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Monitoring of coastline change using Sentinel-2 MSI data. A case study in Thanh Hoa Province, Vietnam

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Abstract. Vietnam is a coastal country with a coastline of more than 3,260 km, stretching from north to south. Coastal change in Vietnam is complicated further by the effects of climate change, including erosion and accretion, causing great impacts on infrastructure and the environment. This article presents the results of assessing coastline changes in Thanh Hoa Province (North Central region of Vietnam) from Sentinel-2 MSI satellite image data for the period 2015–23. Three Sentinel-2 MSI images taken in December 2015, December 2020 and December 2023 were used to calculate the water indices, including Normalised Difference Water Index (NDWI), Modified Normalised Difference Water Index (MNDWI) Argumented Normalised Difference Water Index (ANDWI) and Automated Water Extraction Index (AWEIsh), then extract the shoreline using the thresholding method and select the water index with the highest accuracy through comparing the overall accuracy and Kappa coefficient. The coastlines of 2015, 2020 and 2023 years are overlaid to evaluate the coastal changes in the study area. The results received in the study provide objective and timely information, helping managers effectively monitor and respond to coastline changes.

Introduction

Vietnam has a terrain stretching from north to south with a long coastline and many estuaries. Vietnam's coastline is winding, with many straits, coastal bays and about 114 estuaries flowing into the sea. Vietnam is also one of the countries most heavily affected by climate change, causing sea level rise and natural disasters such as storms and floods (Truong et al. 2022). This natural feature leads to complex shoreline change, affecting coastal ecosystems, infrastructure and production activities.

Assessing riverbank and coastal changes from remote-sensing data is an issue of practical significance and has been researched by many scientists around the world. Studies on the application of remote-sensing techniques in monitoring shoreline changes are based on the difference in spectral reflectance of "water" and "non-water" objects. Water bodies can be clearly distinguished from other land-cover objects due to the difference in spectral reflectance characteristics, especially in the near-infrared and short-wave infrared ranges. In this waveband, water absorbs most of the electromagnetic radiation energy, so these spectral bands are often used to classify "water" and "non-water" objects. Many methods of water extraction from optical satellite images have been proposed, such as the thresholding method (Foody 2002), band rationing method (Alesheikh et al. 2007) and spectral water indices method (Acharya et al. 2018).

Water indices calculated from multispectral satellite images have been effectively used in water body extraction and have proven themselves far simpler to apply than thresholding and classification methods. Until now, many water indices have been proposed for water extraction, such as Normalised Difference Water Index (NDWI) (McFeeters 1996), Modified Normalised Difference Water Index – MNDWI (Xu 2006), Water Ratio Index – WRI (Shen and Li 2010), Enhanced Water Index – EWI (Yan et al. 2007), Multi-Band Water Index – MBWI (Wang et al. 2018), Augmented Normalised Difference Water Index – ANDWI (Rad et al. 2021), and Land Surface Water Index – LSWI (Chandrasekar et al. 2010). In 2014, Feyisa et al. proposed the Automatic Water Extraction Index (AWEI) based on a linear combination of the blue, green, NIR, SWIR1 and SWIR2 bands of Landsat TM. The AWEI index includes two indices – AWEInsh and AWEIsh – of which, AWEInsh is mainly used in areas with an urban background, while AWEIsh is primarily designed to remove shadow pixels (Feyisa et al. 2014). In general, the water indices calculated from multispectral images can be divided into two groups: the indices using 02 spectral bands (green and NIR or SWIR1), such as NDWI, MNDWI, LSWI and the indices using multiple image bands, including visible (red, green, blue) and infrared bands (NIR, SWIR1, SWIR2), such as ANDWI, AWEInsh and AWEIsh. Some studies have used many different water indices to classify "water" and "non-water" from multispectral images, thereby selecting the water index with the highest accuracy for the study area (Mustafa et al. 2017; Trinh et al. 2020; Liu et al. 2022; Serban et al. 2022; Laonamsai et al. 2023). The results obtained in the above studies show that each water index has different effectiveness in water extraction for different study areas. Thus, for each specific study area, it is necessary to experiment with different water indices and select the index with the highest accuracy in monitoring shoreline changes.

Most of the spectral water indices proposed so far use Landsat data; however, Landsat images with a spatial resolution of 30 m face many limitations when monitoring coastline changes in small areas. These limitations can be overcome when using Sentinel-2 MSI satellite images with spatial resolutions up to 10 m. In 2021, Jiang et al. proposed the Sentinel Water Index (SWI) using RedEdge1 (band 5) and SWIR1 (band 11) bands of Sentinel-2 MSI image to extract water objects (Jiang et al. 2021). Sentinel-2 MSI image data are also used to assess coastline changes in many different studies around the world (Astiti et al. 2019; Taufik et al. 2019; Liu et al. 2022; Castillo-Campo et al. 2023) and in Vietnam (Duong et al. 2021). Darwish and Smith combined the use of multi-resolution remote-sensing data, including Landsat 8 OLI, Sentinel-2 MSI and PlanetScope images for assessing coastline change in El-Alamein, Egypt (Darwish and Smith 2021). The thresholding method used in these studies to automatically classify "water" and "non-water" objects from water indices, the most common of which is the use of Otsu algorithm (Adhikari 2019; Tang et al. 2022).

