Earth Science Informatics (2022) 15:137–149
https://doi.org/10.1007/s12145-021-00714-2

RESEARCH ARTICLE

Geospatial quantitative analysis of the Aral Sea Shoreline changes using RS and GIS techniques

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Received: 28 July 2021 / Accepted: 7 October 2021 / Published online: 15 October 2021

Abstract
The variations in the lake area, water level, and water volume change of the Aral Sea from 1987 to 2018 were analyzed in this study, which is based on the multi-temporal Landsat images and remote sensing water body index (Normalized Difference Water Index, NDWI). Lake shorelines were automatically digitized and visualized using Net Shoreline Movement (NSM) and Linear Regression Rate (LRR) by Digital Shoreline Analysis System (DSAS). The surface area, water level, and water volume change of the North Aral Sea were not changed significantly in 1987-2018. The maximum lake area appeared in March 2015 with 3550.15 km^2, the minimum lake area appeared in October 2001with 2830.56 km^2. However, since 2010 the South Aral Sea split into the East Aral Sea and the West Aral Sea, the area change has shrunk dramatically. The area of the East Aral Sea decreased by 17852.65 km^2 (89.99 %) from March 2011 to September 2018. The area of the West Aral Sea decreased by 2203.62 km^2 (35.96 %) from August 2014 to March 2017. The distance of lake shoreline changes and rates of net movement along transects were determined by DSAS. The two largest positive values of NSM were 18715.93 and 12268.67 m, which showed lake shoreline retreat, occurred in the periods of 2010-2018 in the East Aral Sea and 1987-1999 in the South Aral Sea, respectively. The two periods in which the largest negative value of NSM appeared was (1987-1993) and (2001-2010) in the North Aral Sea, and the lake shoreline expanding distance was 145.43 and 545.84 m, respectively.

Keywords The Aral Sea · Spatial-temporal change · Digital Shoreline Analysis System · Geospatial quantitative analysis · Lake shoreline change

Introduction

Under the background of global warming, the study of inland lake area change is not only of great significance for water resources management and sustainable development strategy but also provides a reference for evaluating the impact of climate change and human activities on lakes (Mason et al. 1994; Chaudhari et al. 2018; Yang et al. 2020; Peng et al. 2021). Inland lakes are an important part of water resources in arid or semi-arid areas (Bai et al. 2011; Zhan et al. 2021; Yue et al. 2021). In recent years, due to climate warming and unreasonable development and utilization of human beings, several inland lakes are on the verge of drying up (Bosch et al. 2007; Lioubimtseva 2014; Aladin et al. 2019). The Aral Sea used to be one of the largest inland lakes in the world (Micklin 2010). At 68,000 km^2 in 1960, the Aral Sea was ranked as the world's fourth-largest inland lake (Gaybullaev et al. 2012; Massakbayeva et al. 2020). However, since the 1960 s a large amount of water was used for agricultural irrigation projects, the Aral Sea began to shrink dramatically in the second half of the 20th century. The Aral Sea surface area decreased by 53,720 km^2 (79 %) from 1960 to 2010, with the Aral Sea disintegrated into two separate water bodies (Zavialov et al. 2003; Aralgenefund 2011; Gaybullaev et al. 2012).

Communicated by H. Babaie

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At the beginning of the 21st century, the shrinking process of the Aral Sea continued (Cretaux et al. 2013; Micklin 2016). The area of the Aral Sea shrank dramatically by approximately 60,156 km^2 (about 88 %) and the total loss of water volume was approximately 1000 km^3 from 1960 to 2018 (Yang et al. 2020).

With the decrease of water level, the Aral Sea was naturally divided into the South Aral Sea (Large Aral Sea) and the North Aral Sea (Small Aral Sea) in 1986-1988 (Micklin 1988; Zavialov et al. 2003; Loodin 2020; Yang et al. 2020). In 2010, the South Aral Sea was further divided into the East Aral Sea and the West Aral Sea. As called "one of the planet's worst environmental disasters", the shrinking of the Aral Sea has led to economic and social consequences including health problems, the loss of fishery activities and employment, and economic dwindling (Micklin 2014; Micklin 2016). Moreover, the Aral Sea's shrinkage caused many ecological and environmental issues, such as the aggravation of drought due to water shortage, and its consequences including desertification, salinization, and soil degradation (Zavialov et al. 2009; Gaybullaev et al. 2012; Aladin et al. 2019; Loodin 2020; Yang et al. 2020).

Previous studies have focused primarily on the lake area change, water balance, hydrological model of the Aral Sea based on quantitative analysis of meteorological data, hydrological data, and satellite image data (Bai et al. 2011; Izhitskiy et al. 2016; Krapivin et al. 2019; Sun and Ma 2019; Massakbayeva et al. 2020; Yang et al. 2020; Yue and Liu 2021). Remote sensing technology has paved the way for large-scale geospatial analysis and dynamic environmental monitoring of the Aral Sea surfaces water area (Berdimbetov et al. 2021). Commonly used methodology for surface water area extraction contains supervised classification, unsupervised classification, the multispectral water body index, and the single-band threshold method (Yue et al. 2020). The widely used indices for the Aral Sea surface water area extraction is Normalized Difference Water Index (NDWI) (Mcfeeters 1996). NDWI can extract lake shorelines of the Aral Sea in long time series of remote sensing images and expressed them graphically. However, NDWI cannot quantitatively express and analyze the spatial position information of the lake shoreline, the purpose of NDWI is to calculate the area of the surface area. Developed by USGS (United States Geological Survey), Digital Shoreline Analysis System (DSAS) is introduced to digitized and visualized the shorelines changes analyses not only in the coastline but also in the lake shoreline (Himmelstoss et al. 2018; Yue and Liu 2019; Matin and Hasan 2021).

The existing studies on the Aral Sea mainly focus on the extraction of the lake area and the analysis of its temporal variation characteristics, and lack of quantitative analysis on the geospatial variation of the Aral Sea shoreline. Therefore, the objectives of this study were as follows: (1) to extract the Aral Sea surface area using Normalized Difference Water Index (NDWI), to retrieve water level from LEGOS/GOHS and calculate the volume change during 1987-2018; and (2) to quantitative analysis of the geospatial location and evolution of lake shoreline change using Digital Shoreline Analysis System (DSAS) from 1987 to 2018.

Materials and methods

Study area

The Aral Sea (N45°0′0,E60°0′0″) (Fig. 1) located at the junction of Uzbekistan and Kazakhstan in Central Asia, the water supply mainly depends on the Amu Darya and Syr Darya. The climate of the Aral Sea belongs to the extreme continental climate. It was affected by the periodic drought climate in history, and the lake water level changed greatly (Krivinogov 2014). In 1960, the recorded maximum lake level was 53 m, and the surface area was 68,000 square km (Micklin 2004). After the 1960 s, due to the water diversion project, the Amu Darya and the Syr Darya were largely used for agriculture and industry. Coupled with the continuous drought since the 1970 s, the lake level of the Aral Sea decreased sharply, the lake water level decreased and the salinity increased, resulting in a large amount of dry salt accumulation near the lake basin. Temporal variation and spatial scale dependency of climate and environmental changes in the Aral Sea and the Aral Sea basin can be divided into global changes, regional changes, and local changes. Global changes were primarily linked to hydrological balance, regional changes linked to land-use changes, and local changes linked to the Aral Sea degradation (Lioubimtseva 2015).

