Tools for Shoreline Change Analysis and Detection

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A shoreline is the point of the physical border between land and water. While this definition looks simple, it is indeed challenging in its practical application. The position of the shoreline changes through time due to cross-shore and alongshore sediment movement in the littoral zone, and through changes in water levels. Shoreline change analysis and detection studies have progressed from using simple observation (description) from historical maps and topographical maps to employing high-resolution multi-temporal satellite images with remote sensing and Geographic Information System (GIS) approaches for a better understanding of the subject.

shoreline change | coastal erosion | sea level rise | climate change | GIS | remote sensing

1. Introduction

Coastal systems and large inland water environments are under threat of climate change/variability and sea level rise. Several research studies have stressed the impacts of climate change, climate variability (extreme events) and sea level rise on global shorelines and related erosion [1][2][3]. The situation is further aggravated by the current anthropogenic pressure (urbanization) [4]. As reiterated by Ware et al. [5], human settlement has always been concentrated along the coast and large inland waterbodies. This assertion was earlier stressed by Blackburn et al. [6], who reported that 16 of the world's megacities are found within coastal regions and large deltas. A recent study by Bamunawala et al. [7] projected that the collective impacts of climate change (sea level rise, temperature, and precipitation) and anthropogenic influences (urbanization) will cause 90% of global shorelines to retreat.

A shoreline is the point of the physical border between land and water [8]. While this definition looks simple, it is indeed challenging in its practical application [9]. The position of the shoreline changes through time due to cross-shore and alongshore sediment movement in the littoral zone, and through changes in water levels [9][10]. The temporal nature and time scale of shorelines must, therefore, be considered in shoreline investigation [9][10]. An understanding of the temporal and time scales in shoreline position is essential for science, engineering, and coastal managers [11]. Shoreline position detection is, thus, important especially considering the long history of human habitation of the coast and the banks of large waterbodies and their recent adaptation [10]. This has meant that the term shoreline change is not limited to only the coast but encompasses lake and lagoon environments as well [12][13][14]. Credit in this sense, should, thus, be given to earlier geoscientists such as Carr [15], de Boer and

Carr [16], El-Ashry and Wanless [17], and Gulliver [18], whose work contributed to the advancement of information on shoreline change .

2. Tools for Shoreline Change Analysis and Detection

The term shoreline was used in the 1800s [18], while the term shoreline change appeared in the 1960s [17]. However, the combined term shoreline change analysis first appeared in the scientific articles in the late 1970s [19]. During this time, computations and the development of diverse geospatial tools including aerial photography, satellite imagery, and Light Detection and Ranging (LiDAR) were made to formalize the shoreline change analysis process. As reiterated by Burningham and Fernandez-Nunez [10], the awareness about coastal hazards and risks such as shoreline recession and their impacts on coastal inhabitants increased during this time.

The changing nature of the shoreline position drew the attention of coastal researchers to develop and adopt shoreline indicators. As emphasized by Boak and Turner [9], shoreline indicator is utilized as a proxy to show shoreline position. Boak and Turner [9] classified shoreline indicators into 3 groups. Group 1included those indicators that are based on visible coastal features (e.g., an earlier high-tide line or the wet/dry boundary). Studies such as Boye, et al. [20] and Mahapatra, et al. [21] employed these indicators. Group 2 was based on tidal data (e.g., mean high water or mean sea level) with studies such as Crapoulet et al. [22] and Moore et al. [23] utilizing these indicators. Group 3 was based on the application of image processing skills to extract proxy shoreline characteristics. Studies such as Luijendijk et al. [24] and Vos et al. [25] have employed the third indicator. Studies such as Pollard et al. [26] and Salmon et al. [27] have also utilized a combination of the three indicators.

There exist several sources of data for shoreline change analysis. However, the choice of data usage is dependent on availability [9]. Data are, thus, sourced from historical land-based photographs, coastal maps and charts, aerial photography, beach surveys, Global Positioning System (GPS), remote sensing, Multispectral/hyperspectral imaging, Airborne Light Detection and Ranging technology (LiDAR), microwave sensors, and video imaging [9]. It must be stated that each of these sources has strengths and weaknesses (see Boak and Turner [9]). The use of the Unmanned Aerial Vehicle (UAV) to source data for shoreline change analysis has gained popularity in recent times [28].

