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RESEARCH ON DEVELOPMENT AND ZONING OF SALINITY IN BEN TRE PROVINCE USING MULTI-LAVEL, MULTI-RESOLUTION, MULTI-TEMPORAL REMOTE SENSING TECHNOLOGY

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INTRODUCTION

1. Rationale for the study

Vietnam is the country most severely affected by climate change among developing countries. According to a 2007 World Bank study, Vietnam is the second most at-risk country in the world due to rising sea levels, the inevitable consequence of which is the increase in the intensity of widespread saline intrusion in the Mekong Delta. This trend negatively affects the livelihoods of millions of people who depend on agriculture and aquaculture. Located in the East of the Mekong Delta, adjacent to the sea, Ben Tre is considered to be heavily affected by climate change. With a coastline of over 65km, relatively low and flat terrain, and located between large river mouths, Ben Tre is often strongly affected by saltwater intrusion. The aquaculture land area has expanded significantly further inland, combined with the degradation of coastal protection forests, allowing saltwater to penetrate deep into the fields, causing soil salinization, lack of domestic water, and serious reduction in rice-growing land, affecting livelihoods and food security in the region.

Researching the current status, developments and zoning of salinity is an effective method to help managers monitor and assess the impact of salinity intrusion, and at the same time propose appropriate measures to prevent and cope with climate change that is becoming increasingly complex and unpredictable in the Mekong Delta. There are many methods to research, assess and identify salinity-affected areas such as: direct field monitoring using rapid measuring devices, using borehole systems, through surface conductivity on radar images; or indirectly identifying affected areas through ecological indicators such as surface cover interpreted from remote sensing images such as MODIS, LANDSAT, Sentinel, VNREDSat-1.

Salinity intrusion must be quantified based on data from many discrete measurement points distributed over a large area with many different types of land use, traditional salinity monitoring methods show certain disadvantages. With the development of remote sensing technology, remote sensing now provides many types of data such as ground reflectance spectrum, aircraft images, multispectral satellite images, hyperspectral, radar, remote sensing technology brings a new approach to research, evaluate the evolution and zoning of salinity on a large scale. Combining the results and indicators obtained from remote sensing data with ground data is a new, objective approach that supports managers in zoning and determining the level of salinity impact, thereby having timely adaptive solutions suitable to the conditions of each locality.

The thesis "Research on the evolution and zoning of salinity intrusion in Ben Tre province using multi-layer, multi-resolution, multi-temporal remote sensing technology" has established a scientific basis for studying the evolution and zoning of salinity intrusion using a multi-layer, multi-resolution, multi-temporal remote sensing approach combined with field data. The results of testing, analysis, and evaluation of the thesis demonstrate the effectiveness of the technology in determining the mechanism, evolution, and zoning of salinity intrusion affected areas in the research area using the proposed remote sensing technology. Therefore, the thesis "Research on the evolution and zoning of salinity intrusion in Ben Tre province using multi-layer, multi-resolution, multi-temporal remote sensing technology" is urgent, topical, and has scientific and practical significance.

2. Aims of the study:

Establishing scientific basis and methodology for applying multi-layer, multi-resolution, multi-temporal remote sensing technology to improve the effectiveness of research on the evolution and zoning of saline intrusion in general and for the coastal area of Ben Tre province in particular.

3. Main research contents of the thesis:

- Research on integrated methods, analysis processes, assessment and zoning of salinity using multi-layer, multi-resolution, multi-temporal remote sensing data.
- Research on reflection, scattering, and absorption characteristics to determine the level of salinity from satellite images.
- Determine direct indicators (salinity index SI - Salinity Index), indirect indicators (such as humidity, evaporation, temperature, surface coverage, etc.) and correlation with supporting information to determine the level of salinity from satellite images.
- Collect and build a database of terrain, geomorphology, soil, current land use status, meteorological, hydrological and environmental monitoring data, including databases, multi-resolution, multi-temporal satellite images of Ben Tre province - the pilot research area.
- Determine the current status of salinity distribution, assess the level and succession of salinity using remote sensing data in Ben Tre province.

CHAPTER 1. OVERVIEW OF MULTI-LATENSE, MULTI-RESOLUTION, MULTI-TEMPORAL REMOTE SENSING TECHNOLOGY IN RESEARCH, ASSESSMENT AND ZONING SALINITY

1.1. Research on the application of multi-layer, multi-resolution, multi-temporal remote sensing in salinity research in the world

1.1.1. Ground spectrum

At the ground level, handheld spectrometers such as the GER3700 and ASD allow for the measurement of soil reflectance spectra over continuous wavelength bands from 400 – 2500nm with high spectral resolution. Data from these devices are fed into spectral libraries, which serve as the basis for classifying satellite and aerial images.

1.1.2. Multispectral remote sensing

In the study of salinity intrusion, multispectral images allow to distinguish between saline and non-saline soils and to identify soils with severe salinity. Multispectral remote sensing data are often used in combination with other thematic layers such as topography, geology, hydrology, soils, water quality, land use maps to improve accuracy. Multispectral image data often include the thermal infrared band (such as LANDSAT), which is a band where soil absorption and reflection are strongly influenced by chemical components such as sulfate, phosphate, and chloride. Information from thermal channels can be used to separate soils that are similar in their reflectance spectra in the visible band.

1.1.3. Hyperspectral remote sensing

Hyperspectral imagery provides a large number of spectral bands with high spectral resolution, allowing the differentiation of salt-tolerant from salt-intolerant plants, as well as the identification of more detailed characteristics of saline soils than multispectral imagery. Several studies have demonstrated the applicability of hyperspectral data in salinity studies. These studies have concluded that soil organic matter, soil moisture, and saline areas can be distinguished if data from airborne sensors are combined with field data.

1.1.4. Radar Remote Sensing

The application of radar remote sensing in the field of saline intrusion is still limited compared to optical remote sensing. The reason is partly due to the complexity of the data, partly due to the limited ability to access and collect radar remote sensing data. In general, for this field, researchers believe that channels C, P, especially channel L, are special in their ability to identify saline soil.

1.2. Research on the application of multi-layer, multi-resolution, multi-temporal remote sensing in the study of salinity in water in Vietnam

1.2.1. Research on application of multi-layer, multi-resolution, multi-temporal remote sensing technology

The need to use remote sensing data and field verification data is very diverse in many agencies and units in resource investigation work. Along with the abundance and availability of multi-spectral, multi-resolution remote sensing data as present, the solution to combine multi-layer remote sensing data as presented above including ground-based remote sensing, aircraft-based remote sensing and satellite remote sensing is a very effective integrated and complementary solution for specialized research.

Research on domestic radar remote sensing in Vietnam, there have been many studies on saline intrusion, however, the main research directions focus on the method of using dynamic models, simulating flow, water quality and sediment transport in rivers, irrigation systems, etc., research methods combined with geological characteristics of the research area, and integrating with the issue of climate change. There are not many studies using remote sensing data in detecting and monitoring saline intrusion in Vietnam, only stopping at using multispectral remote sensing images, almost not yet approaching hyperspectral remote sensing and radar remote sensing data.

1.2.2. Remote sensing in saltwater intrusion and soil salinity research.

In general, the need to monitor soil salinity for investigation, statistics and land use planning requires in-depth, large-scale research with appropriate approaches. In Vietnam, research on salinity has only stopped at direct measurement and statistics of salinity intrusion areas through the establishment of survey maps. However, this method still has many limitations such as time-consuming, laborious and low update capacity.

1.3. Scientific basis in salinity research

1.3.1. Salinity and saline soils

Saline soil is soil that contains dissolved salts at a higher concentration than normal, which is harmful to plants. To assess soil salinity, people use the quantity EC, which is the electrical conductivity of the soil, with the unit dS/m (1dS/m = 0.64‰). Saline soil is soil with an electrical conductivity >4 dS/m at 25°C, equivalent to a dissolved salt concentration of about 2.56 ‰ according to the usual calculation in Vietnam.

In this study, salinity is understood as the salinization of soil in agricultural production. Accordingly, saline soil is soil containing a sufficient amount of soluble salt to affect the growth and development of crops. Salinization is the process of intrusion and accumulation of salts and alkaline metals in the soil and water environment, causing this environment to become salty, or from less salty to more salty.

