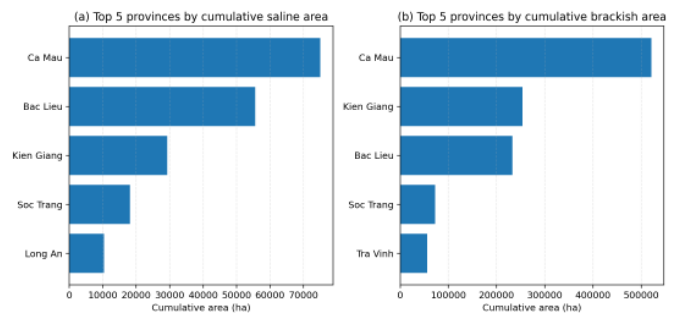


Figure 8. Provinces with the largest cumulative saline and brackish areas during 2020–2024.

TABLE 6. Provincial hotspot summary based on cumulative class areas during 2020–2024.

Province	Cumulative saline area (ha)	Cumulative brackish area (ha)	Cumulative freshwater area (ha)
Ca Mau	75,017	521,077	428,724
Kien Giang	29,251	253,478	168,054
Bac Lieu	55,592	232,672	201,687
Soc Trang	18,127	72,170	115,957
Tra Vinh	7,212	56,063	101,411
Long An	10,346	22,833	40,139

IV. DISCUSSION

Although the present study does not incorporate direct field-based salinity measurements for calibration or validation, the

observed spatial patterns are consistent with well-documented salinity intrusion dynamics in the Mekong Delta reported in previous studies (Eslami et al., 2021; Kaveney et al., 2023; Loc & Park, 2025). The concentration of saline and brackish zones in coastal provinces such as Ca Mau, Bac Lieu, and Soc Trang corresponds closely with areas known to experience strong dry-season salinity intrusion. In addition, the progressive inland expansion of transitional brackish zones observed in the satellite-derived maps is consistent with hydrological studies describing increasing salinity pressure associated with reduced dry-season discharge and tidal influence. Therefore, although the SI-based classification represents a surface spectral indicator rather than direct salinity measurements, the spatial consistency with previous hydrological and agricultural studies supports the reliability of the remote-sensing assessment.

The results reveal a clear and persistent coastal–inland salinity gradient across the Mekong Delta. Higher SI values and larger saline or brackish areas were concentrated in coastal provinces directly influenced by marine and estuarine processes, whereas inland provinces were dominated by lower SI values and larger freshwater areas. This spatial pattern is consistent with the hydrological and geomorphological characteristics of the delta, where tidal influence, reduced dry-season discharge, and low topographic gradients facilitate inland salinity propagation (Eslami et al., 2021; Loc & Park, 2025).

The annual maps and class statistics indicate that salinity intrusion in the study area is highly dynamic over time. The period 2020–2021 was characterized by moderate saline expansion and brackish growth, whereas 2022 represented the strongest salinity signal in terms of total saline area. During 2023–2024, brackish areas remained dominant while freshwater areas continued to decline.

One of the most important findings of the study is that the brackish class expanded more strongly than the saline class over the five-year period. While the saline class peaked at 73,024 ha in 2022 and then decreased, the brackish class expanded from 145,189 ha in 2020 to 348,225 ha in 2023 and remained high in 2024 at 291,947 ha. This indicates that salinity intrusion in the Mekong Delta should not be interpreted solely as the expansion of highly saline areas, but also as the widening of the transition belt between freshwater and saline conditions.

From a hydrological and land-management perspective, this brackish zone is especially significant because it represents areas where salinity stress may be increasing but has not yet fully shifted to strongly saline conditions. In practical terms, these transition areas may be more sensitive to seasonal hydrological fluctuations, water-control infrastructure, and changes in dry-season freshwater availability.

The strongest expansion of the saline class occurred in 2022, when total saline area rose to 73,024 ha. Province-level data show that this spike was associated particularly with major increases in Ca Mau, Bac Lieu, and Kien Giang, indicating that the southern and southwestern coastal sectors were especially exposed during that year. At the same time, the freshwater class dropped sharply from 439,513 ha in 2021 to 234,001 ha in 2022, while the brackish class nearly doubled relative to 2021. Taken

together, these changes suggest that 2022 marked a substantial regional shift in the freshwater–salinity balance.

Even though saline area declined again in 2023 and 2024, the continued dominance of the brackish class and the continued contraction of freshwater area indicate that salinity pressure remained structurally significant rather than returning fully to early-period conditions.