Tools used for shoreline change analysis differ. Previous shorelines change analyses were simple, as they were made by directly comparing already existing maps [10]. This period gave little or no room for accuracy and uncertainty estimates. This method of shoreline change analysis changed entirely during the 1970s due to the advancement in computer technology and the related Geographic Information System (GIS). This period allowed for the combination of diverse data types, the ability to scale, and correct geospatial elements and digitize shorelines, which transformed shoreline change analysis into a more computational perspective [10]. An earlier tool for shoreline change analysis was the Coastal Feature Mapping system developed by Underwood and Anders [29]. This tool estimates position coordinates (X and Y) through varying ground control points and finally plots multiple shoreline maps for estimating change rates [29]. Again, the Digital Shoreline Analysis System (DSAS) was developed by the United States Geological Survey (USGS). Since its original development in the early 1990s, the

DSAS has undergone a series of enhancements. The first version (V.1.0) was created in 1992 by Danforth and Thieler [30], the second (V.2.0) in 2003 by Thieler et al. [31], the third version (V.3.0) in 2005 by Thieler et al. [32], the fourth version (V.4.0) in 2009 by Thieler, et al. [33], and the fifth in 2018 consisting of versions (V.5.0 and V.5.1) by Himmelstoss et al. [34][35].

The high utilization of the DSAS software is due to its easy incorporation into ArcGIS/ArcMap. This has made its utilization in shoreline change research undoubtable [36][37]. However, other GIS software such as the QGIS has also received attention in recent times. As reiterated by Burningham and Fernandez-Nunez [10], researchers nowadays use the QGIS to generate a shoreline database and create shapefiles or other form of geospatial files and import them into programming environments such as Python, MATLAB, or R, to perform shoreline change analysis. Studies such as De Lima et al. [38] and Griffiths et al. [39] have used QGIS in assessing shoreline change. Tools such as the AMBUR and the Open Digital Shoreline Analysis System (ODSAS) have also been widely recognized due to their capabilities in estimating coastal variations [40][41][42]. Additionally, the utilization of models and algorithms has increased in recent times, and this has provided a place for machine learning in shoreline change analysis [43][44][45].

In summary, the research field of shoreline change has seen advancements, especially, in the data sources, approaches, and tools. The field began with the detection of shoreline positions through historical maps, aerial photographs, and now through high resolution satellite images. The remote sensing approach dominates the field. It is interesting to note that field measurements and surveys through the employment of GPS has consistently been utilized in the research field. Researchers use GPS surveys to establish control. GPS surveys are also used to validate remote sensing data. The DSAS has remained an important tool in the research field and shows dominance. However, there has been an increasing utilization of other software such as the QGIS, GRASS, Terset-IDRISI, ERDAS, CoastSat, AMBUR, etc. for coastal variation analysis. The increasing utilization of models, algorithms, and programming environments for research in the field has, therefore, provided room for machine learning in the shoreline change analysis and detection field. It is interesting to note that some of the studies that lead to a cluster are related to one direct citation.

Shoreline change analysis and detection studies have progressed from using simple observation (description) from historical maps and topographical maps to employing high-resolution multi-temporal satellite images with remote sensing and GIS approaches for a better understanding of the subject.

The potency of geospatial approaches and tools such as remote sensing, GIS, and machine learning have not been completely discovered. There is a need for more utilization considering their enormous benefits. The introduction of machine learning could offer suitable tools and techniques required for the growth of automatic shoreline extraction globally.