1.3.2. Mechanism of soil salinity and salinization

The mechanism of salinization and soil salinization includes the following forms:

- Saltwater intrusion due to seawater entering the inland due to tidal inflow or rising sea levels, creating a process of saltwater intrusion into coastal areas.

- The movement and infiltration of saltwater into the freshwater layer under the influence of groundwater development in coastal areas. This salty groundwater continues to seep into the adjacent land of the profile, thus causing salinization of soil and water.

- Seawater intrusion into rivers, especially in the dry season, when the amount of water flowing into the sea decreases, the tide from the sea carries salt deep into the river and surrounding areas, causing salinization of river water and surrounding areas. In coastal estuaries, saltwater can intrude below the freshwater layer, because saltwater has a larger density than fresh water, it forms a "wedge" of saltwater lying below and going deep into the coastal plain.

- Saltwater intrusion from the sea flows into rivers, through canals, and leaks into the cultivated soil layer. The expansion of coastal aquaculture areas is also a factor causing soil salinity through the osmosis mechanism.

- Evaporation: dissolved salts accumulate in places where evaporation is dominant, salty groundwater in the ground moves to the surface through capillary action, creating conditions for saltwater to intrude and cause soil salinization. Here, water is only a carrier for salt to move in the soil, and the water carrying salt in the soil is concentrated through evaporation and transpiration.

- Infiltration due to irrigation and water supply: due to unmeasured, salt or brackish water can be used to lead into irrigation systems, irrigating agricultural areas. This type often occurs in agricultural production areas intertwined with aquaculture. The level of salinization depends on the composition and concentration of salt in the water, the amount of water, irrigation methods, permeability and soil characteristics.

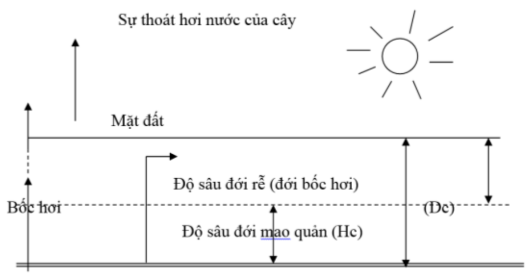


Figure 2 1. Relationship between evaporation, rhizosphere and capillary zone

1.3.3. Soil salinity

Currently, the world often uses the EC quantity, which is the electrical conductivity of the soil, to assess soil salinity. The unit of measurement for electrical conductivity EC is Siemen, denoted as S. Previously, this unit was denoted as mho. In practice, a unit smaller than S by a thousand times is often used, which is milliSiemen/cm, denoted as mS/cm, or deSiemen/m, denoted as dS/m.

+The unit dS/m = mS/cm = mmho/cm

+ Conversion according to salt concentration: 1dS/m = 0.64‰

Saline soil is soil with an electrical conductivity >4 dS/m at 25°C, equivalent to a dissolved salt concentration of about 2.56‰ according to the usual calculation in Vietnam.

Table 1- 1. Soil salinity classification according to EC (dS/m)

Class	***Saturated EC***	***EC (1:5)***
Non-saline	*0 - 4*	*0 - 0,6*
Slightly	*4 - 8*	*0,6 - 1,2*
Moderately	*8 - 15*	*1,2 - 2,3*
Highly	*>15*	*>2,3*

Table 1-2. Irrigation Water Salinity Classes

Class	***EC (dS/m)***	***Description***
I	*< 0,25*	*Freshwater*
II	*0,25 - 0,75*	*Slightly saline, usable*
III	*0,75 - 2,25*	*Moderately saline, harms rice*
IV	*2,25 - 5,00*	*Very saline, unsuitable*

1.3.4. Classification of saline soil

- Saline soil
- Sodic soil

Table 1- 3. Classification of some types of saline soil

Loại đất mặn	**EC (ds/m)**	**SAR**	**ESP (%)**	**pH**
Saline	>4	<13	<15	<8.5
Sodic	<4	>13	>15	>8.5
Saline-sodic	>4	>13	>15	

Table 1- 4. Classification of salinity levels affecting crops

Class	**EC (dS/m)**	**Salt (‰)**	**Crop Response**
Non-saline	0 – 2	0 – 1,28	Negligible impact
Slightly	2 – 4	1,28 – 2,56	Yield may be limited
Moderately	4 – 8	2,56 – 5,12	Many crops yield reduced
Saline	8 – 16	5,12 – 10,24	Only salt-tolerant crops survive
Very saline	> 16	> 10,24	Very few crops can tolerate

Table 1 -5. Salinity classification according to FAO

Class	**EC (mS/cm)**	**Salt (%)**
Non-saline	< 4	< 0,15
Slightly	4 - 8	0,15 - 0,35
Moderately	8 - 15	0,35 - < 0,65
Highly saline	> 15	> 0,65

Table 1-6. Salinity by Four Soil Parameters

Class	***EC (1:5)***	***% TMT***	***% Cl-***	***% SO_4^{2-}***
Non-saline	*0 - 0,5*	*< 0,25*	*< 0,075*	*< 0,03*
Slightly	*0,5 - 1,0*	*0,25 - 0,5*	*0,075 - 0,150*	*0,03 - 0,06*
Moderately	*1,0 - 2,5*	*0,5 - 1,0*	*0,15 - 0,30*	*0,06 - 0,12*
Highly	*trên 2,0*	*> 1,0*	*> 0,3*	*> 0,12*

1.3.5. Traditional methods for determining soil salinity by measuring soil salinity:

1.3.5.1. Laboratory method

1.3.5.2. Field method

1.3.5.3. Determining salinity through ecosystem changes and land use changes

Conclusion:

Remote sensing in soil salinity research is a combination of image interpretation, satellite image color combination interpretation, and digital satellite image analysis. With many advantages in terms of time and diversity of image types, remote sensing technology has gradually been used to study issues related to salinity intrusion, replacing traditional methods. The application of multi-layer, multi-resolution, multi-temporal remote sensing technology in research, assessment, and zoning of salinity intrusion combined with field data to calculate the area is feasible and provides quite high accuracy, especially for rice-growing areas affected by salinity intrusion.

CHAPTER 2. SCIENTIFIC BASIS AND METHODOLOGY FOR COMBINING MULTI-LAYER, MULTI-RESOLUTION, MULTI-TEMPORAL REMOTE SENSING DATA IN SALINITY EVOLUTION AND ZONING STUDIES

2.1. Scientific Basis for Applying Multi-Layer, Multi-Resolution, Multi-Temporal Remote Sensing Technology in Salinity Research, Assessment, and Zoning

2.1.1. Fundamentals of Optical Remote Sensing

Remote sensing imagery is used to gather information about the Earth's surface by recording electromagnetic radiation reflected from one or more portions of the spectrum. Each surface feature interacts uniquely with electromagnetic energy, resulting in distinct patterns of reflectance and absorption.

2.1.2. Saline Soil Indicators in Remote Sensing Imagery

- Presence of salt-tolerant vegetation and other signs such as reduced crop yields
- Soils with electrical conductivity (EC) > 4 dS/m exhibit weaker reflectance across the 500 – 2380 nm wavelength range

The correlation between soil-surface color, EC values, and sodium absorption ratios indicates that the hue of salt crust on the soil surface can serve as a reliable indicator for assessing the degree of salinity intrusion.