Landsat data

The MSS/TM/ETM+/OLI sensors of Landsat series satellites which comes from the U.S. Geological Survey (https://earthexplorer.usgs.gov/) has been used to extract the lake area for a long time, including 400 images from 1987 to 2018 are used to extract the lake area. The image selection should be clear and cloudless over the lake boundary. The data preprocessing process includes strip repair, splicing, and apparent reflectance calculation. For the SLC failure image, the simple gap-filling expansion toolbox in ENVI is used to fill in the blank.

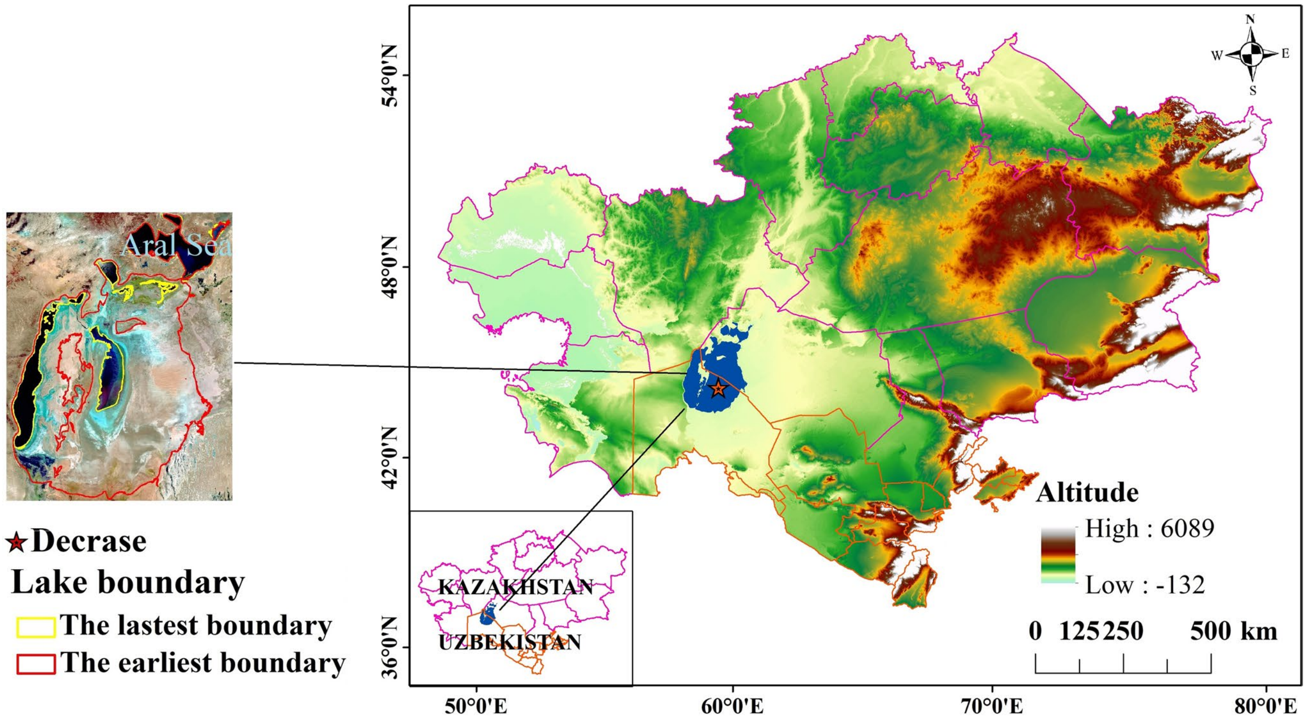

Fig. 1 The location of the Aral Sea

Hydroweb data

The data of Aral Sea water level from 1992 to 2016 used in this paper is a data center Hydroweb established by LEGOS/GOHS (www.LEGOS.obs-mip.fr/soa/hydrologie/HYDROWEB). The data center can provide water level and area information of more than 150 inland lakes in the world for free. The area and water level information are activated and fused by multiple satellite data, such as ASAR, MODIS, Landsat, and a variety of radar altimetry data, such as ERS-1, GFO, ERS-2, JASON-1, ENVISAT. In this paper, we used the Hydroweb data from 1993/8/13 to 2016/10/18. The data sources used in this study are shown in Table 1.

Methodology

Lake area extraction

The normalized difference water index (NDWI) proposed by Mcfeeters (1996) is selected for Lake area extraction, and the formula is as follows:

$$NDWI = (\rho_{\mathrm{Green}} - \rho_{NIR})/(\rho_{\mathrm{Green}} + \rho_{NIR}) \quad (1)$$

Where ρ_{Green} is the green band and ρ_{NIR} is the near-infrared band.

Table.1 The data used in the study

Data	Describe	Spatial resolution	Height Accuracy	Purposes
Landsat MSS/TM/ETM+/OLI	green band, near-infrared band	30 m	----	To extract lake area by using NDWI and obtain lake shorelines based on DSAS
LEGOS/GOHS	ERS-1, TOPEX Poseidon, GFO, ERS-2, JASON-1, JASON-2, ENVISAT,etc.	ERS-1(30 m), ENVISAT (30 m)	ERS-1(10 cm), ERS-2(10 cm), TOPEX Poseidon(6 cm), JASON-1(4.2 cm), ENVISAT(2.5 cm)	To extract lake water level

Lake volume change

The volume algorithm proposed by Taube (2000) is used to calculate the water volume change of the lake. The calculation formula is as follows:

$$\Delta V = \frac{1}{3}(H_1 - H_0) \times (A_0 + A_1 + \sqrt{(A_0 \times A_1)}) \quad (2)$$

Where ΔV is the volume change of the lake; H_0 and A_0 are the initial water level and area of each lake during the study period; H_1 and A_1 are the water level and area data during the study period. In the calculation of volume, the area data closest to the time of each period of water level data acquisition is selected.

DSAS (Digital Shoreline Analysis System) spatial analysis

Digital Shoreline Analysis System (DSAS) is a free software application in ArcGIS of ESRI (Thieler et al. 2017). DSAS can be used to calculate the variation distance and rate of the vector boundary of shoreline in time series. DSAS generates equidistant splines perpendicular to the baseline based on the multi-stage shoreline provided by the user and the baseline drawn by the user and calculates the distance between the baseline and the measurement position of each shoreline on the DSAS cross-section (Cenci et al. 2017). Based on the distance between the baseline and the intersection of the shoreline, DSAs can generate six statistics parameters, including Shoreline Change Envelope (SCE), Net Shoreline Movement (NSM), End Point Rate (EPR), Linear Regression Rate (LRR), Weighted Linear Regression (WLR) and Least Median of Squares (LMS). In this paper, we choose Net Shoreline Movement (NSM) and Linear Regression Rate (LRR) to obtain the intersection of the sample line and the shoreline of each period. The NSM records the distance between the oldest and the youngest lake shorelines on the sample line, the negative value of NSM indicates that the lake is expanding, while the positive value of NSM indicates that the lake is shrinking (Yue and Liu 2019; Yue et al. 2020). LRR is to fit all points of a spline by the least square method, and the slope of the line fitted is the linear regression rate (Dewidar and Bayoumi 2021). The principle of NSM and LRR is described as follows: (1) The baseline should be drawn around all the extracted shorelines. The inner side of the baseline should contain all the shorelines to be analyzed, usually, the baseline should be paralleled to the all extracted shorelines; (2) The extracted multi-phase lake shorelines from 1987 to 2018 are transformed and merged into the same layer; (3) DSAS is used to generate multiple transects perpendicular to the baseline to calculate the distance between the intersection point of each extracted shorelines and the baseline, the transects were perpendicular to the baseline at a constant 30 m interval (Transect spacing=30 m); (4) The spatial distribution of NSM was positive/negative to quantitatively describe the spatial change of the lake area. NSM equals the distance between the baseline and the youngest lake shoreline (the purple line represents the shoreline of 2009) minus the distance between the baseline and the oldest lake shoreline (the blue line represents the shoreline of 2004) (Fig. 2). The regression equation of the relationship between shoreline-baseline distance and time