References

1. Le Cozannet, G.; Bulteau, T.; Castelle, B.; Ranasinghe, R.; Wöppelmann, G.; Rohmer, J.; Bernon, N.; Idier, D.; Louisor, J.; Salas-Y.-Mélia, D. Quantifying uncertainties of sandy shoreline change projections as sea level rises. Rep. 2019, 9, 42. https://doi.org/10.1038/s41598-018-37017-4.
2. Nicholls, R.J.; Cazenave, A. Sea-Level Rise and Its Impact on Coastal Zones. Science 2010, 328, 1517–1520. https://doi.org/10.1126/science.1185782.
3. Oppenheimer, M.; Glavovic, B.C.; Hinkel, J.; van de Wal, R.; Magnan, A.K.; Abd-Elgawad, A.; Cai, R.; Cifuentes-Jara, M.; DeConto, R.M.; Ghosh, T.; et al. Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. In IPCC Special Report on the Ocean and Cryosphere in a Changing Climate; Portner, H.-O., Roberts, D.C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Mintenbeck, K., Alegría, A., Nicolai, M., Okem, A., et al., Eds.; The Intergovernmental Panel on Climate Change: Geneva, Switzerland, 2019.
4. Alvarez-Cuesta, M.; Toimil, A.; Losada, I. Reprint of: Modelling long-term shoreline evolution in highly anthropized coastal areas. Part 2: Assessing the response to climate change. Eng. 2012, 169, 103985. https://doi.org/10.1016/j.coastaleng.2021.103985.
5. Ware, D.; Buckwell, A.; Tomlinson, R.; Foxwell-Norton, K.; Lazarow, N. Using Historical Responses to Shoreline Change on Australia’s Gold Coast to Estimate Costs of Coastal Adaptation to Sea Level Rise. Mar. Sci. Eng. 2020, 8, 380. https://doi.org/10.3390/jmse8060380.
6. Blackburn, S.; Marques, C.; de Sherbinin, A.; Modesto, F.; Ojima, R.; Oliveau, S.; Bolde, C.C.P. Mega-Urbanisation on the Coast. In Megacities and the Coast: Risk, Resilience, and Transformation; Pelling, M., Blackburn, S., Eds.; Routledge/Taylor & Francis Group: New York, NY, USA; London, UK, 2013; pp. 25–26.
7. Bamunawala, J.; Ranasinghe, R.; Dastgheib, A.; Nicholls, R.J.; Murray, A.B.; Barnard, P.L.; Sirisena, T.A.J.G.; Duong, T.M.; Hulscher, S.J.M.H.; van der Spek, A. Twenty-first-century projections of shoreline change along inlet-interrupted coastlines. Rep. 2021, 11, 14038. https://doi.org/10.1038/s41598-021-93221-9.
8. Dolan, R.; Hayden, B.P.; May, P.; May, S.K. The reliability of shoreline change measurements from aerial photographs. Shore Beach 1980, 48, 22–29.
9. Boak, E.H.; Turner, I. Shoreline Definition and Detection: A Review. Coast. Res. 2005, 21, 688–703. https://doi.org/10.2112/03-0071.1.
10. Burningham, H.; Fernandez-Nunez, M. Shoreline change analysis. In Sandy Beach Morphodynamics; Jackson, D.W.T., Short, A.D., Eds.; Elsevier: Amsterdam, The Netherlands, 2020; pp. 439–460. https://doi.org/10.1016/b978-0-08-102927-5.00019-9.
11. Douglas, B.C.; Crowell, M.; Winter, F. Long-term shoreline position prediction and error propagation. Coast. Res. 2000, 16, 145–152.