This article presents the results of assessing coastline changes in the coastal area of Thanh Hoa Province (North Central Vietnam) from Sentinel-2 MSI satellite image data for the period 2015–23. Water indices, including NDWI, MNDWI, ANDWI and AWEIsh are used to classify "water" and "non-water" objects, thereby evaluating accuracy through Kappa coefficient and overall accuracy to select the index with the highest accuracy. The received results are vectorised and overlaid to evaluate shoreline changes in the period 2015–2023.

Materials and methods

Study area

Thanh Hoa is a province in the North Central Coast of Vietnam, located 150 km from Hanoi capital (Fig. 1). The province has a natural area of more than 11,000 km2 and is the fifth largest

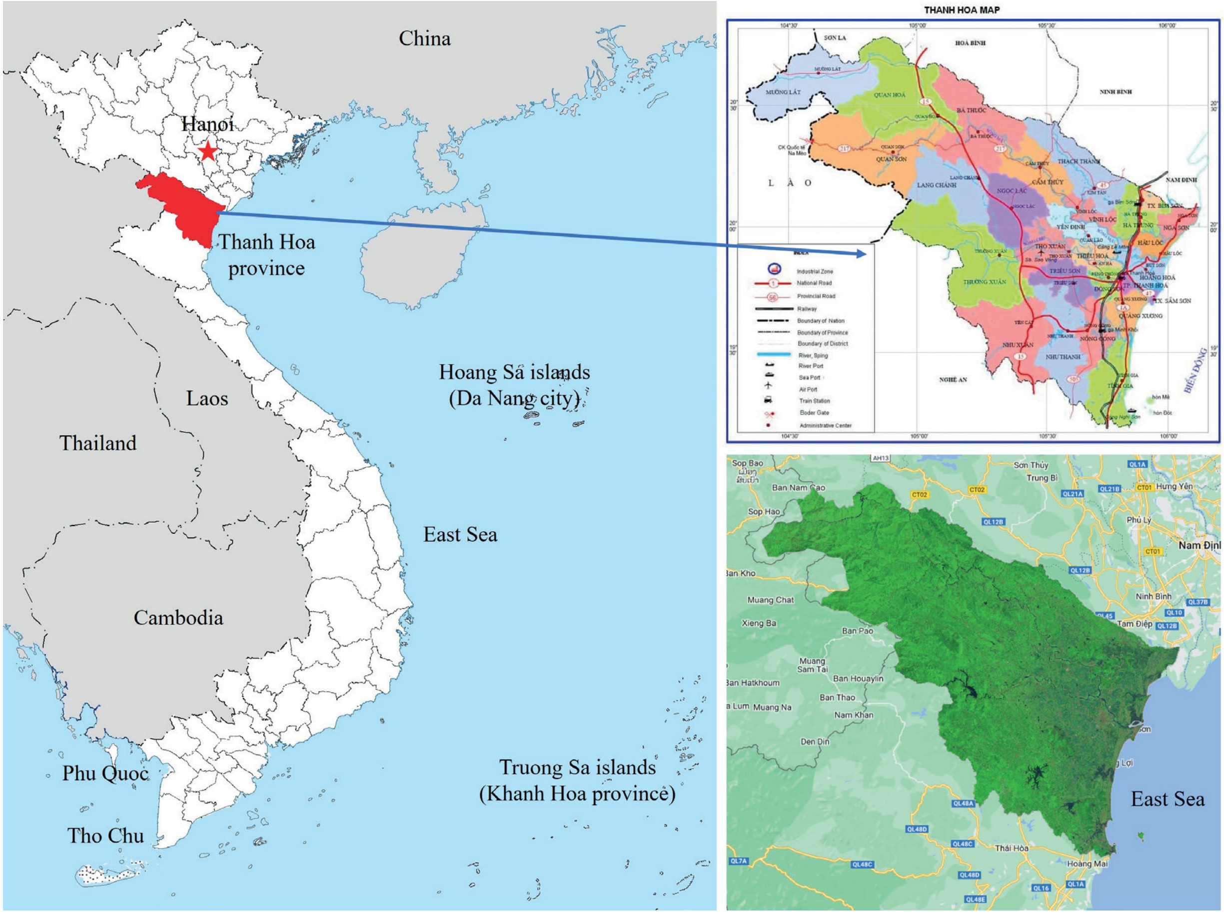

Fig. 1. Geographical location of study area
Source: Authors'

province in Vietnam. Thanh Hoa has a diverse and rich ecosystem with all types of terrain (midland mountains, plains and coastal areas), in which the coastline is 102 km long. Along the coast there are five river mouths that are convenient for sea transport.