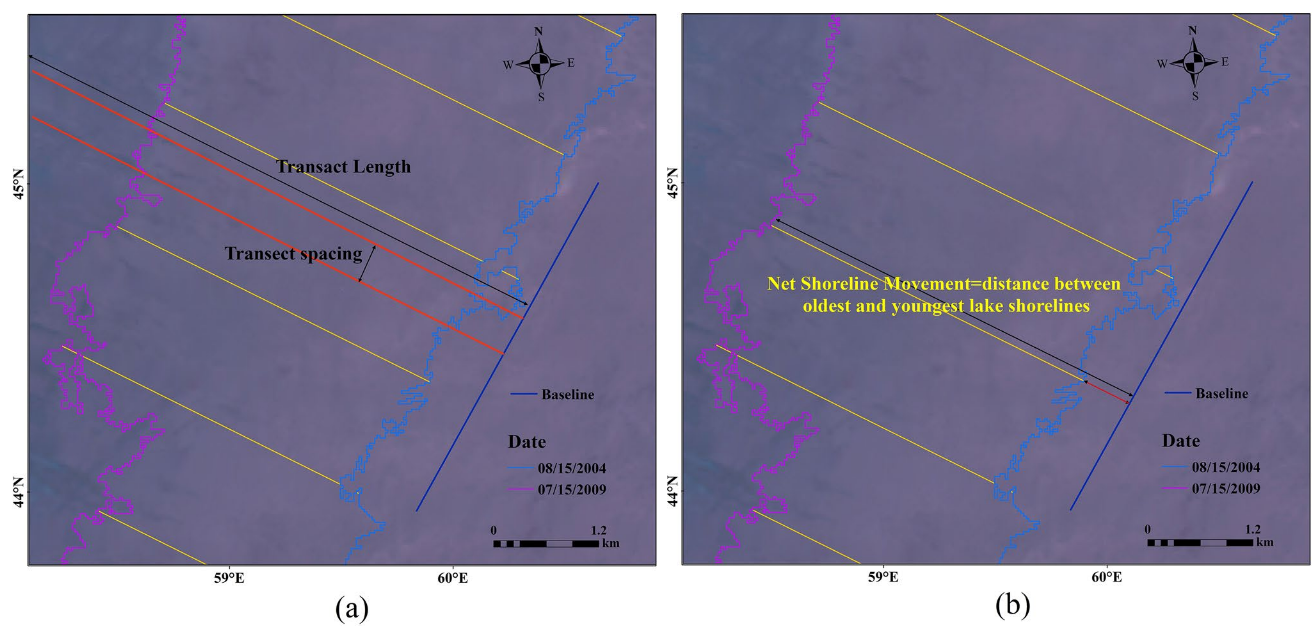

Fig. 2 Description of NSM and LRR

is established, and the slope of the linear regression equation is Linear Regression Rate (LRR).

Results

Temporal variation of the lake area, water level, and lake volume

Due to the expanding irrigation and reduction of river discharge, the Aral Sea has continuously shrunk and the shoreline has retreated since the 1960 s. We can see from the Landsat images (Fig. 3), the Aral Sea separated into two water bodies in 1987, which called as "Small Aral Sea" in the north and "Large Aral Sea" in the south, here we named as the North Aral Sea and the South Aral Sea (The left side of Fig. 3). In 2010, as the surface area of the South Aral Sea shrinks, the South Aral Sea split into the East Aral Sea and the West Aral Sea (The middle of Fig. 3), this situation continues to this day. Based on the surface area change trend process of the Aral Sea, we can divide the changes of the Aral Sea into three different stages according to the three important year nodes: 1987, 2010, and 2018 (The right side of Fig. 3).

The area changes of the North Aral Sea in 1987–2018 can be divided into two periods: rise (1987-2015) and decline (2015-2018) (Fig. 4). The valley value of the surface area was 2830.56 km^2 in October 2001, and the peak value was 3550.15 km^2 in March 2015. The water level of the North Aral Sea in 1987-2018 can be divided into two periods: rise (1993-2014) and decline (2014-2016). The valley value of water level was 40.15 m in August 2005, and the peak value was 42.82 m in May 2014. The ΔV of the North Aral Sea from 1987 to 2018 can be divided into two periods: rise (1994-2014) and decline (2014-2016). The valley value was -3.59 km^3 in August 2005 and the peak value was 5.01 km^3 in May 2014 (Fig. 6b).

The South Aral Sea separated into the East Aral Sea and the West Aral Sea in 2010 (Fig. 5), due to the lack of water level data of the South Aral Sea, only the area change trend of the South Aral Sea was analyzed. The area of the South Aral Sea showed a significant downward trend from 1987 to 2009, with a peak of 40242.49 km^2 in May 1987 and a valley of 16277.63 km^2 in August 2008, with an average change rate of -573.64 km^2/month (Fig. 6d).

During 2010-2018, the area of the East Aral Sea showed a fluctuating downward trend (Fig. 6a). The peak area was 19837.48 km^2 in March 2011, and the valley area was 1984.83 km^2 in September 2018, with an average change rate of -179.77 km^2/month. The water level of the East Aral Sea showed a downward trend. The peak value of the water level appeared in April 2011, which was 28.6 m, and the valley value appeared in September 2011, which was 27.3 m, with an average change rate of -0.036 m/month. The ΔV showed a downward trend. The peak value of water change appeared in April 2011, which was 12.43 km^3, and the valley value appeared in September 2011, which was -7.82 km^3, with an average change rate of -0.58 km^3/month.

From 2010 to 2018, the area of the West Aral Sea can be divided into two stages: rise and decline (Fig. 6c). During 2011-2017, the area of the West Aral Sea showed a fluctuating trend, with a valley of 3925 km^2 in August 2014 and a peak value of 6128.62 km^2 in March 2017, with an average change rate of -3.37 km^2/month. During 2017-2018, the area of the West Aral Sea showed a significant downward trend, with the peak value of 6128.62 km^2 in March 2017 and the valley value of 2722 km^2 in November 2018, with an average change rate of -233.6 km^2/month. During 2010-2016, the water level of the West Aral Sea showed a downward trend, with the peak value of 27.6 m in July 2011 and the valley value of 22.38 m in June 2016, with an average change rate of -0.13 m/month. The ΔV showed a downward trend. The valley value of water volume change was -24.29 km^3 in June 2016, and the peak value was 2.43 km^3 in May 2017, with an average change rate of -0.67 km^3/month.