2.1.3. Spectral Reflectance Characteristics of Soil in Salinity Intrusion Studie

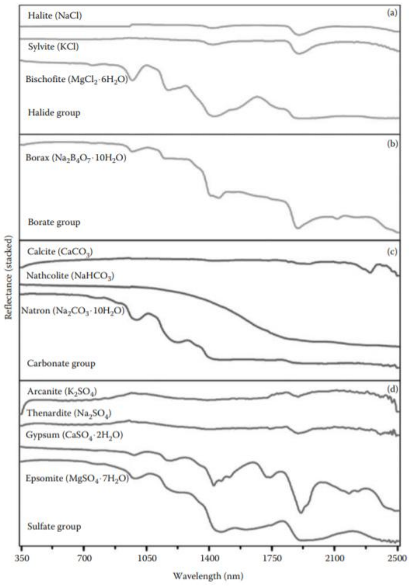


Figure 2-1. Spectral reflectance curves of salt minerals

2.2.4. Spectral reflectance characteristics of plants in salinity studies

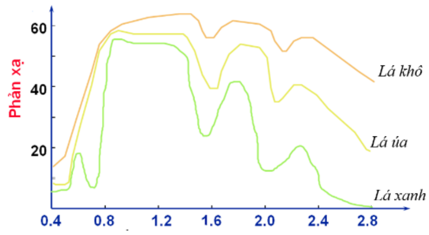


Figure 2 2. Spectral reflectance characteristics of leaves according to growth states

The spectral reflectance characteristics of plants vary according to wavelength and different growth stages of plants. Solar radiation is partially reflected immediately when it reaches the leaf surface. The spectral reflectance characteristics of plants depend on the characteristics of the leaves including the orientation and structure of the leaves.

2.1.5. Reflection characteristics of water

Water strongly absorbs radiation in the near-infrared and short-wave infrared regions. The reflection spectrum obtained from water originates from 3 sources:

+ Surface/specular reflection;

+ Reflection by suspended matter in water/volume reflection;

+ Bottom reflection.

2.1.6. Remote sensing indices in salinity studies

- Vegetation indices: NDVI, SAVI, EVI, GDVI
- Salt index, salinity index: CRSI, NDSI, SI
- Other physical indices: BI, INT

2.1.7. Scientific basis for applying Radar remote sensing in salinity research

Radar (Radio detection and ranging) is a concept used to detect and determine the location of objects by emitting microwave energy pulses in a direction of interest and then recording the intensity of the reflected pulses from the objects in the receiving field of the device.

2.2. Scientific basis of some machine learning algorithms in salinity research applications

Multilayer perceptron neural network (MLP-NN) - multilayer neural network model, Radial Basis Function neural networks (RBF-NN) - radial neural network model, Gaussian Processes (GP) - Gaussian distribution regression model, Support Vector Regression (SVR) - support vector regression model, and Random Forests (RF) - random forest classification model.

Conclusion

Using multi-spectral, multi-temporal remote sensing data combined with field data allows us to monitor land cover change trends, monitor crop yields, and identify areas with distribution of salt-tolerant and brackish-tolerant plants. The appearance of different types of crops or vegetation also has their own, specific reflections on satellite images and calculated indices from the images. From there, indirect index images can be calculated, helping to delimit the impact and assess the succession of saline intrusion or soil salinization in the research area.

For high-resolution satellite image sources in the world such as: SPOT, IKONOS, QuickBird, ... using information extraction to serve the research on saline intrusion will give reliable and accurate results. However, the proactive source of images as well as the coverage of these types of remote sensing images leading to high costs will be one of the first conditions that need to be considered to ensure feasibility in the research.

Applying multi-layer, multi-resolution, multi-time remote sensing technology in research, assessment, and zoning of salinization combined with field data to calculate the area is reasonable and when applied, the machine family gives quite high accuracy, especially for rice growing areas affected by salinization.

By monitoring the impact of XNM on rice growing areas for many years, we can completely draw out early warnings for people about natural disasters that may occur in the future, while helping managers have appropriate management methods for the situation at different times. From there, it shows that the ability to use radar, hyperspectral, multispectral, high, medium, low resolution, multi-temporal, and aerial remote sensing images in crop research also achieves positive results.

CHAPTER 3. APPLICATION OF REMOTE SENSING IN RESEARCHING ON DEVELOPMENT AND DIVISION OF AFFECTED ZONES OF SALINITY INFLUENCE IN BEN TRE PROVINCE

3.1. Overview of the research area

3.1.1. Overview of Ben Tre province

3.1.1.1. Geographic location

3.1.1.2. Natural conditions

3.1.1.3. Socio-economic conditions

3.1.2. Factors affecting salinity trends in Ben Tre province

3.1.2.1. Natural factors:

- Topography
- Climatic factors
- Hydrological factors
- Tidal regime
- Wave direction
- Upstream flow rate
- Mutual impact between river flow and sea dynamics

3.1.2.2. Human factors:

- due to land use
- due to groundwater exploitation
- due to irrigation systems

3.1.3. Current status of salinity in Ben Tre province

The analysis will use some estuary stations; and some stations on the main stream inside Ben Tre province that have sufficient data to assess the salinity changes in recent years in Ben Tre area. The assessment characteristics are hourly salinity data or maximum daily salinity; the number of times salinity is greater than the thresholds of 1g/l; 2g/l; and 4g/l.

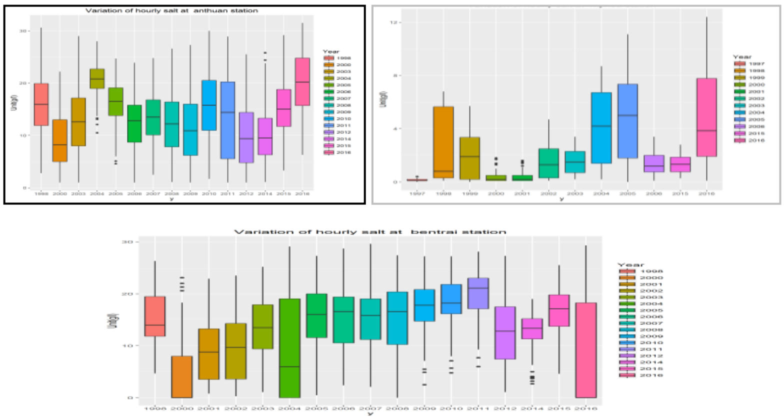


Figure 3-1 Evolution of hourly salinity characteristics over the years at some salinity measuring stations in Ben Tre province

Through the assessment of salinity changes and maintained salinity values according to thresholds at stations along Ham Luong River and Cua Tieu and Cua Dai Rivers in Ben Tre area, it can be seen that salinity is a complex phenomenon that is cumulatively affected by many factors such as upstream flow, water use, tides, riverbed morphology, monsoon winds, etc. In the same river system, the maximum salinity value changes over time differently. For example, in My Tho in 1998, it was an extreme salinity year; in My Hoa in 2016, it was an extreme year.

Spatial assessment of salinity: From the assessments of the overview of salinity developments in Ben Tre province, it shows that some years have historical salinity values in terms of both scope of influence and level of influence, such as the years 2020, 2016, 1998, 2005, 2008.

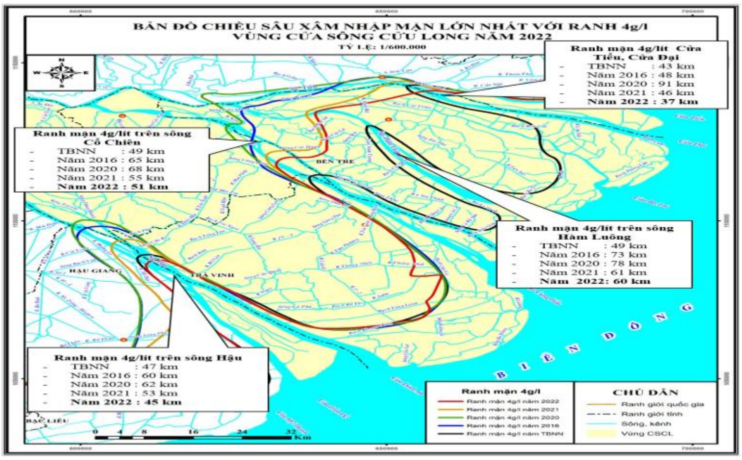


Figure 3-2. The largest saline intrusion range (4g/l)

Conclusion

Ben Tre has been implementing many measures to respond to climate change such as implementing many farming models and key projects to respond to climate change in the long term. In addition, there are climate change mitigation projects such as coastal afforestation projects, greenhouse gas emission reduction activities, and power system conversion, but Ben Tre has been and will be affected by climate change and salinity. According to the Ben Tre climate change scenario in 2020, we see that the area affected by salinity is increasing, salinity penetrates deep into the fields and increases gradually over the years. Salinity penetrates deep into the fields and over a long period of time, which will increasingly affect the province's agriculture. In addition, salinity intrusion remains at a high level without decreasing according to the law, so the work of responding to climate change and salinity still faces many difficulties.