The freshwater class reached its maximum area in 2021 and then declined continuously through 2024. This is one of the clearest warning signals in the dataset. While freshwater remained the largest class overall, its reduction from 439,513 ha in 2021 to 213,420 ha in 2024 indicates a major contraction of freshwater-dominated land conditions over a relatively short multi-year period.

This contraction has important implications for inland water and agricultural systems. In the context of the Mekong Delta, where many farming systems depend on stable freshwater access, the narrowing of freshwater areas suggests increasing vulnerability not only in coastal provinces, but also at the inland margins of transition zones.

The province-level results show that salinity intrusion is highly uneven across the Mekong Delta. Ca Mau remained the strongest and most persistent hotspot in both saline and brackish classes throughout the study period. Bac Lieu and Kien Giang also exhibited large and fluctuating salinity-related extents, while Soc Trang and Tra Vinh maintained consistently elevated coastal salinity influence. These provinces represent the main frontline of land-surface salinity stress in the regional pattern.

Inland provinces such as An Giang and Dong Thap, and the urban core of Can Tho, retained a much stronger freshwater signature. However, the presence of non-zero saline and brackish areas in these provinces indicates that inland salinity-related transition is not absent; rather, it is weaker and more spatially limited than in coastal hotspot provinces. This distinction supports the interpretation that salinity intrusion is a regional gradient phenomenon rather than a binary coastal-versus-inland contrast.

The observed dynamics can plausibly be linked to dry-season climatic stress, reduced upstream discharge, sea-level rise, and water-regulation measures, all of which have been highlighted in previous work on the Mekong Delta (Eslami et al., 2021; Kaveney et al., 2023; Loc & Park, 2025). These interpretations are consistent with the spatial and temporal behavior seen in the data, particularly the inland extension of brackish areas and the contraction of freshwater zones. However, because the study did not directly integrate hydrodynamic or meteorological datasets, such causal explanations should be framed as informed interpretations rather than fully tested causal results.

The study demonstrates the practical value of using Sentinel-2, Google Earth Engine, and an SI-based classification framework for regional salinity monitoring. This approach is spatially consistent, cost-efficient, and well suited to conditions in which field observation networks remain limited. At the same time, the study has several limitations that should be acknowledged explicitly in the manuscript. The analysis targets land-surface salinity-related patterns rather than salinity conditions in major water bodies; it does not directly

incorporate hydrodynamic modelling or measured salinity observations for validation; and the classification is based on SI thresholds and thus remains sensitive to index behavior, dry-season surface conditions, and the effectiveness of land/water masking. These limitations do not negate the value of the results, but they do mean that the findings should be interpreted as a robust remote-sensing assessment of salinity-related surface conditions rather than a full hydrological salinity model.

Several limitations of the present study should be acknowledged. First, the analysis focuses on salinity-related surface spectral responses rather than direct measurements of water or soil salinity. Consequently, the SI classification should be interpreted as an indicator of salinity influence on land-surface conditions rather than a direct measurement of salinity concentration. Second, the operational SI thresholds applied in this study were selected based on the observed distribution of index values within the study area and were not calibrated using field electrical conductivity (ECe) measurements. Third, the analysis was limited to dry-season composites derived from Sentinel-2 imagery and did not explicitly incorporate hydrodynamic or meteorological datasets that may influence salinity intrusion dynamics. Future studies should integrate field observations, hydrological datasets, and long-term environmental monitoring to further refine classification thresholds and improve the interpretation of satellite-based salinity indicators.

#### V. CONCLUSIONS

This study developed a multi-temporal remote-sensing framework using Sentinel-2 imagery and Google Earth Engine to monitor salinity-related surface conditions in the Mekong Delta during 2020–2024. The results reveal a persistent coastal–inland salinity gradient, with the strongest salinity influence concentrated in coastal provinces such as Ca Mau, Bac Lieu, Soc Trang, Tra Vinh, and Kien Giang.

Saline areas peaked in 2022, whereas brackish areas expanded substantially and reached their maximum extent in 2023. In contrast, freshwater areas declined continuously after 2021, indicating a progressive inland shift of the freshwater–salinity transition zone.

These findings demonstrate the usefulness of cloud-based geospatial analysis for regional environmental monitoring and provide important insights for land-use planning, water-resource management, and climate-adaptation strategies in the Mekong Delta. Future research should integrate field salinity

measurements and hydrodynamic datasets to refine classification thresholds and improve the interpretation of salinity-related surface patterns.

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