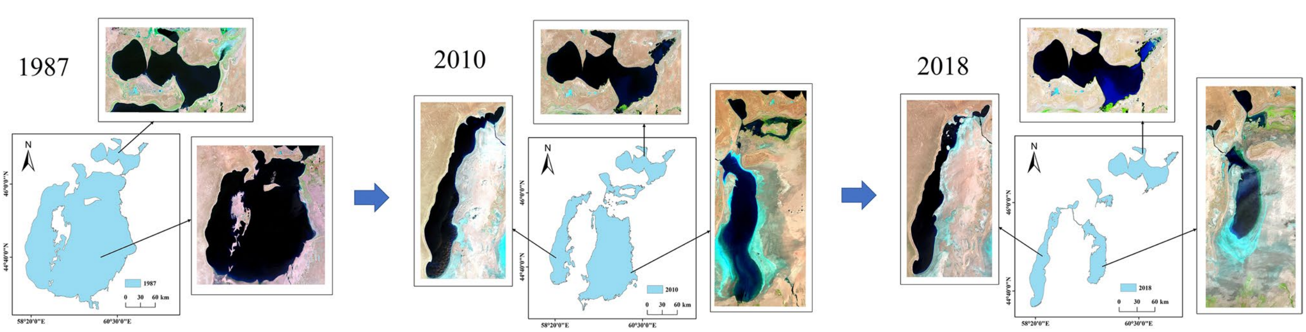

Fig. 3 Evolution history of the Aral Sea from 1987-2018

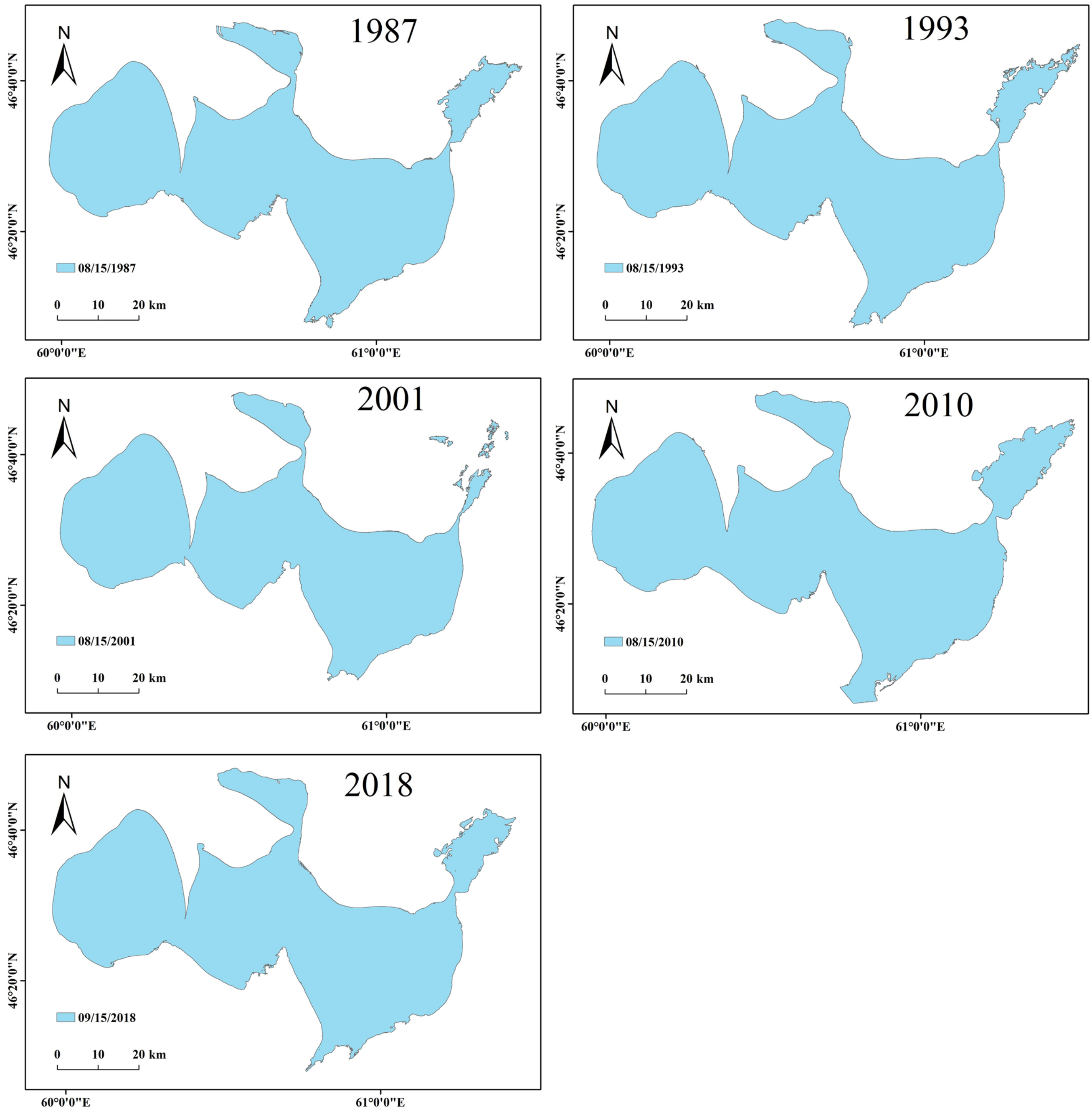

Fig. 4 Comparative change maps of the North Aral Sea surface area in the period 1987–2018

Quantitively and geo-spatially analyses of the lake shorelines

Spatial analysis of lake shorelines of the North Aral Sea

Figure 7 shows the variation of NSM change from 1987 to 2018 in the North Aral Sea. Based on the DSAS calculation, the average value of NSM in the North Aral Sea was -145.43 m from 1987 to 1993, and the negative value of NSM accounted for 81.11 % of the shoreline, which indicated the North Aral Sea showed an expansion trend in the period of 1987-1993. The shoreline of 1993 was more expansive than in 1987 (Fig. 7(a)). From 1993 to 2001, the average value of NSM in the North Aral Sea was 665.6 m, and 65.82 % was positive which means that 65.82 % of the shoreline was in a state of shrinking. The shrinking area is mainly in the south and northeast of the North Aral Sea and the shoreline of 2001 was more regressive than in 1993

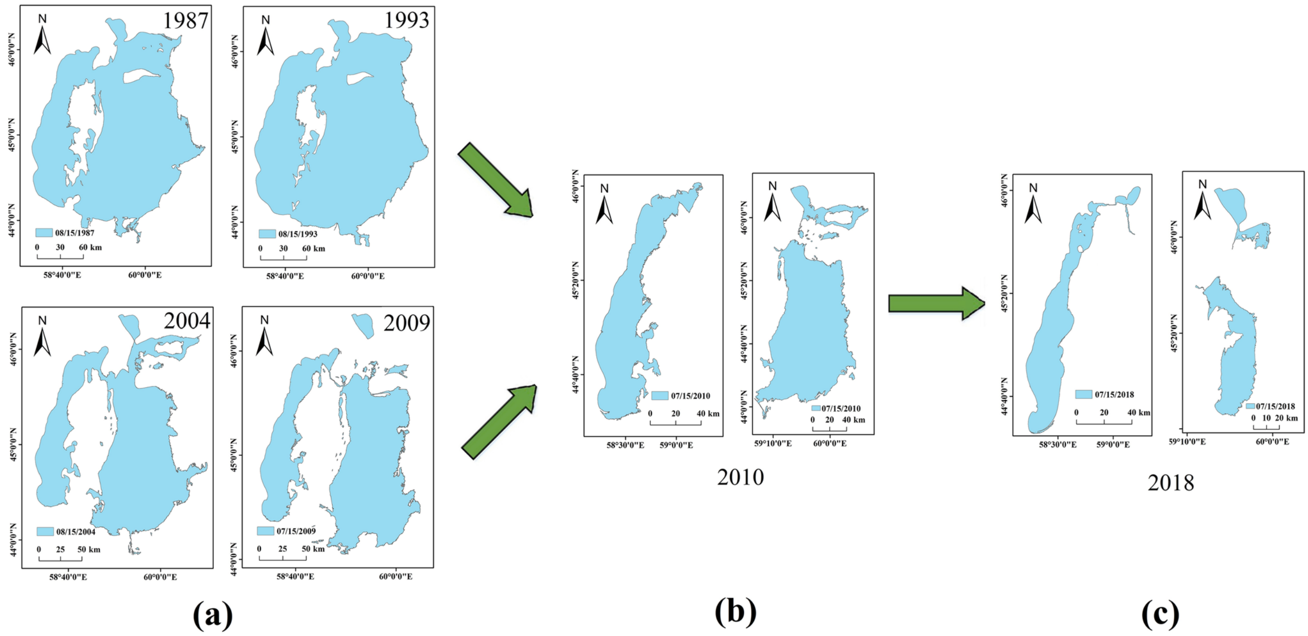

Fig. 5 Comparative change maps of the Aral Sea surface area in the period 1987–2018. (**a**) the South Aral Sea in 1987-2009; (**b**) the East Aral Sea (right) and the West Aral Sea (left) in 2010; (**c**) the East Aral Sea (right) and the West Aral Sea (left)in 2018