3.2. Research on the application of salinity assessment and zoning using radar remote sensing data - pilot in Ben Tre.

3.2.2. Methodological approach to research on salinity assessment on land using radar imagery

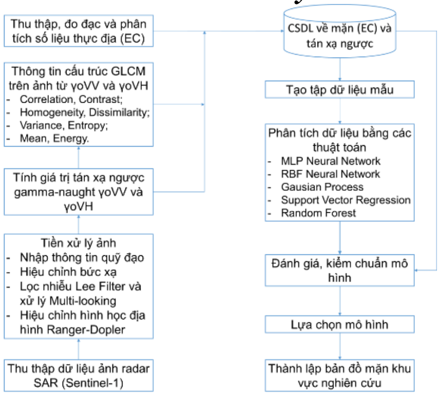


Figure 3 3: Process of analyzing and creating a map of salinity intrusion in soil using Sentinel-1 radar image data

3.2.3. Results of applying Sentinel-1 radar remote sensing data in assessing and zoning salinity in Ben Tre

Evaluation and model selection

The results of establishing and evaluating the Multilayer Perceptron Neural Network algorithm model to estimate soil salinity (EC) based on 18 input layers are shown in the statistical table below. The number of hidden neurons used by the algorithm ranges from 1 to 30. The error values of RMSE, MAE and correlation coefficient r are used to evaluate the developed model based on the training dataset and the accuracy assessment results based on the validation dataset.

Regarding the validation results, the GP model has the highest correlation (RMSE = 2.885, MAE = 1.897 and r = 0.808), followed by the RBF-NN model (RMSE = 2.732, MAE = 1.586 and r = 0.772). The remaining three models, the SVR model (RMSE = 3.946, MAE = 2.091, and r = 0.664), the MLP-NN model (RMSE = 3.450, MAE = 2.646, and r = 0.624), and the RF model (RMSE = 3.417, MAE = 2.269, and r = 0.581), had low predictive performance.

Table 3 1. Summary table of results of 5 machine learning algorithm models in the research area

Soil Salinity Model	Training Set			Validation Set		
	RMSE	MAE	r	RMSE	MAE	r
Multilayer Perceptron Neural Networks (MLP-NN)	3.744	2.936	0.836	3.450	2.646	0.624
Radial Basis Function Neural Networks (RBF-NN)	3.702	1.822	0.716	2.732	1.586	0.772
Gaussian Processes (GP)	3.170	1.860	0.839	2.885	1.897	0.808
Support Vector Regression (SVR)	4.784	1.868	0.685	3.946	2.091	0.664
Random Forests (RF)	2.008	1.252	0.949	3.417	2.269	0.581

Application of soil salinity mapping

Based on the above analysis results, it can be concluded that the Gaussian Processes (GP) model is the best for soil salinity mapping in the study area. GP has the second highest correlation coefficient in the group of models developed based on the training dataset, and ranks first when testing the model. Although the developed RF model has a high correlation coefficient, when testing the accuracy, the result is the lowest among the 5 methods. Therefore, the GP model was used to estimate the soil salinity (EC) value for each pixel of Sentinel-1 image in Ben Tre province.

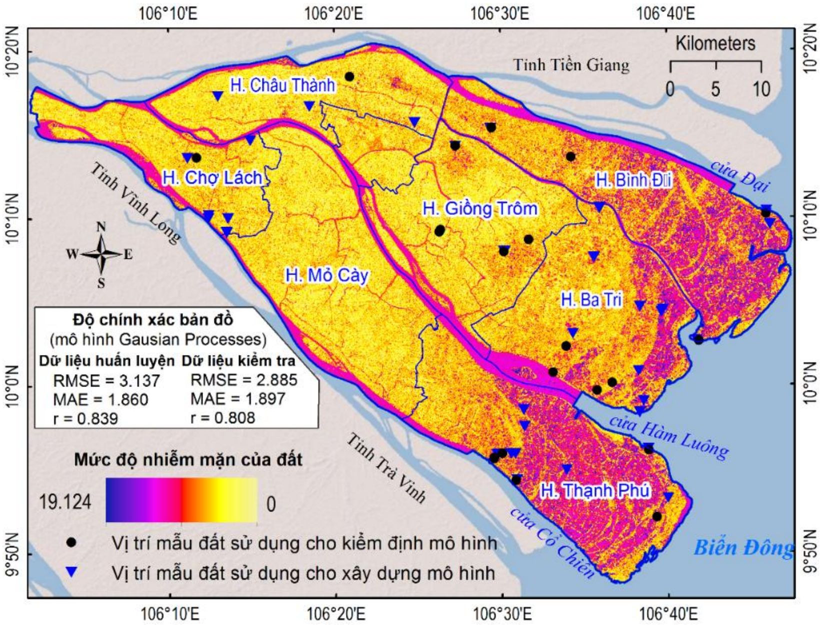


Figure 3 4. Soil salinity map of Ben Tre province using Gaussian Processes (GP) model

The estimated soil salinity map shows that areas in three coastal districts, Binh Dai, Ba Tri and Thanh Phu, have high salinity. This is because the three districts are located near the sea where saltwater can easily intrude into the mainland when the tide rises, and seawater goes deep inland through the mouths of Dai, Ham Luong and Co Chien rivers. More importantly, these are also the three districts with the largest salt production and aquaculture areas in Ben Tre province.

3.3. Research on application of assessment and zoning of salinity by optical remote sensing data - pilot in Ben Tre.

3.3.1. Optical remote sensing data in salinity research

There are many types of optical remote sensing data that can be used in salinity intrusion assessment research. The selection of data to use needs to consider the number of spectral channels, spectral resolution, spatial resolution, coverage, temporal resolution (repetition frequency), synchronization and applicability in multi-temporal research. The data used in the thesis includes multi-spectral Sentinel-2 images, LANDSAT5, 7, 8 and 9 images. This is a freely available image data source with spatial resolution from medium (Landsat: 30m) to high (Sentinel-2: 10m) for research in the entire Ben Tre province.