12. Baral, R.; Pradhan, S.; Samal, R.N.; Mishra, S.K. Shoreline Change Analysis at Chilika Lagoon Coast, India Using Digital Shoreline Analysis System. Indian Soc. Remote Sens. 2018, 46, 1637–1644. https://doi.org/10.1007/s12524-018-0818-7.
13. Dereli, M.A.; Tercan, E. Assessment of Shoreline Changes using Historical Satellite Images and Geospatial Analysis along the Lake Salda in Turkey. Earth Sci. Inform. 2020, 13, 709–718. https://doi.org/10.1007/s12145-020-00460-x.
14. Vivek, G.; Goswami, S.; Samal, R.N.; Choudhury, S.B. Monitoring of Chilika lake mouth dynamics and quantifying rate of shoreline change using 30 m multi-temporal Landsat data. Data Brief 2019, 22, 595– https://doi.org/10.1016/j.dib.2018.12.082.
15. Carr, A.P. Shingle Spit and River Mouth: Short Term Dynamics. Inst. Br. Geogr. 1965, 36 117. https://doi.org/10.2307/621458.
16. De Boer, G.; Carr, A.P. Early Maps as Historical Evidence for Coastal Change. J. 1969, 135, 17–39. https://doi.org/10.2307/1795560.
17. El-Ashry, M.T.; Wanless, H.R. Photo interpretation of shoreline changes between capes Hatteras and Fear (North Carolina). Geol. 1968, 6, 347–379. https://doi.org/10.1016/0025-3227(68)90001-7.
18. Gulliver, P.F. Shoreline topography. Am. Acad. Arts Sci. 1899, 8, 151–258.
19. Tanner, W.F. Standards for Measuring Shoreline Change; Coastal Research: Tallahassee, FL, USA, 1978; p. 85.
20. Boye, C.B.; Addo, K.A.; Wiafe, G.; Dzigbodi-Adjimah, K. Spatio-temporal analyses of shoreline change in the Western Region of Ghana. Coast. Conserv. 2018, 22, 769–776. https://doi.org/10.1007/s11852-018-0607-z.
21. Mahapatra, M.; Ratheesh, R.; Rajawat, A.S. Shoreline Change Analysis along the Coast of South Gujarat, India, Using Digital Shoreline Analysis System. Indian Soc. Remote Sens. 2014, 42, 869–876. https://doi.org/10.1007/s12524-013-0334-8.
22. Crapoulet, A.; Héquette, A.; Marin, D.; Levoy, F.; Bretel, P. Variations in the response of the dune coast of northern France to major storms as a function of available beach sediment volume. Earth Surf. Process. Landf. 2017, 42, 1603–1622. https://doi.org/10.1002/esp.4098.
23. Moore, L.J.; Ruggiero, P.; List, J.H. Comparing Mean High Water and High Water Line Shorelines: Should Proxy-Datum Offsets be Incorporated into Shoreline Change Analysis? Coast. Res. 2006, 22, 894–905. https://doi.org/10.2112/04-0401.1.
24. Luijendijk, A.; Hagenaars, G.; Ranasinghe, R.; Baart, F.; Donchyts, G.; Aarninkhof, S. The state of the world’s beaches. Rep. 2018, 8, 1–11. https://doi.org/10.1038/s41598-018-24630-6.

25. Vos, K.; Harley, M.D.; Splinter, K.D.; Simmons, J.A.; Turner, I.L. Sub-annual to multi-decadal shoreline variability from publicly available satellite imagery. Eng. 2019, 150, 160–174. https://doi.org/10.1016/j.coastaleng.2019.04.004.

26. Pollard, J.A.; Spencer, T.; Brooks, S.M.; Christie, E.K.; Möller, I. Understanding spatio-temporal barrier dynamics through the use of multiple shoreline proxies. Geomorphology 2020, 354, 107058. https://doi.org/10.1016/j.geomorph.2020.107058.

27. Salmon, C.; Duvat, V.K.E.; Laurent, V. Human- and climate-driven shoreline changes on a remote mountainous tropical Pacific Island: Tubuai, French Polynesia. Anthropocene 2019, 25, 100191. https://doi.org/10.1016/j.ancene.2019.100191.

28. Zanutta, A.; Lambertini, A.; Vittuari, L. UAV Photogrammetry and Ground Surveys as a Mapping Tool for Quickly Monitoring Shoreline and Beach Changes. Mar. Sci. Eng. 2020, 8, 52. https://doi.org/10.3390/jmse8010052.

29. Underwood, S.G.; Anders, F.J. Evaluation of the Coastal Features Mapping System for Shoreline Mapping (No. CERC-91-13); Coastal Engineering Research Center: Vicksburg, MS, USA, 1991; p. 49.

30. Danforth, W.W.; Thieler, E.R. Digital Shoreline Mapping System (DSMS) User's Guide, Version 1.0; US Geological Survey: Reston, VI, USA, 1992; p. 33.

31. Thieler, E.R.; Martin, D.; Ergul, A. Digital Shoreline Analysis System (DSAS) Version 2.0: An ArcView Extension for Calculating Shoreline Change (No. 2003-76); US Geological Survey: Reston, VI, USA, 2003.

32. Thieler, E.R.; Himmelstoss, E.A.; Zichichi, J.L.; Miller, T.L. Digital Shoreline Analysis System (DSAS) Version 3.0: An ArcGIS Extension for Calculating Shoreline Change; Open-File Report 2005–1304; US Geological Survey: Reston, VI, USA, 2005.