(Fig. 7(b)). From 2001 to 2010, the average value of NSM in the North Aral Sea was -545.84 m, and the negative NSM accounted for -83.25 % of the shoreline. It can be seen that the North Aral Sea was in the expansion trend at this stage and the shoreline of 2010 was more expansive than in 2001 (Fig. 7(c)). From 2010 to 2018, the average value of NSM in the North Aral Sea was 267.36 m, and the proportion of positive NSM was 77.61 %. The North Aral Sea was in a decreasing trend at this stage and the shoreline of 2018 was more regressive than in 2010 (Fig. 7(d)).

During 1987-1993, the average value of LRR in the North Aral Sea was -22.87 m/a, and 81.11 % was negative. From 1993 to 2001, the average value of LRR was 74.25 m/a, and the positive LRR accounted for 65.51 %, the shrinkage and deceleration rate of the North Aral Sea was relatively high at this stage. During 2001-2010, the average LRR was -61.84 m/a, and the negative LRR accounted for 85.65 %, the regional expansion rate of the North Aral Sea was relatively high during this period. From 2010 to 2018, the average LRR was 13.1 m/a, and 70.79 % of the total LRR was positive (Fig. 8).

Spatial analysis of lake shorelines of the West Aral Sea and East Aral Sea

Figure 9(a) shows the changes of NSM and LRR in the West Aral Sea from 2010 to 2018, the average NSM of the West Aral Sea was 2753.113 m, and the positive NSM accounts for 85.67 %. The West Aral Sea was in a shrinking trend at this stage. The average LRR of the Western Aral Sea was 240.96 m/a, and the positive LRR accounts for 87.64 %. Figure 9(b) shows the changes in NSM and LRR in the East Aral Sea between 2010 and 2018. The average value of NSM was 18175.93 m, and the positive value of NSM accounts for 92.93 %. Therefore, the East Aral Sea in this stage shows a shrinking trend. The average LRR of the East Aral Sea was 1844.74 m/a from 2010 to 2018, and the 78.28 % was positive.

Spatial analysis of lake shorelines of the South Aral Sea

Figure 10(a) and (b) show the change of NSM in the South Aral Sea. The average NSM of the South Aral Sea from 1987 to 1999 was 12268.67 m, and the positive NSM accounted for 62.96 %. Therefore, more than half of the South Aral Sea shoreline was in a state of reduction at this stage. During 2004-2009, the average NSM of the South Aral Sea was 3048.24 m, and the positive NSM accounted for 95.75 %. Therefore, the South Aral Sea was in a state of atrophy at this stage. Figure 10(c) and (d) show the variation of LRR in the South Aral Sea. The average LRR of the South Aral Sea from 1987 to 1999 was 1020.58 m/a, and the positive LRR accounted for 62.96 %. The degradation rate of the South Aral Sea was relatively high at this stage. From 2004 to 2009, the average LRR of the South Aral Sea was 729.44 m/a, and the positive LRR accounted for 95.68 %.

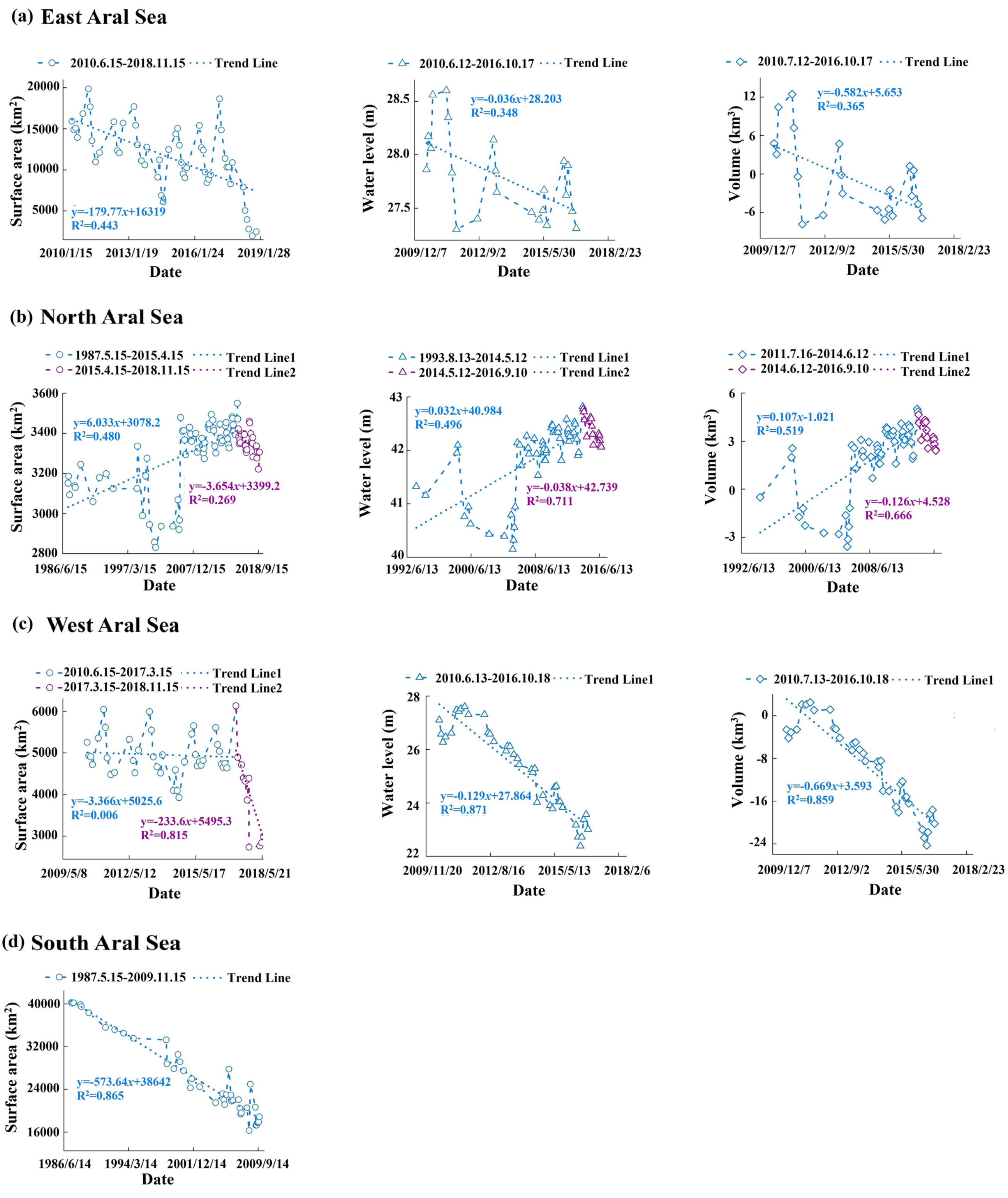

Fig. 6 Variations in the lake area, water level, and water volume of the Aral Sea. (**a**) East Aral Sea, (**b**) North Aral Sea, (**c**) West Aral Sea, (**d**) South Aral Sea