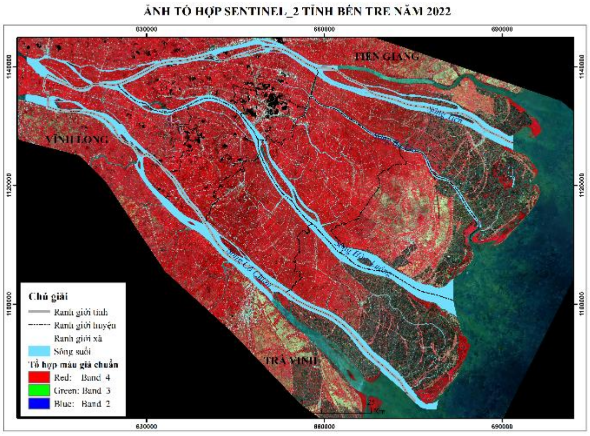


Figure 3-5. Color composite image of the study area in 2022

3.3.2. Field data processing and synchronization

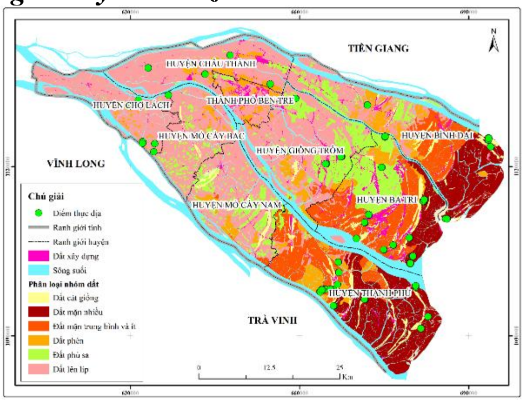


Figure 3 6. Map of field locations in Ben Tre province in 2018

3.3.3. Data integration and salinity zoning process

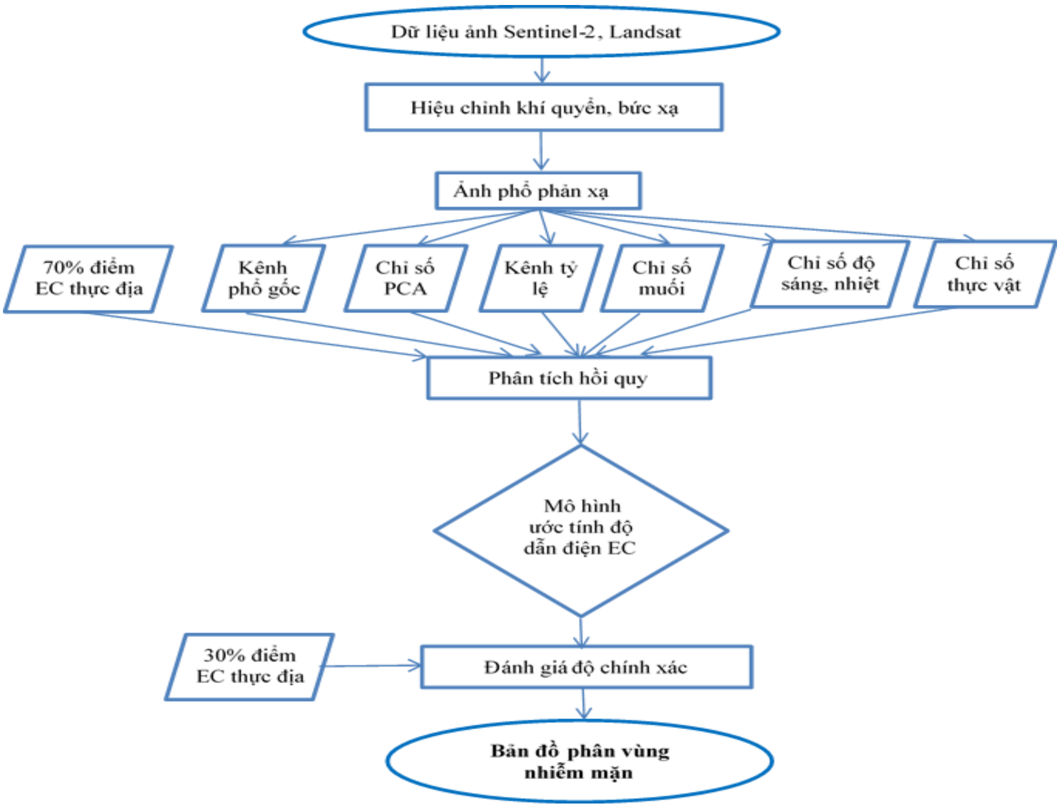


Figure 3-7. Process of salinity zoning from remote sensing and field data

The process of collecting, pre-processing, creating composite images and calculating physical index channels of Sentinel_2 and Landsat images is performed on GoogleEarthEninge (GEE). This is a cloud platform for seamless access and processing of a large number of satellite and aerial images available for free such as Landsat-8, Sentinel, MODIS, etc. Users can access and analyze data from public and private catalogs. Google Earth Engine works through the JavaScript Application Programming Interface (API) called Code Editor: https://code.earthengine.google.com/.

Remote sensing indices in the study of salinity intrusion in Ben Tre:

In the problem of zoning salinity intrusion in Ben Tre province, the researcher divided the physical indices into 5 groups including: original spectral channel group, principal component analysis index group PCA, brightness index group, vegetation index group, salt/salinity index and ratio index. Separate heat index

Multivariate regression analysis model

The physical index channels after calculation are extracted according to EC measurement point data and will be the input variables for the regression analysis models. In which, EC data is the dependent variable, and the index channels are the independent variables.

In this study, the researcher performed regression analysis using the Stepwise method to find the EC estimation model with the highest correlation. In which, the first step is to calculate univariate regression between EC values and all indices including original spectral channels, ratio channels, PCA analysis channels, vegetation index groups and salt index groups. Pearson correlation analysis is applied in this step to find the correlation between EC and index channels. Regression models including linear, ln() and second-order polynomial are performed at the 95% confidence level. Variables with low correlation can be eliminated and not used for the next correlation calculation steps. In other words, it is to reduce the number of insignificant input variables that can be "noise" for the overall regression analysis model. The removed variables are those with $sig>0.05$ and $r \approx 0$ low correlation, which can affect the accuracy of the model.

EC measurement data at each field survey area are assigned coordinates and linked to corresponding pixels on satellite images and index images. The point data to be entered into the calculation models is divided into 2 parts at a ratio of 70/30. Of which, 70% of the points are used to analyze and establish the correlation model, the remaining 30% of the data is used to evaluate the accuracy of the model. The points with field EC values were assigned to Sentinel-2 pixels, 10x10m resolution, a total of 1649 points, of which 1154 points were used for calculation and 495 points for accuracy assessment. With LANDSAT images, 30x30m resolution, the total number of EC correlation analysis points was 556 points, of which 389 points were used for calculation and 167 points for accuracy assessment. The accuracy of the salinity intrusion zoning map was also performed by linear regression analysis at a 95% confidence level between the calculated EC and 30% of the field EC point data. This is to ensure that the calculated EC is accurate not only on a specific dataset but also on other datasets. Two quantitative criteria to evaluate the accuracy of the model are R2 which represents the strength of the linear relationship between the measured EC in the field and the calculated EC; and the mean square error RMSE to measure the error between the two data sets. The smaller the RMSE value, the closer the calculated EC is to the measured EC in the field and vice versa.

3.3.4. Application of Sentinel-2 image assessment to assess salinity zoning in Ben Tre area

Statistical results show that the correlation between Sentinel-2 image channels and field EC data increased significantly $R^2 = 0.517$ compared to univariate correlation assessment. Or as with the ratio channel group, the salt index group, R^2 also increased. The brightness index group calculated from Sentinel-2 images had the lowest regression relationship. Most prominent is the correlation between the composite indexes and field EC values expressed by the S_EC9 model with a high correlation coefficient $r = 0.83$ and a regression coefficient $R^2 = 0.688$. The results of using this model to estimate soil salinity in the entire Ben Tre province are shown in the figure below. Highly saline soils are mainly distributed in Binh Dai, Ba Tri and Thanh Phu districts.

Therefore, to estimate the EC value for the entire Ben Tre province on different types of land cover status, the project analyzed EC with all spectral channels and index channels. The results are shown by the S_EC9 model with a high regression coefficient $R^2 = 0.688$.

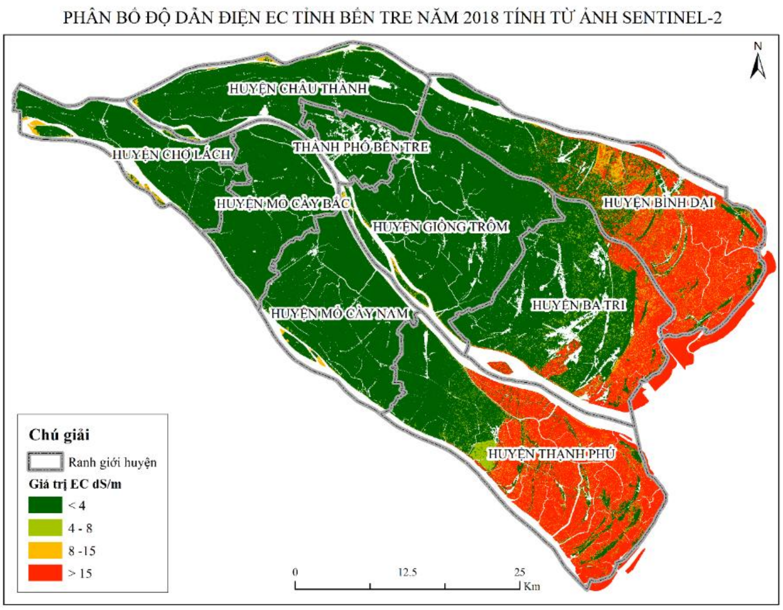


Figure 3-8. EC distribution calculated from Sentinel-2 images in 2018

3.3.5. Application of salinity zoning assessment using LANDSAT images in Ben Tre area

With data calculated from LANDSAT images, NCS performed the same steps as with Sentinel-2 images. The number of field sample points used to develop the model was 389 points. The results of the first step to assess the correlation level of each variable are channels, individual index images shown in the statistical table. The PCA4 variable (sig=0.081, r=0.088) was removed in the following calculations. In general, the correlation between image channels and indices calculated from LANDSAT images with field EC values is higher than that of Sentinel-2 images.