Recently, the coastline of Thanh Hoa Province changed drastically, including erosion and accretion, especially in river mouths (Ma River, Truong Giang River, Yen River). The situation of riverbank and coastal erosion in the study area is becoming more complicated; water has eroded deeply into agricultural land, greatly affecting agricultural activities and people's lives in coastal areas. Figure 2 presents some pictures in the survey in the Hoang Phu commune, Hoang Hoa district, Thanh Hoa Province. This field survey was conducted on December 8, 2023, close to the time of Sentinel-2 MSI image acquisition (December 9, 2023). Hoang Phu commune (Hoang Hoa district) is one of the areas most seriously affected by coastal erosion in recent times.

Materials

In this study, three Sentinel-2 MSI scenes taken on December 1, 2015, December 26, 2020 and December 9, 2023 were used to calculate the difference water indices (NDWI, MNDWI, ANDWI and AWEIsh). Sentinel 2 MSI image data are preprocessed, then cropped according to the study area boundaries (Fig. 3).

The Sentinel-2 mission consists of two satellites (Sentinel-2A and Sentinel-2B) developed to support vegetation, land cover and environmental monitoring. The Sentinel-2 MSI acquires 13 spectral bands ranging from visible and near-Infrared (VNIR) to shortwave infrared (SWIR) wavelengths along a 290-km orbital swath (Table 1). The satellites will provide a revisit time of ten days at the equator with one satellite, and five days with two satellites. Sentinel-2 MSI imagery includes 10-m resolution visible and NIR bands and 20-m resolution SWIR bands.

Fig. 2. Some photos of coastal erosion in Hoang Phu commune, Hoang Hoa district, Thanh Hoa Province during the survey on December 8, 2023
Source: Authors'

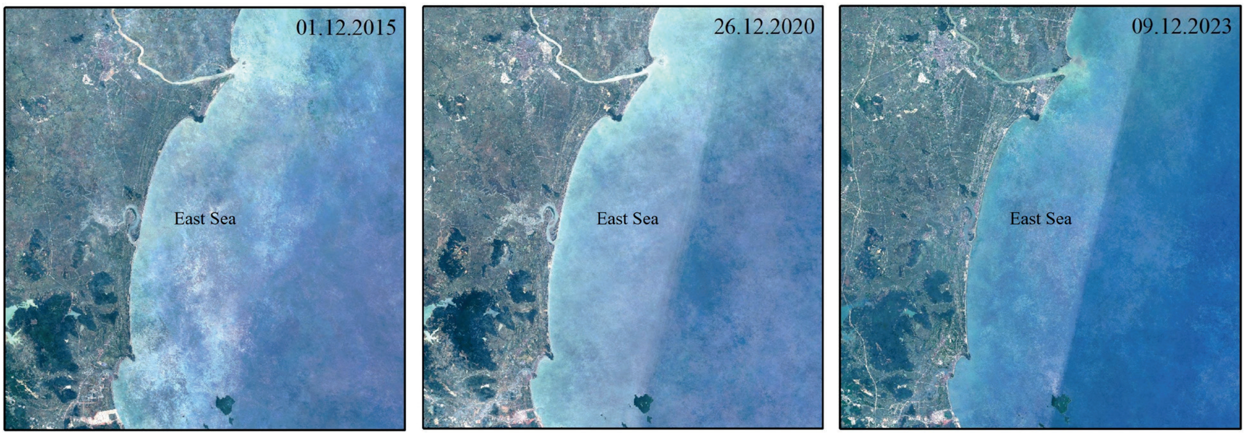

Fig. 3. Sentinel-2 images data of the study area
Source: Authors'

Methodology

In this study, four water indices calculated from Sentinel-2 MSI images, including: NDWI, MNDWI, ANDWI and AWEIsh are used to extract water objects. The NDWI index was proposed by McFeeters based on the high reflectivity of water at green band and strong absorption at NIR band. The NDWI index was calculated according to the following formula (McFeeters 1996):

$$NDWI = \frac{\rho_{GREEN} - \rho_{NIR}}{\rho_{GREEN} + \rho_{NIR}} \quad (1)$$

where: $\rho GREEN$, ρNIR – reflectance values in the green (band 3) and NIR (band 8) bands of the Sentinel-2 multispectral image.

Table 1. Sentinel-2 band characteristics

Sentinel-2 Bands	Central wavelength (μm)	Resolution (m)
Band 1 – Coastal aerosol	0.443	60
Band 2 – Blue	0.490	10
Band 3 – Green	0.560	10
Band 4 – Red	0.665	10
Band 5 – Vegetation Red Edge	0.705	20
Band 6 – Vegetation Red Edge	0.740	20
Band 7 – Vegetation Red Edge	0.783	20
Band 8 – NIR	0.842	10
Band 8A – Vegetation Red Edge	0.865	20
Band 9 – Water vapour	0.945	60
Band 10 – SWIR-Cirrus	1.375	60
Band 11 – SWIR	1.610	20
Band 12 – SWIR	2.190	20