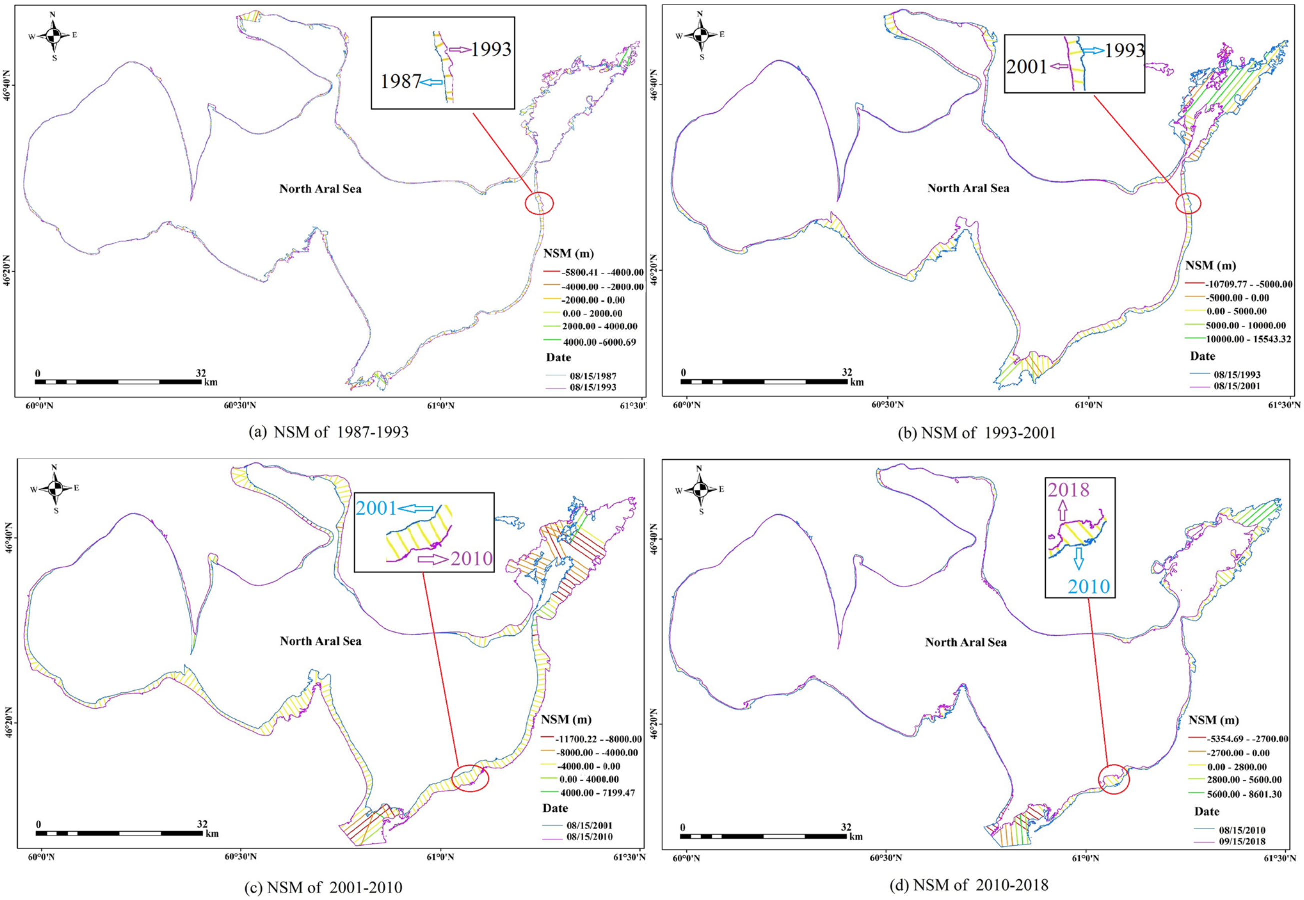

Fig. 7 Changes of NSM in North Aral Sea. (**a**) NSM in 1987-1993, (**b**) NSM in 1993-2001, (**c**) NSM in 2001-2010, (**d**) NSM in 2010-2018

Discussion

Lake shoreline movement analysis based on Linear Regression Rate (LRR) and Net Shoreline Movement (NSM)

The lake shoreline of the Aral Sea extracted from Landsat images was analyzed based on the Net Shoreline Movement (NSM) and Linear Regression Rate (LRR) in the DSAS model. We listed the NSM and LRR value of the Aral Sea in Table 2. According to the definition of NSM, NSM is a distance concept that represents the distance between the latest shoreline and the oldest shoreline. Therefore, a negative NSM value indicates that the lake is expanding, while a positive NSM value indicates that the lake is shrinking.

There are two periods (1987-1993) and (2001-2010) of the North Aral Sea where the NSM value was negative, which indicated that the lake shoreline was expanding with the expansive distance of 145.43 and 545.84 m, LRR was 22.87 m/a and 61.84 m/a, in the periods of (1987-1993) and (2001-2010), respectively. 81.11 % of the shoreline showed a state of expansion in the periods of 1987-1993, while this value was 83.25 % in the periods of 2001-2010. By contrast, in the periods of (1993-2001) and (2010-2018), the NSM value of the North Aral Sea was positive, which represented that the lake shoreline was shrinking with a degradation distance of 665.60 and 267.36 m, LRR was 74.25 m/a and 13.10 m/a, in the periods of (1993-2001) and (2010-2018), respectively. 65.82 % of the shoreline showed a state of shrinkage in the periods of 1993-2001, while this value was 77.61 % in the periods of 2010-2018.

The maximum positive value of NSM occurred in two periods the East Aral Sea in the period of 2010-2018 and the South Aral Sea between 1987 and 1999, lake shoreline was shrinking with a degradation distance of 18715.93 and 12268.67 m, and LRR was 1844.74 m/a and 1020.58 m/a, respectively. 92.93 % of the shoreline in the East Aral Sea showed a state of shrinkage in the periods of 2010-2018, while this value was 62.96 % in the periods of 1987-1999 of the South Aral Sea.

The lake shoreline of the West Aral Sea showed a trend of retreat in the period of 2010-2018, with the average NSM distance 2753.11 m, and 85.67 % of the shoreline was positive value. The NSM distance of the South Aral Sea in the