With multivariate regression functions, the correlation coefficient determined for each data group gives more positive results. The ratio channel group has a relatively high correlation coefficient r and regression coefficient R^2. However, the correlation of the L_EC8 indexes showed the highest correlation and regression ($r = 0.783$ and $R^2 = 0.613$). Therefore, the results of this model were selected to calculate the EC value for the entire Ben Tre province and also the results to analyze the change in the area of saline-intruded land in the province over the years.

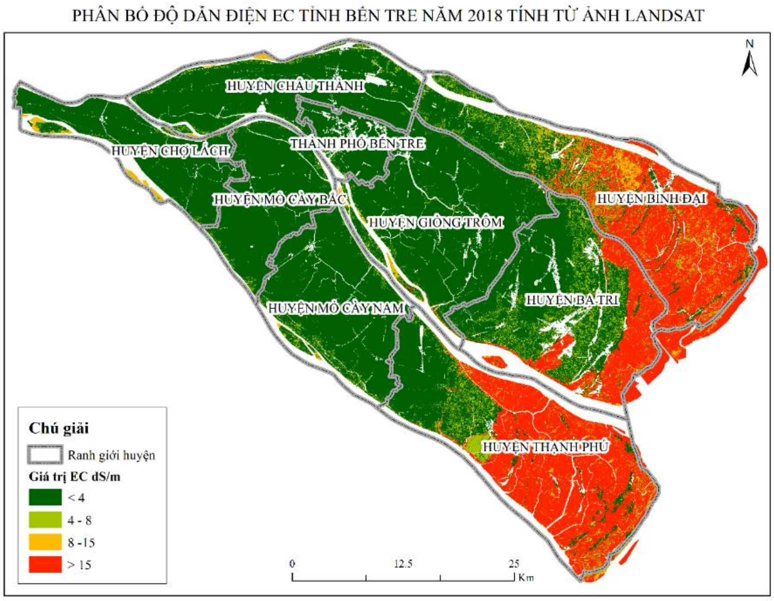


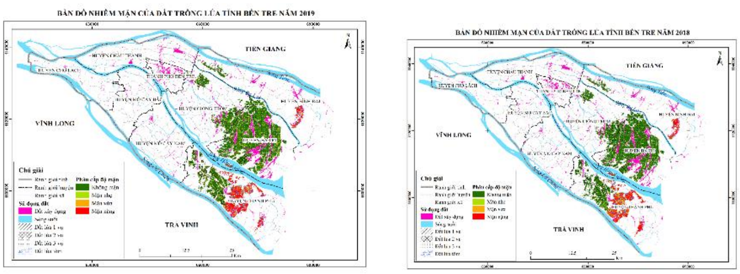
Figure 3-9. EC distribution calculated from Landsat images in 2018

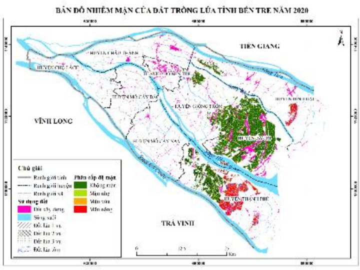
3.4. Establishment of salinity zoning maps for different periods

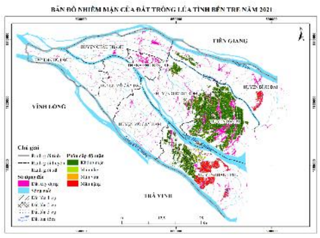
To evaluate the accuracy of salinity estimation models using EC conductivity index from Seninel-2 images (S_EC9) and LANDSAT images (L_EC8), the study used 30% of EC data measured in the field. The results of the correlation assessment between the model EC and the verified EC data are shown through the coefficient of determination R^2 and RSME. In both models calculated from Landsat and Sentinel-2, the coefficient of determination reached $R^2 > 0.7$ and RMSE was 2.06 and 1.69, respectively. This shows that both models are suitable for estimating EC conductivity or soil salinity in the study area. In particular, the S_EC9 model calculated from Sentinel-2 images has a higher correlation coefficient than the L_EC8 model calculated from LANDSAT images, with R^2 of 0.826 and 0.77, respectively. However, because it was only launched into orbit in 2015, the Sentinel-2 satellite image data is not suitable for assessing the evolution of salinity intrusion over the years. Therefore, the L_EC8 model of LANDSAT images is applied to calculate the salinity of the study area of Ben Tre province in the years 2005, 2010 and 2015, 2018, 2020, 2022 according to 4 salinity levels corresponding to the EC value (dS/m) of the Ministry of Agriculture and Rural Development.

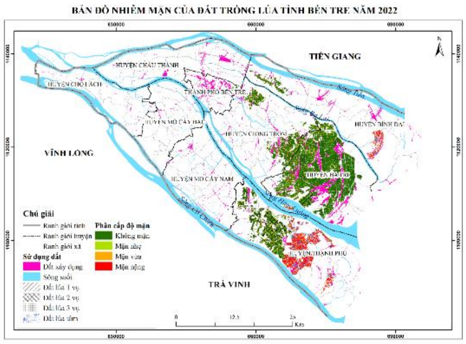
3.4.1. Zoning of salinity in rice fields

Monitoring and tracking salinity intrusion on rice fields in Ben Tre province using Sentinel-2 images in the period 2018-2022. The EC conductivity value is determined from the S_EC7 model, from which the EC values are classified to produce a salinity classification map on rice fields in Ben Tre province.







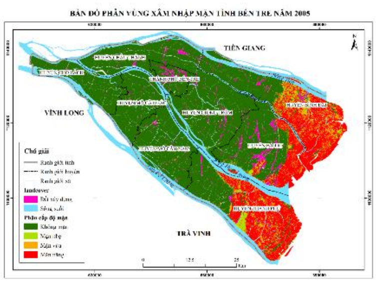


Map of salinity distribution on rice land in Ben Tre province from 2018 to 2022

Maps of salinity distribution on rice land in Ben Tre province from 2018-2022 extracted from Sentinel_2 images combined with the dry season show the change of salinity soil types on different rice growing areas.

3.4.2. Salinity zoning of the whole Ben Tre province

The L_EC8 estimation model of LANDSAT images is applied to determine the EC value of the whole Ben Tre province by year. The soil salinity classification scale is based on the EC value classification. The salinity zoning map of the whole Ben Tre province from 2005-2022 is shown in the figures below.



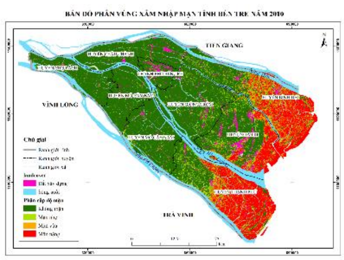
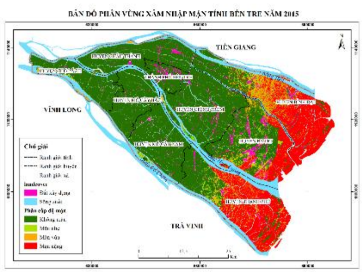
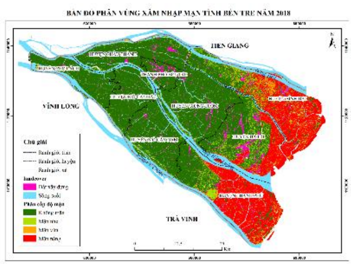
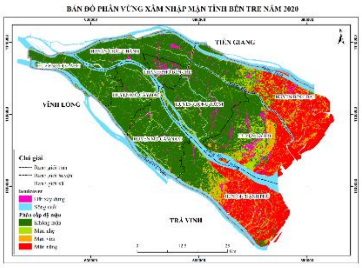
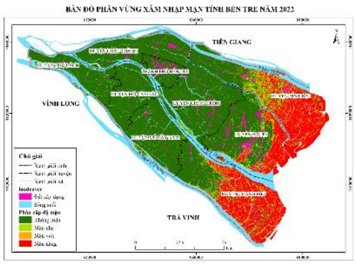


Figure 3-10. Map of intrusion zoning in Ben Tre province in 2005, 2010









The above figure shows the map of saline intrusion zoning of Ben Tre province in the dry seasons of the years: 2005, 2010, 2015, 2018, 2020 and 2022. In which, the dry seasons of 2016 and 2020 are the historical saline years of the province.