Xu (2006) developed the MNDWI index, which uses the SWIR1 band (band 11 of Sentinel-2 MSI image) instead of the NIR band (band 8). The MNDWI index is calculated by the following formula (Xu 2006):

$$MNDWI = \frac{\rho_{GREEN} - \rho_{SWIR1}}{\rho_{GREEN} + \rho_{SWIR1}} \quad (2)$$

The ANDWI index (Rad 2021) is based on the use of spectral reflectance in the visible (blue, green, red) and infrared bands (NIR, SWIR1, SWIR2) to increase the contrast between water and other objects. ANDWI is calculated using the following formula:

$$AWEI_{sh} = \rho_{BLUE} + 2.5\rho_{GREEN} - 1.5(\rho_{NIR} + \rho_{SWIR1}) - 0.25\rho_{SWIR2} \quad (3)$$

According to Feyisa et al. (2014), five spectral bands of Sentinel-2 MSI data were used to calculate the AWEIsh index using the following equation:

$$ANDWI = \frac{\rho_{BLUE} + \rho_{GREEN} + \rho_{RED} - \rho_{NIR} - \rho_{SWIR1} - \rho_{SWIR2}}{\rho_{BLUE} + \rho_{GREEN} + \rho_{RED} + \rho_{NIR} + \rho_{SWIR1} + \rho_{SWIR2}} \quad (4)$$

Otsu's thresholding algorithm has been used to extract "water" and "non-water" objects from water indices. The Otsu algorithm is an automatic threshold selection method for the reduction of a greyscale image to a binary image containing two classes. In this method, the optimal threshold value is selected based on maximising the inter-class variance (Li and Wang 2015). This method is very effective for classifying "water" and "non-water" objects from greyscale images, such as water indices images. The accuracy of classifying "water" and "non-water" objects from water indices using the Otsu thresholding algorithm is evaluated and compared through the overall accuracy value and Kappa index, after which the water index with the highest accuracy is selected. The results of water extraction are vectorised and corrected for tidal effects to create the shoreline changes map.

Flowchart for the methodology used in this study to evaluate coastline dynamic using Sentinel-2 MSI data is shown in Figure 4.

Results and discussion

Sentinel-2 MSI image data for the period 2015–2023 are preprocessed and then used to calculate four water indices, namely NDWI, MDNWI, ANDWI and AWEIsh. The water indices calculated from Sentinel-2 MSI data in this study are shown in Figures 5–8. The water indices images show water objects as bright white pixels because the spectral reflectance value of water is much higher in the visible bands than in the NIR and SWIR bands. By contrast, "non-water" objects such as vegetation and soil are represented by dark pixels in water index images due to their spectral reflectance being higher in the infrared wavelength than in the visible wavelength.

Next, the Otsu method is used to extract the water object from the water indices image. To evaluate the accuracy of water object classification,