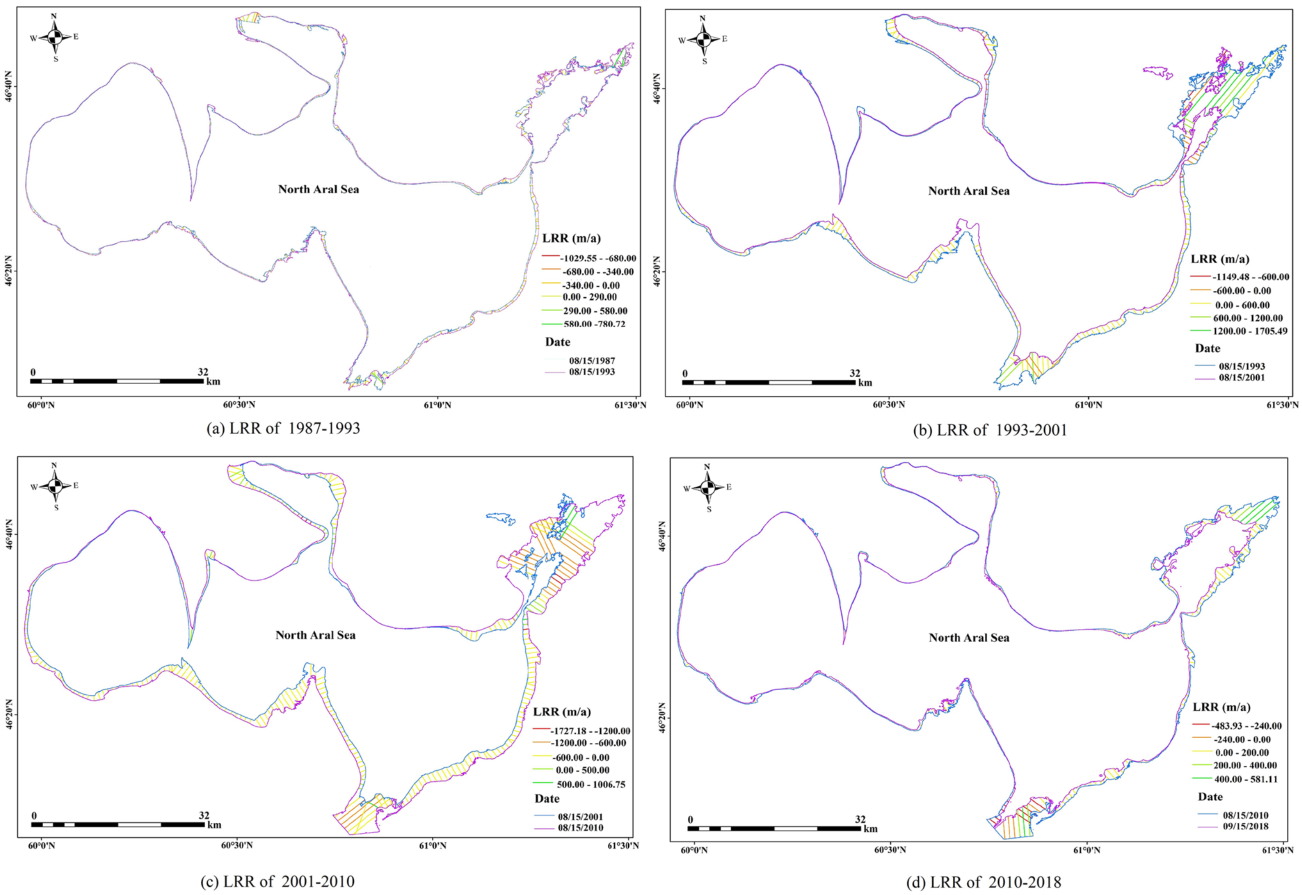

Fig. 8 Changes of LRR in North Aral Sea. (**a**) LRR in 1987-1993, (**b**) LRR in 1993-2001, (**c**) LRR in 2001-2010, (**d**) LRR in 2010-2018