The area of heavily saline land is distributed along the coastline from North to South with the current land use status mainly being mangrove forests, brackish water aquaculture areas and salt-making areas of the province, concentrated in three districts of Binh Dai, Ba Tri and Thanh Phu. In which, Thanh Phu district has the largest area of saline land, followed by Binh Dai district and finally Ba Tri district.

The distribution of saline land types extracted from Landsat images for the entire Ben Tre province shows the continuous change in the area of saline land over different years. In 2015, a part of the province's rice-growing land was affected by salinity and turned into slightly saline land. By 2020, a part of this area was changed into moderately saline land, leading to people being unable to produce rice and having to leave the land fallow for many seasons. Inland districts such as Cho Lach, Chau Thanh, and Mo Cay Bac also suffered from salinity in perennial crop land.

3.5. Assessment of the current status and evolution of salinity

The current status of salinity in Ben Tre province has changed over time with the trend of increasing salinity and decreasing non-saline land, especially in the coastal districts of Binh Dai, Ba Tri and Thanh Phu. In the context of ongoing climate change, the dry season comes earlier and lasts longer, leading to a lack of water from upstream, causing seawater to penetrate deep into the fields, directly affecting crops and people's daily water. In addition, the spontaneous conversion of land use from rice cultivation to aquaculture by people is one of the causes of salinity in the soil.

From 2005 to 2022, the area of non-saline land in the province has decreased and salinity has tended to increase, mostly mild salinity. Within 17 years, the non-saline area has decreased by 11,985ha; On average, each year, the area of saline land decreased by 705 hectares/year. The area of saline land increased accordingly: the area of slightly saline land increased the most: 9,648 hectares, followed by heavily saline land at 1,337 hectares, and moderately saline land at 999 hectares.

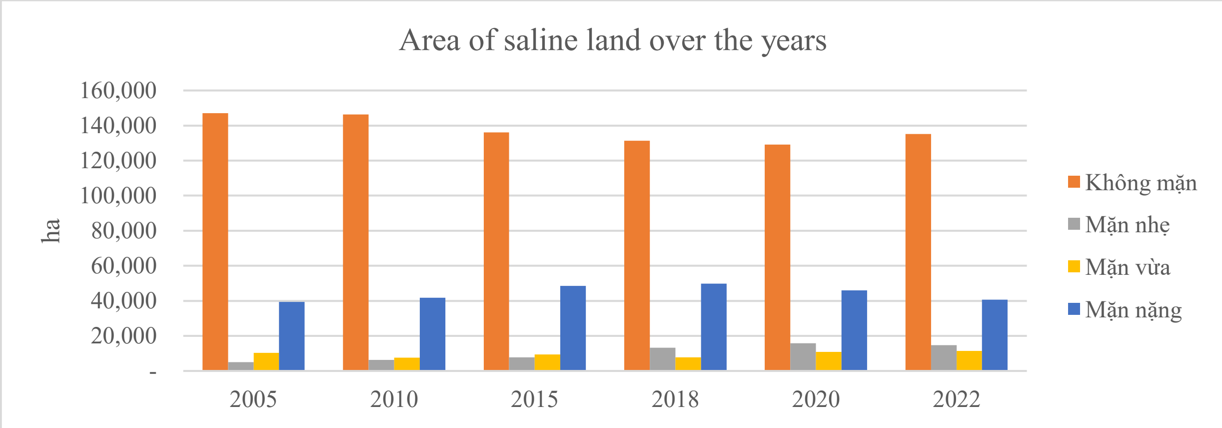
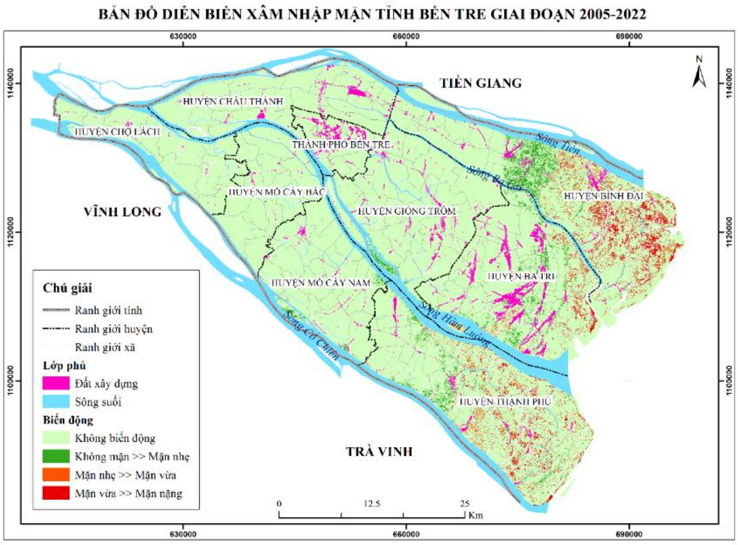


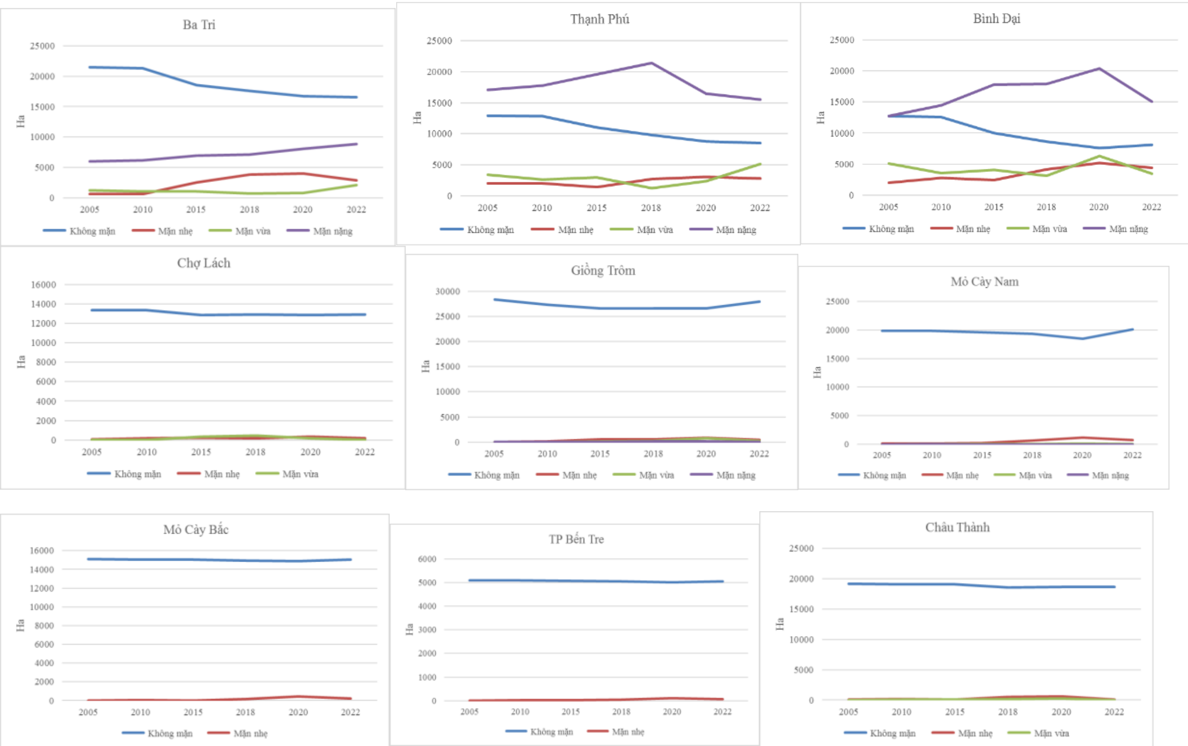
Figure 3-11: Changes in saline land area in Ben Tre province over the years



Map of salinity changes in Ben Tre province from 2005 to 2022

The above figure shows the changes in saline soil types in Ben Tre province from 2005 to 2022. The changes in these soil types are from non-saline soil to slightly saline soil, slightly saline soil to moderate saline soil, and from moderate saline soil to heavily saline soil. In the coastal districts of Binh Dai, Ba Tri, and Thanh Phu, this transition process is the most intense. The change from non-saline soil to slightly saline soil is the largest: 8,000ha, while moderate saline soil to heavily saline soil is 5,535ha. The land area changing from moderate saline soil to heavily saline soil is mainly brackish water aquaculture areas, areas growing 1 rice crop - 1 shrimp crop switching to industrial shrimp farming, people directly pumping in salt water.