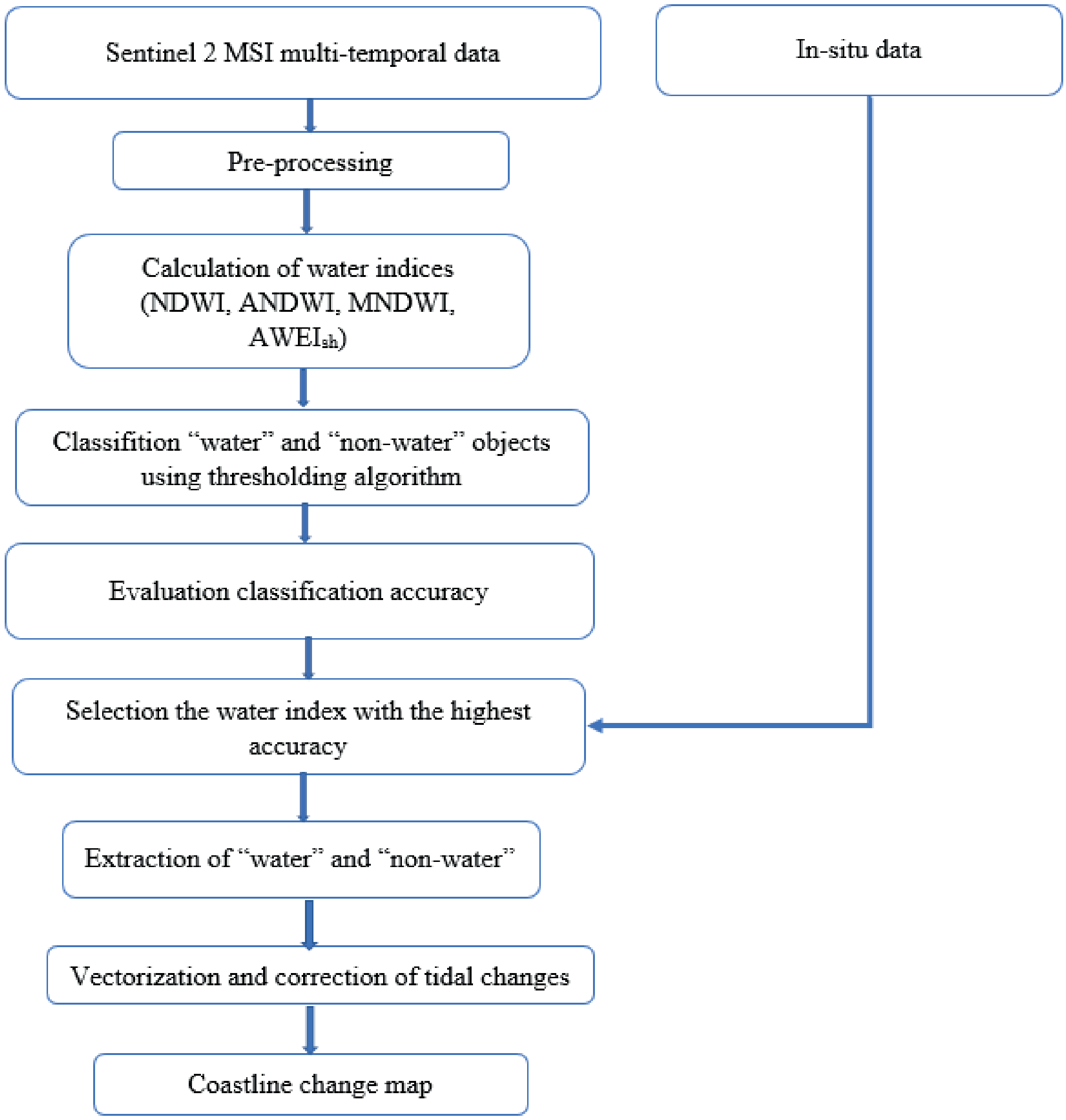

Fig. 4. Flowchart of the methodology for coastline change mapping

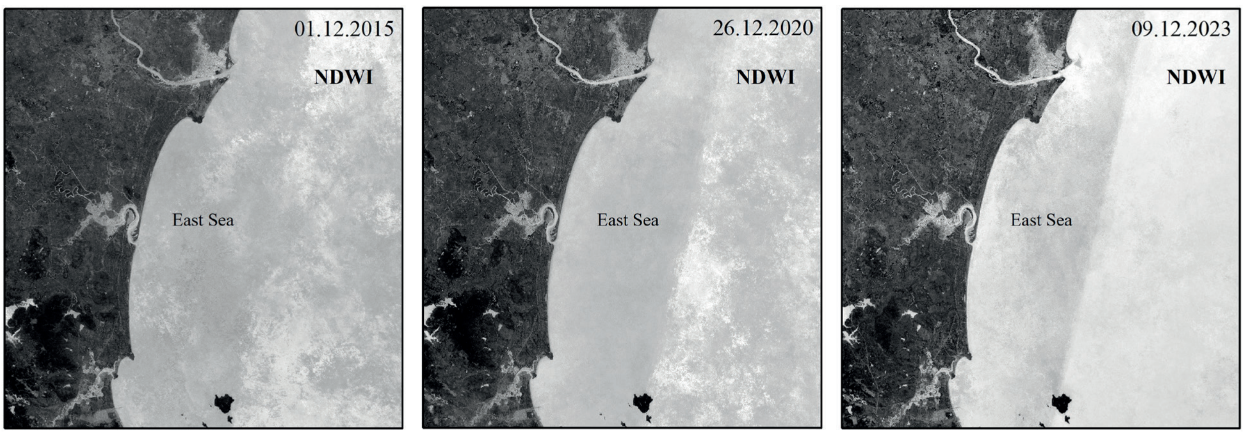

Fig. 5. NDWI index, calculated from Sentinel-2 MSI images

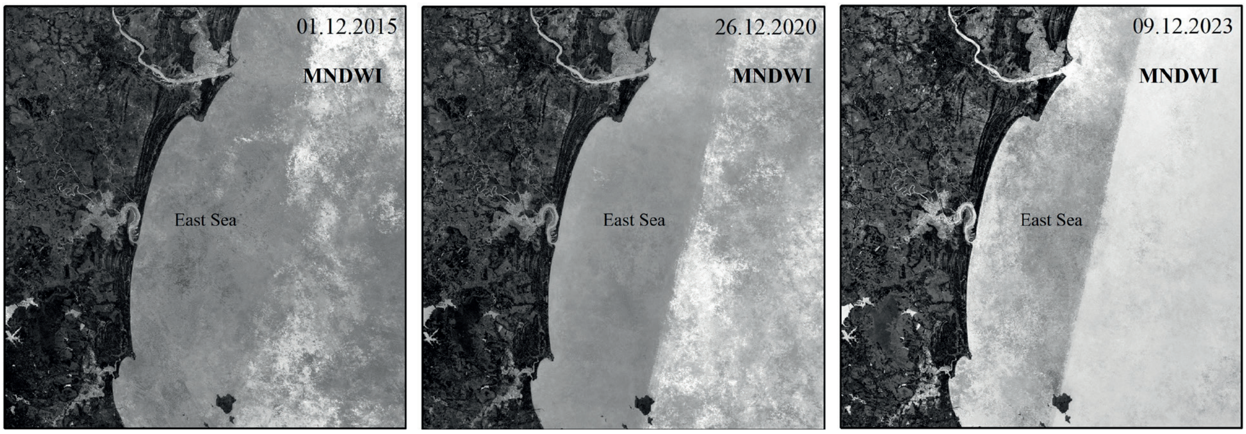

Fig. 6. MNDWI index, calculated from Sentinel-2 MSI images

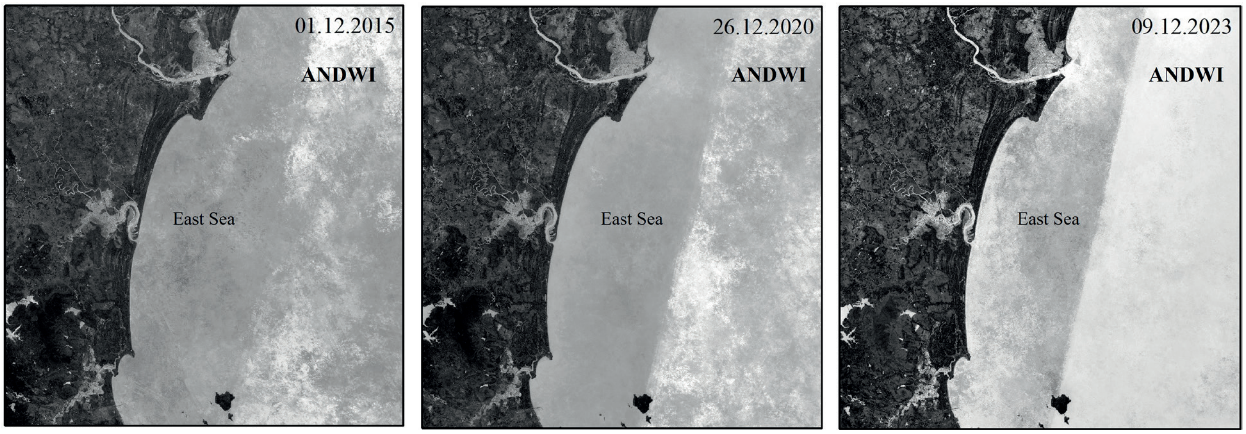

Fig. 7. ANDWI index, calculated from Sentinel-2 MSI images

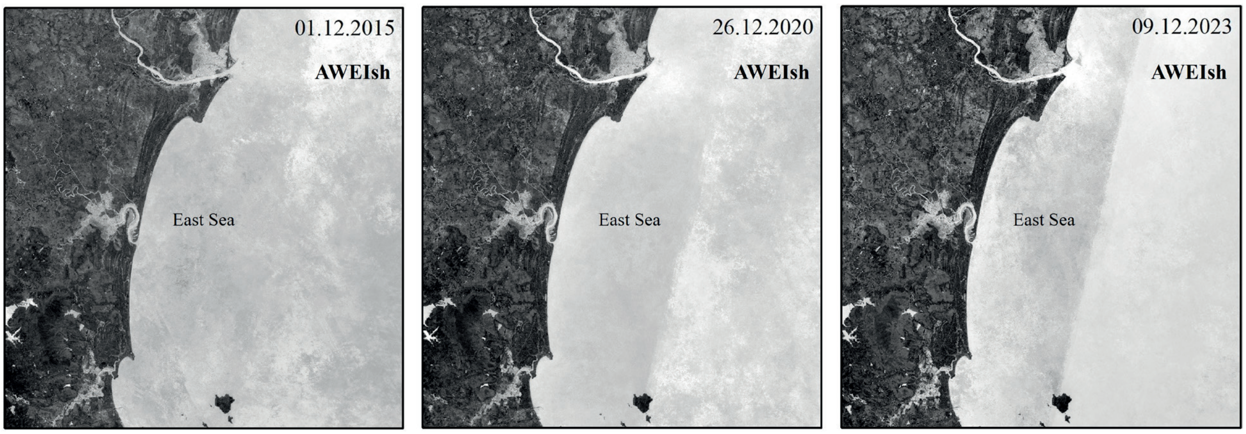

Fig. 8. AWEIsh index, calculated from Sentinel-2 MSI images

the Kappa index and overall accuracy were used in the study. Table 2 presents the results of evaluating the accuracy of water object classification from four different water indices (NDWI, MDNWI, ANDWI and AWEIsh) using the overall accuracy value and Kappa index. The obtained results show that the classifying of water objects using the MNDWI index has high accuracy compared to the other water indices (NDWI, ANDWI and AWEIsh) in all three cases using Sentinel-2 MSI images taken on December 1, 2015, December 26, 2020 and December 9, 2023. The Kappa index when classifying water objects from the MNDWI index reached 0.904, 0.913 and 0.911 for Sentinel-2 MSI images taken on December 1, 2015, December 26, 2020 and December 9, 2023, respectively.