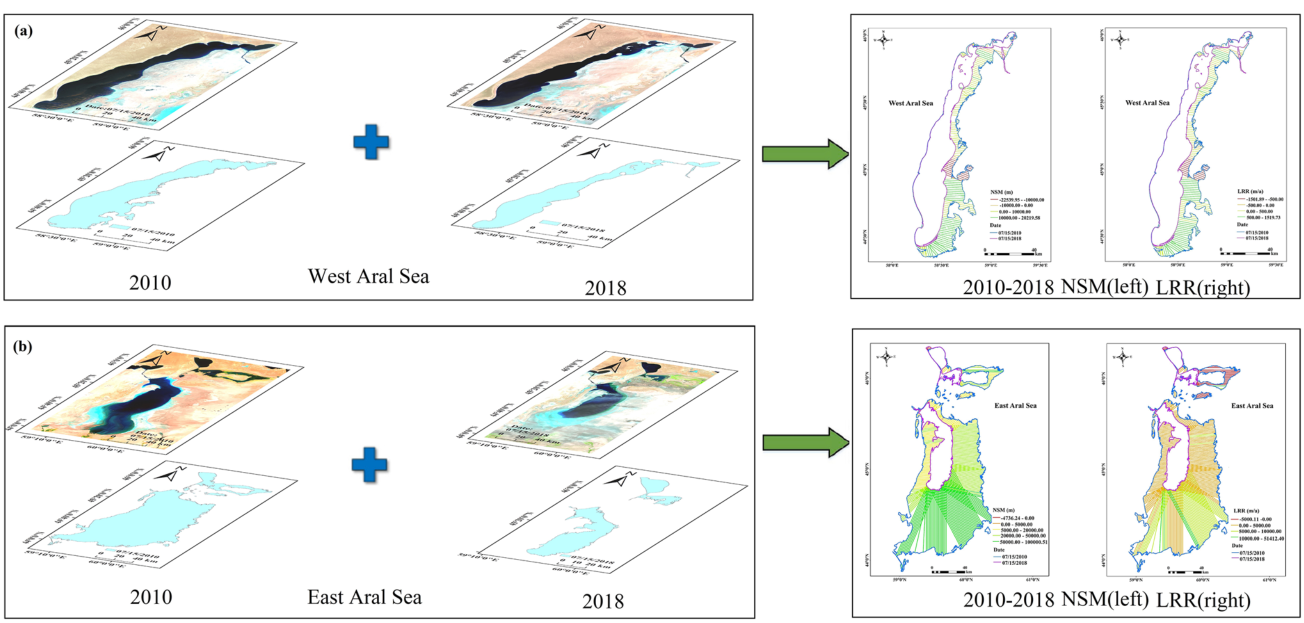

Fig. 9 Changes of NSM and LRR in West Aral Sea and East Aral Sea

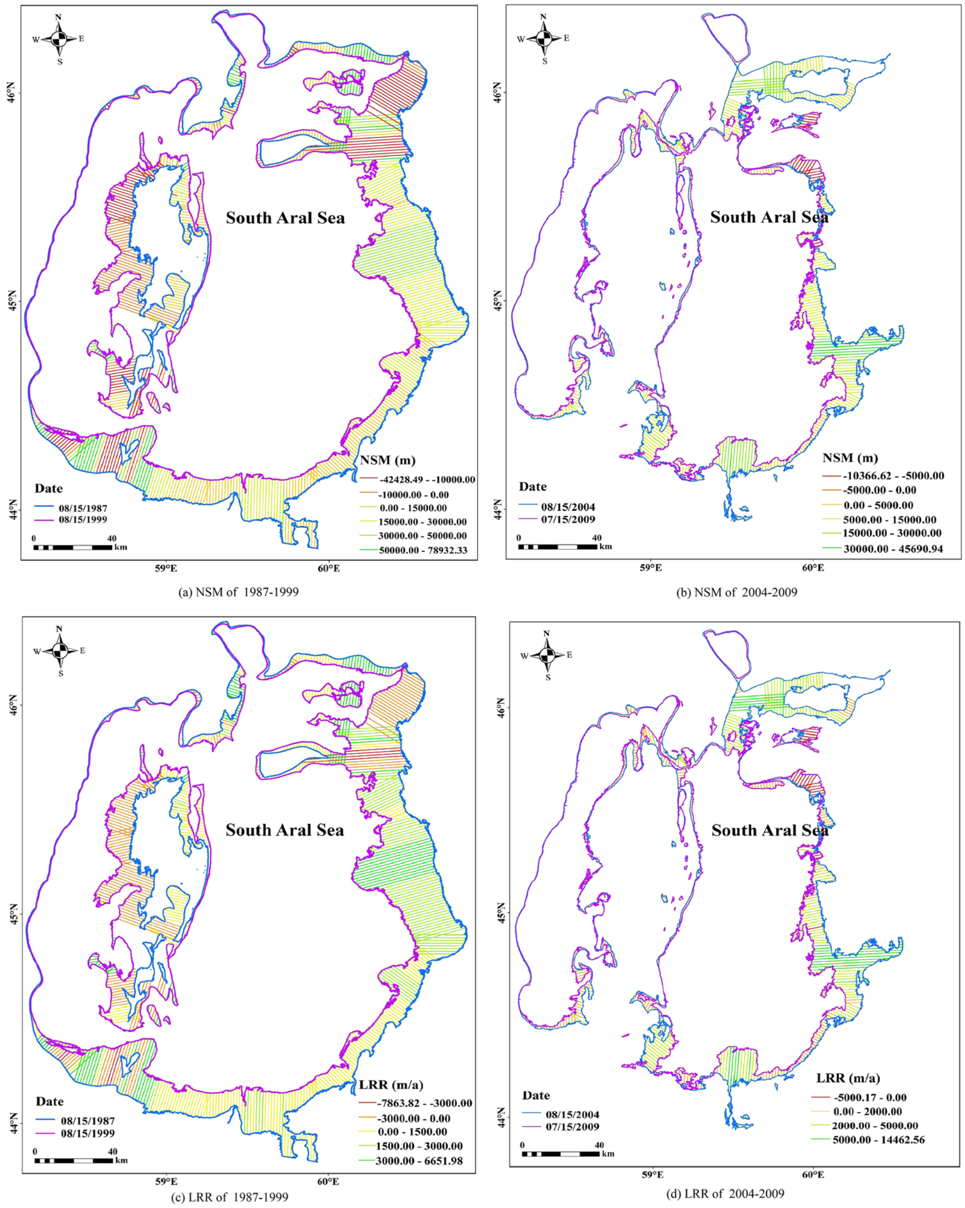

Fig. 10 Changes of NSM and LRR in South Aral Sea. (**a**) NSM in 1987-1999, (**b**) NSM in 2004-2009, (**c**) LRR in 1987-1999, (**d**) LRR in 2004-2009

Table.2 NSM and LRR value of the Aral Sea

The Aral Sea	Time	NSM		LRR	
		Average distance (m)	proportion (%)	Average distance (m/a)	proportion (%)
The East Aral Sea	2010-2018	18715.93	92.93	1844.74	78.28
The West Aral Sea	2010-2018	2753.11	85.67	240.96	87.64
The South Aral Sea	1987-1999	12268.67	62.96	1020.58	62.96
	2004-2009	3048.24	95.75	729.44	95.68
The North Aral Sea	1987-1993	-145.43	81.11	-22.87	81.11
	1993-2001	665.60	65.82	74.25	65.51
	2001-2010	-545.84	83.25	-61.84	85.65
	2010-2018	267.36	77.61	13.10	70.79

NOTE: The negative NSM indicates that the lake is expanding, while the positive NSM indicates that the lake is shrinking period of 2004-2009 was 3048.24 m, and 62.96% of the shoreline showed a positive value.

Digital Shoreline Analysis System (DSAS)

Digital Shoreline Analysis System (DSAS) is an analysis system based on the ArcGIS platform developed by the U.S. Geological Survey for analyzing the temporal and spatial change rate of coastline (Himmelstoss et al. 2018). The system can simulate the temporal and spatial change rate of coastline in a period (Murat et al. 2019; Mullick et al. 2020; Matin and Hasan 2021). However, DSAS was rarely used in the lake shoreline analysis. Whether it is the lake shoreline or the coastline, the shoreline is the boundary between land and water. Nowadays, the shoreline can be delineated and digitized using two strategies i.e. manual visual interpretation and computer automatic interpretation. Manual visual interpretation may be advantageous over computer automatic interpretation in high interpretation accuracy and continuous extraction of coastline. Computer automatic interpretation has become the main research direction worldwide because of its high efficiency and reusability. It has been proved that it is not difficult to extract the shoreline, while quantitatively express the geospatial location and evolution of the extracted shoreline is still a challenge. Several previous studies extract the lake shoreline of the Aral Sea successfully used the multispectral water body index (Micklin 2016; Deliry et al. 2020; Yang et al. 2020. However, the distance from the earliest shoreline to the latest shoreline and the change rate of shoreline through long time series is still unknown. Hence the present study attempts to use net movement along transects and rates of shoreline change provided by the DSAS program for shoreline digitization and visualization.

Conclusions

This study extracts the Aral Sea surface area based on Landsat images from 1987 to 2018, combined with the Hydroweb data, we established a long time series dataset of the lake area, water level, and lake volume change of the Aral Sea. Moreover, we attempt to investigate the geo-spatial location and evolution of lake shoreline change of the Aral Sea in the different periods from 1987 to 2018. For instance, the North Aral Sea from 1987 to 2018, the South Aral Sea from 1987 to 2010, the West Aral Sea, and the East Aral Sea from 2010 to 2018.

The analysis shows that the maximum and minimum area of the North Aral Sea in 1987–2018 was 3550.15 km^2 in March 2015 and 2830.56 km^2 in October 2001, respectively. The maximum and minimum water level was 42.82 m in May 2014 and 40.15 m in August 2005, respectively. The maximum and minimum ΔV was 5.01 km^3 in May 2014 and -3.59 km^3 in August 2005, respectively. The area of the South Aral Sea showed a great shrinking from 1987 to 2009, with a largest of 40242.49 km^2 in May 1987 and a smallest of 16277.63 km^2 in August 2008. Similar to the South Aral Sea, the area of the East Aral Sea was greatly reduced from 2010 to 2018, with a maximum of 19837.48 km^2 in March 2011 and a minimum of 1984.83 km^2 in September 2018, respectively. The maximum and minimum water levels were 28.6 m in April 2011 and 27.3 m in September 2011, respectively. The maximum and minimum ΔV was 12.43 km^3 in April 2011 and -7.82 km^3 in September 2011, respectively. The area of the West Aral Sea showed a fluctuating trend, with two valley values of 3925 km^2 in August 2014 and 2722 km^2 in November 2018 and one peak value of 6128.62 km^2 in March 2017.

The two greatest lake shorelines' shrinking distance was 18715.93 m from 2010 to 2018 of the East Aral Sea and 12268.67 m between 1987 and 1999 of the South Aral Sea, respectively. Instead, the two periods of largest lake shoreline expansion were (1987-1993) and (2001-2010) in the North Aral Sea, and the lake shoreline expanding distance was 145.43 and 545.84 m, respectively. The results of this study provide a geospatial and quantitative analysis scenario of the changing configuration of lake shorelines in the Aral Sea, which is helpful to conduct more investigations and monitoring of lake shoreline and hopeful to aid decision-makers in implementing effective lake shoreline management.

Acknowledgements The authors sincerely thank the National Aeronautics and Space Administration (NASA) and U.S. Geological Survey (USGS) for providing the Landsat data, and LEGOS/GOHS for providing the water level data. The authors would also like to thank the anonymous reviewers whose comments have greatly contributed to the improvement of this study.

Author contributions Methodology and writing, H. Y., data curation, Y. L., modified the whole paper, H. Y., Y. L. and QY.W.

Funding The research is supported by the Natural Science Basic Research Program of Shaanxi (2020JM-514), the project of Shaanxi Coal and Chemical Industry Group (2018SMHKJ-A-J-03), and Xi'an University of Science and Technology (2019YQ3-04).

Data availability There are no linked research data sets for this submission.

Declarations

Conflict of interest The authors declare no conflict of interest.

Ethical statement All ethical practices have been followed in relation to the development, writing, and publication of the article.

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