The distribution of saline soil area in the dry season of each district also changes over time. Depending on the type of soil and land use, each district has different changes in soil types. In coastal districts, the area of moderately and heavily saline soil tends to increase, while in other districts, the area of slightly saline soil increases and the area of non-saline soil decreases.


Ba Tri
Ha
Không mặn
Mặn nhẹ
Mặn vừa
Mặn nặng
Thạnh Phú
Ha
Không mặn
Mặn nhẹ
Mặn vừa
Mặn nặng
Bình Đại
Ha
Không mặn
Mặn nhẹ
Mặn vừa
Mặn nặng
Chợ Lách
Ha
Không mặn
Mặn nhẹ
Mặn vừa
Giồng Trôm
Ha
Không mặn
Mặn nhẹ
Mặn vừa
Mặn nặng
Mỏ Cày Nam
Ha
Không mặn
Mặn nhẹ
Mặn vừa
Mặn nặng
Mỏ Cày Bắc
Ha
Không mặn
Mặn nhẹ
TP Bến Tre
Ha
Không mặn
Mặn nhẹ
Châu Thành
Ha
Không mặn
Mặn nhẹ
Mặn vừa

CONCLUSION

The results of the thesis "Research on the evolution and zoning of salinity in Ben Tre province using multi-layer, multi-resolution, multi-temporal remote sensing technology" have drawn the following conclusions and recommendations:

CONCLUSION

1. Soil salinity remains a serious problem worldwide, affecting the natural environment, causing damage to agriculture, and food security. Therefore, the establishment of soil salinity maps is very important, providing useful information on soil salinity levels, which can be useful for land use planning and management. Remote sensing technology has been developing rapidly, bringing practical applications to the community. The increasingly diverse sources of remote sensing data require research and development with appropriate methods to optimally exploit the information that remote sensing can provide.

Assess the evolution and zoning of salinity intrusion in the study area, specifically the production land affected by salinity based on the exploitation of technology, multi-layer, multi-resolution, multi-temporal remote sensing data. In addition, using multi-spectral, multi-temporal remote sensing data combined with field data allows us to monitor land cover change trends, monitor crop yields, and identify areas with distribution of salt-tolerant and brackish-tolerant plants. The appearance of different types of crops or vegetation also has its own, specific reflections on satellite images and calculated indices from the images. From there, indirect index images can be calculated, helping to delimit the impact and assess the succession of saltwater intrusion or soil salinization in the study area. In addition, using satellite images to monitor crop yields also helps managers accurately assess the impact of saltwater intrusion on the agricultural sector of the study area.

2. The study has successfully applied this multi-layer, multi-resolution, multi-temporal remote sensing integration technology in analyzing, assessing succession and zoning saltwater intrusion, piloted in Ben Tre province. Assessing the salinity intrusion in the study area, delimiting the salinity intrusion areas in Ben Tre province.

Research on radar remote sensing applications, through 5 machine learning algorithms Multilayer perceptron neural network, Radial Basis Function neural networks, Gaussian Process, Support Vector Regression and Random Forest to analyze Sentinel-1 SAR radar remote sensing data to estimate soil salinity. The results show that the model using Gaussian Process algorithm on Sentinel-1 SAR radar images gives the best correlation results.

Research on salinity intrusion assessment by multispectral remote sensing using multivariate regression model exploiting 2 types of satellite image data LANDSAT and Sentinel-2 shows relatively high correlation results. The multivariate regression model on Sentinel-2 images has a slightly higher correlation coefficient R2 than the regression model from LANDSAT images. However, Sentinel-2 satellite images only started to be available from 2015, while LANDSAT satellites have been operating continuously for a long time, LANDSAT 5 images from 1984, LANDSAT 8 from 2013. Therefore, the researcher has applied and exploited LANDSAT satellite data to assess the salinity intrusion in Ben Tre from 2005 to 2022.

3. The results of the assessment of salinity intrusion succession in Ben Tre show changes in space and time. The total area of saline land tends to increase gradually from 2005 to 2022. The salinity evolution of the province follows the rule of increasing gradually from the mainland to the coast, from non-saline land to saline land, from less saline land to more saline land.

RECOMMENDATIONS

1. Since 2015, land use in Ben Tre has changed significantly, specifically the conversion of land use purposes from shrimp-rice to specialized shrimp, from rice land to aquaculture or industrial shrimp farming, causing the area of saline land in the province to increase. In addition, the province's irrigation system is still not complete and synchronized, so in the dry season, high tides combined with monsoon winds, low water from upstream have made it possible for saline water to penetrate deep into the mainland along rivers and canals. Applying the results of the project can combine the zoning of the impact of saline intrusion to have response measures and make plans to reduce the harmful effects of saline intrusion and climate change.

2. Research and assessment of saline intrusion based on the application of remote sensing technology is an effective scientific method that allows monitoring and assessing the evolution of saline intrusion over time over a large geographical area. The approach of using multi-layer, multi-resolution, multi-temporal remote sensing data is a new, modern method that allows combining the superiority of many sources and many types of data together to supplement the limitations and increase the efficiency in research and resource investigation. The research results and scientific methods of the thesis can be completely deployed and applied to different geographical areas in the problem of saltwater intrusion research.

NEW CONTRIBUTIONS OF THE THESIS

1) Using a combination of methods, types of multi-resolution, multi-temporal, multi-layer remote sensing data and selecting appropriate assessment methods to assess and zonate the salinity impact in Ben Tre province

2) The thesis has analyzed, evaluated and calculated the application of machine learning algorithms to develop map construction processes based on multi-layer, multi-temporal, multi-resolution remote sensing data to build salinity zoning maps, salinity evolution maps in Ben Tre province

3) The results of the thesis have been analyzed and presented in the form of salinity evolution maps according to a 5-year cycle and calculated according to a 17-year cycle

4) The thesis has identified appropriate machine learning algorithms and satellite image data to be able to build and monitor salinity evolution in the entire Ben Tre province and can be applied to coastal provinces. This can help managers and authorities assess the impact of salinity under the impact of climate change.

LIST OF THE PUBLICATIONS RELATED TO THE DISSERTATION

1. Lê Minh Hằng, Vũ Văn Trường, Lê Vũ Hồng Hải (2020); Nghiên cứu kết hợp tư liệu ảnh viễn thám quang học và ảnh Sentinel-1A đa thời gian trong phân loại lớp phủ khu vực Hà Nội; Tạp chí Khoa học - Trường Đại học Sư phạm TP Hồ Chí Minh Tập. 15 Số. 11(b) (2018); ISSN: 1859-3100.
2. Phạm Việt Hòa, Nguyen Vu Giang ,Nguyen An Binh ,Lê Vũ Hồng Hải ,Tien Dat Pham ,Mahdi Hasanlou, Dieu Tien Bui (2019); Soil Salinity Mapping Using SAR Sentinel-1 Data and Advanced Machine Learning Algorithms: A Case Study at Ben Tre Province of the Mekong River Delta (Vietnam); Remote Sens., EISSN 2072-4292, Published by MDPI.
3. Lê Minh Hằng , Lê Vũ Hồng Hải , Nguyễn Văn Dũng (2026); Đánh giá khả năng sử dụng chỉ số RVI(radar vegetation index) trên ảnh vệ tinh sentinel-1 trong giám sát lớp phủ thực vật, thử nghiệm tại tỉnh thanh hóa, việt nam; Tạp chí Khoa học Kỹ thuật Mỏ - Địa chất; Số 1(2026); ISSN; 1859-1469

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