Meanwhile, the Kappa index reached 0.877, 0.887 and 0.885 for the NDWI index; 0.886, 0.891, 0.890 for the ANDWI index; and 0.895, 0.896, 0.902 for the AWEIsh index. The threshold value to extract a water object from the MNDVI index for Sentinel-2 images in 2015, 2020 and 2023 is 0.043, 0.051 and 0.052, respectively.

Similarly, the overall accuracy value when classifying water objects using the MNDWI index from three Sentinel-2 MSI images in the period 2015–23 reached 95.25%, 95.67% and 95.56%, respectively. This accuracy was also significantly higher when using NDWI (93.87%, 94.37% and 94.28%), ANDWI (94.31%, 94.60% and 94.52%) and AWEIsh water indices (94.81%, 94.76% and 95.09%).

From this result, the MNDWI index was selected to extract the shoreline of the coastal area of Thanh Hoa Province. Tide levels at the time of acquiring Sentinel 2 MSI satellite images vary. Therefore, the coastline needs to be referenced to a unified tidal level to limit the influence of tides on the results of coastline extraction from remote-sensing images. In this study, the tide level in Hoang Phu commune, Hoang Hoa district (Thanh Hoa province) on December 1, 2015, December 26, 2020 and December 9, 2023 at 10:30 a.m. is referenced from the website cau-ca.com. This is close to the time of acquiring Sentinel 2 MSI images in the northern region of Vietnam. The tide level in the study area on December 1, 2015, December 26, 2020 and December 9, 2023 is not much different, from 1.7 m to 2.2 m. For consistency, in the study, the shoreline was adjusted to a tidal level of 1.7 m.

The coastline change map in the study area for the period 2015–2023 established from Sentinel-2 MSI satellite images is shown in Figure 9. Analysis of the obtained results shows that coastline change occurs strongly in the area of Ma River estuary and Ghep creek (Yen River). For the remaining coastal areas, the coastline is relatively stable with little change in the period 2015–2023.

Shoreline changes in Ma River estuary

The red square in Figure 9 and the enlarged image show the coastline changes in the Ma River estuary area (Hoang Hoa district and Sam Son city) using Sentinel-2 MSI images. It can be seen that the area on both sides of the Ma River estuary eroded strongly in the period 2015–2023. In the northern coastal area of the Ma River estuary (south of Hoang Phu commune), erosion occurred continuously in the period 2015–2023 with an average speed of over 53 m/year. In the central area of Hoang Phu commune (the headland protruding into the sea, shown by red square 1), the coastline accreted strongly in the period 2015–2020 (average speed of 56 m/year), then eroded in the period 2020–2023 (average erosion rate 37 m/year). The shoreline erosion and accretion in the estuary area is strong due to the impact of hydrodynamic factors as well as sand mining activities in the estuaries. The northern coastline of Hoang Phu commune (above red square 1) recorded coastline accretion at an average rate of about 35 m/year during the period 2015–2023.

In the southern area of the Ma River estuary, the rate of coastal erosion in the period 2015–2023 is slower than the northern area, averaging about 15 m/year. Further south in the Ma River estuary area (Sam Son city), the coastline tends to be stable, with minor changes during this period.

Table 2. Accuracy of shoreline extraction using different water indices

Water index	Accuracy					
	01.12.2015		26.12.2020		09.12.2023	
	Accuracy (%)	Kappa	Accuracy (%)	Kappa	Accuracy (%)	Kappa
NDWI	93.87	0.877	94.37	0.887	94.28	0.885
MNDWI	**95.25**	**0.904**	**95.67**	**0.913**	**95.56**	**0.911**
ANDWI	94.31	0.886	94.60	0.891	94.52	0.890
$AWEI_{sh}$	94.81	0.895	94.76	0.896	95.09	0.902