33. Thieler, E.R.; Himmelstoss, E.A.; Zichichi, J.L.; Ergun, A. Digital Shoreline Analysis System (DSAS) Version 4.0: An ArcGIS Extension for Calculating Shoreline Change; Open File Report 2008–1278, U.S.A; US Geological Survey: Reston, VI, USA, 2009.

34. Himmelstoss, E.A.; Henderson, R.E.; Kratzmann, M.G.; Farris, A.S. Digital Shoreline Analysis System (DSAS) Version 5.1 User Guide;S. Geological Survey Open: Reston, VI, USA, 2021; p. 104. https://doi.org/10.3133/ ofr20211091.

35. Himmelstoss, E.A.; Henderson, R.E.; Kratzmann, M.G.; Farris, A.S. Digital Shoreline Analysis System (DSAS) Version 5.0 User Guide; Open-File Report 2018–1179; Geological Survey Open: Reston, VI, USA, 2018; p. 126.

36. Mishra, M.; Sudarsan, D.; Kar, D.; Naik, A.K.; DAS, P.P.; Santos, C.A.; da Silva, R.M. The development and Research trend of using dsas tool for shoreline change analysis: A

scientometric analysis. Urban Environ. Eng. 2020, 14, 69–77. https://doi.org/10.4090/juee.2020.v14n1.069077.

37. Santos, C.A.G.; Nascimento, T.V.M.D.; Mishra, M.; da Silva, R.M. Analysis of long- and short-term shoreline change dynamics: A study case of João Pessoa city in Brazil. Total Environ. 2021, 769, 144889. https://doi.org/10.1016/j.scitotenv.2020.144889.
38. De Lima, L.T.; Fernández-Fernández, S.; Espinoza, J.M.D.A.; Albuquerque, M.D.G.; Bernardes, C. End Point Rate Tool for QGIS (EPR4Q): Validation Using DSAS and AMBUR. ISPRS Int. J. Geo-Inf. 2021, 10, 162. https://doi.org/10.3390/ijgi10030162.
39. Griffiths, D.; House, C.; Rangel-Buitrago, N.; Thomas, T. An assessment of areal and transect-based historic shoreline changes in the context of coastal planning. Coast. Conserv. 2019, 23, 315–330. https://doi.org/10.1007/s11852-018-0661-6.
40. Jackson, C.W., Jr.; Alexander, C.R.; Bush, D.M. Application of the AMBUR R package for spatio-temporal analysis of shoreline change: Jekyll Island, Georgia, USA. Geosci. 2012, 41, 199–207. https://doi.org/10.1016/j.cageo.2011.08.009.
41. Hoeke, R.K.; Zarillo, G.A.; Synder, M. A GIS-Based Tool for Extracting Shoreline Positions from Aerial Imagery (BeachTools); US Army Corps of Engineer Research and Development Center, Coastal and Hydraulics Lab: Vicksburg, MS, USA, 2001.
42. Gómez-Pazo, A.; Payo, A.; Paz-Delgado, M.V.; Delgadillo-Calzadilla, M.A. Open Digital Shoreline Analysis System: ODSAS v1.0. Mar. Sci. Eng. 2022, 10, 26. https://doi.org/10.3390/jmse10010026.
43. Dominici, D.; Zollini, S.; Alicandro, M.; Della Torre, F.; Buscema, P.M.; Baiocchi, V. High Resolution Satellite Images for Instantaneous Shoreline Extraction Using New Enhancement Algorithms. Geosciences 2019, 9, 123. https://doi.org/10.3390/geosciences9030123.
44. Heo, J.; Kim, J.H.; Kim, J.W. A new methodology for measuring coastline recession using buffering and non-linear least squares estimation. J. Geogr. Inf. Sci. 2009, 23, 1165–1177. https://doi.org/10.1080/13658810802035642.
45. Hisabayashi, M.; Rogan, J.; Elmes, A. Quantifying shoreline change in Funafuti Atoll, Tuvalu using a time series of Quickbird, Worldview and Landsat data. GIScience Remote Sens. 2018, 55, 307–330. https://doi.org/10.1080/15481603.2017.1367157.