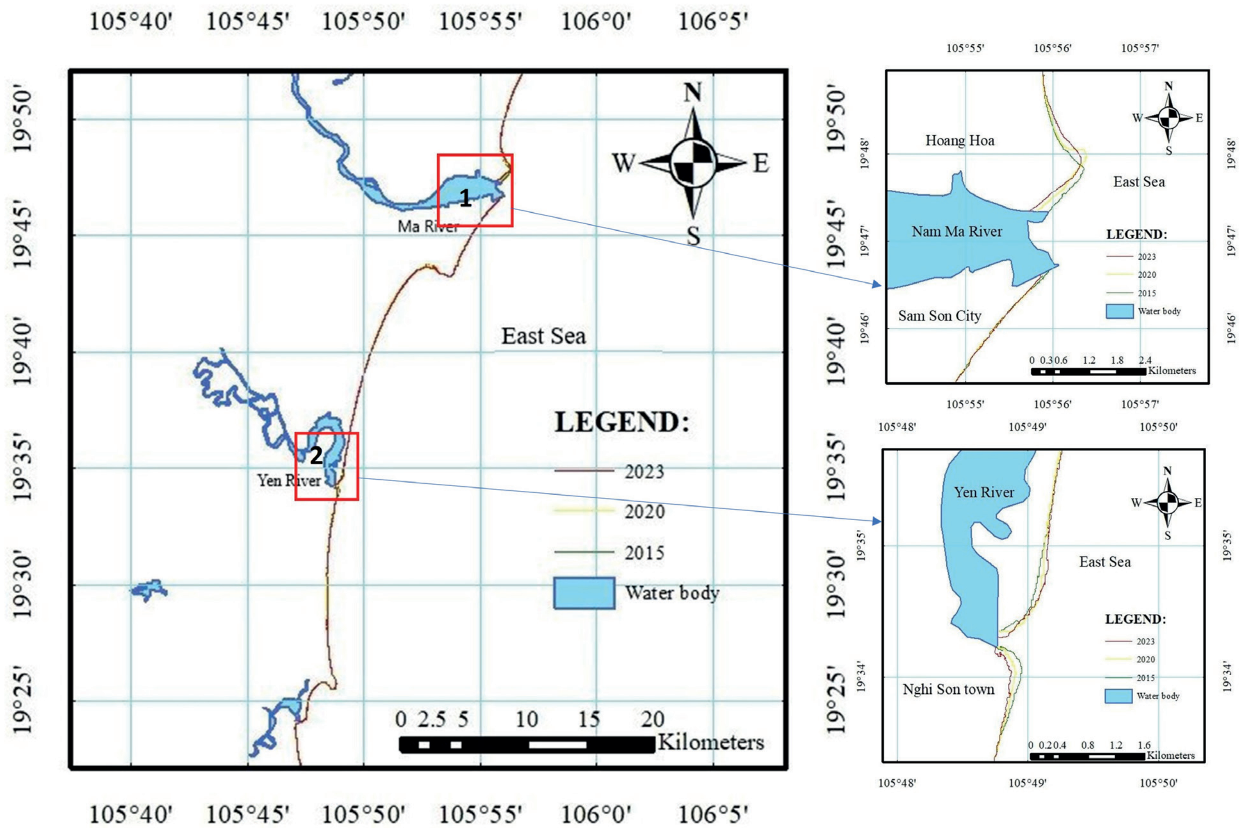

Fig. 9. Shoreline changes in Thanh Hoa coastal area in the period 2015–2023

Shoreline changes in Yen River estuary

Figure 9 also shows the results of mapping the shoreline changes in Ghep creek – the coastal area between Quang Xuong district and Nghi Son town (Thanh Hoa Province) from Sentinel-2 MSI images (red square 2 in Fig. 9). This creek is the mouth of the Yen River flowing into the East Sea.

Analysis of the results shows that the north of Ghep creek recorded coastal accretion at a slow rate of ~10 m/year in the period 2015–2023. Meanwhile, in the south of Ghep creek, the coastline was eroded at a rate of ~20 m/year in the period 2015–2020 and increasing to 25 m/year in the period 2020–2023. In coastal areas away from Ghep creek, the shoreline was relatively stable during the period 2015–2023.

Conclusion

In this study, Sentinel-2 MSI remote-sensing image data collected in the 2015–2023 period were used to evaluate the shoreline change in coastal area of Thanh Hoa Province (North Central Coast of Vietnam). Three Sentinel-2 MSI image scenes taken on December 01, 2015, December 26, 2020, and December 9, 2023 were used to calculate water indices, namely NDWI, MDNWI, ANDWI and AWEIsh. The result of evaluating the accuracy of classifying water objects from four different water indices using the Otsu automatic thresholding algorithm show that the MNDWI index has the highest accuracy through comparing the Kappa and overall accuracy values. The results received in the study show the complex changes of the coastline in Thanh Hoa Province in the period 2015–2023, including coastal erosion and accretion. Strong shoreline changes often occur in the area where a river flows into the East Sea (Ma River, Yen River). The highest coastal erosion rate in the Ma River estuary reaches over 50 m/year in the period 2015–2023, while in the Yen estuary area, the average erosion rate is over 20 m/year. In addition, in the northern area of Ma River estuary and Yen River (Ghep creek), shoreline accretion is recorded at average speeds of ~35 m/year (Ma River estuary) and ~10 m/year (Yen River estuary). In other areas, the shoreline changes are insignificant for the period 2015–2023.

Sentinel-2 MSI data have the highest spatial resolution up to 10 m and five-day temporal resolution can be effectively used for monitoring and mapping the shoreline changes. The method and results obtained in this study can be used for monitoring and managing coastlines, especially under the influence of climate change and rising sea levels.

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Disclosure statement

No potential conflict of interest was reported by the authors.

Author contributions

Study design: LHT, TGL; data collection: VPL, TP To; statistical analysis: XBT, QVT; result interpretation: LHT, TGL, VPL; manuscript preparation: LHT, TGL, QVT; literature review: LHT, TGL, XBT.

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