



Mapping total suspended matter along Moroccan coast using satellite data series

H. Azidane¹ · S. Haddout² · K. A. Alawad³ · M. Boko⁴ · M. E. Bouhaddioui⁵ · B. Magrane⁶

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Abstract

Remote-sensing techniques are a powerful technique for monitoring turbidity over the whole littoral areas. Different sensors can be used to quantify and analyze water quality parameters such as colored dissolved organic matter, total suspended sediments, chlorophyll-a, and pollutants. Therefore, the goal of this paper is to investigate the inter-annual and spatio-temporal variability's of total suspended matter (TSM) concentration in the water surface layer. The coastal of the Atlantic Ocean, Morocco is taken an application area. The results show that high TSM (18 g m^{-3}) is observed during winter season, and lower TSM (2 g m^{-3}) is observed during summer season. In addition, the relationship between TSM and wind speed; and with ocean current was analyzed, and the results show that: (1) sand dredging areas usually coincide with region that have high TSM levels; (2) the wind and ocean current were both important to TSM variation; (3) the increased level of sand dredging in response to rapid economic growth has deeply influenced the TSM pattern since 2012 due to the resuspension of sediment in some areas. Visual interpretation of location led to the conclusion that the dredging activities were more located on the northern and western Morocco. Time series of MODIS images revealed a significant increase in water turbidity from 2012 onwards on the northern Morocco. Moreover, strong wind events in the northern Sahara can significantly increase the TSM in turbid coastal waters.

Keywords Total suspended matter · Remote sensing · Turbidity · Time series · Morocco

Introduction

The coastal areas are zones of primary importance from human and ecological perspectives. Nearly all of the maritime resource is on a narrow continental shelf which is affected by ecological pressures owing to a large-scale

population increase in the coastal areas (half of the world's population lives at least 60 km from a coast, and the proportion will be 70% in 2020) (FAO 2014).

In recent years, a number of remote-sensing sensors are available to resource managers for developing effective marine ecosystem management initiatives, including the use of information technology for analyzing and understanding an ecosystem as a whole and not simply the targeted resource or a specific zone (Gutierrez et al. 2016).

Remote-sensing techniques are powerful tools to obtain specific information of Earth observation, including space and temporal characteristics, and aerial observation of the coastal zone. Substances in surface water can significantly change the characteristics and properties of coastal zone (Ritchie et al. 2003). Remote-sensing data provide not only photographic representation of the coastal and marine surfaces, but also physical observations of different properties of these ecosystems. These spectral characteristics can be used to access the major factors affecting water quality in coastal water bodies (e.g., total suspended matter and dissolved organic matter) (Vanhellemont and Ruddick 2014;

✉ H. Azidane
hind.azidane@uit.ac.ma

¹ Faculty of Sciences, Department of Geology, Ibn Tofail University, B.P. 133, Kenitra, Morocco

² Faculty of Science, Department of Physics, Ibn Tofail University, B.P. 133, Kenitra, Morocco

³ Faculty of Marine Sciences, Marine Physics Department, King Abdulaziz University, Jeddah 21589, Saudi Arabia

⁴ Laboratory of Climatology, National University of Benin, Cotonou, Benin

⁵ National School of Mines, B.P. 753, 14000 Agdal-Rabat, Morocco

⁶ Water Service of Kenitra City, Ministry of Energy, Mines, Water and Environment, B.P. 203, 14000 Kenitra, Morocco

Tang et al. 2013; Zhu et al. 2013); (1) to identify, characterize, and analyze river plumes (Mendes et al. 2014), (2) to extract estuarine/coastal sandy bodies (Teodoro and Gonçalves 2012), (3) to identify beach features/patterns (Teodoro 2015), and (4) to evaluate the changes and integrity (health) of the coastal lagoon habitats (Vahtmäe and Kutser 2013), at various scale. In fact, the remote sensing creates new opportunities for identifying which parameters function as regulators of marine/coastal ecosystems activity at local and regional levels and how these variables differ across spatial and temporal scales.

According to our knowledge, there is no research on the total suspended sediments along the Moroccan coast using remote-sensing tool. Therefore, more studies are needed to have a detailed picture of the total suspended sediments status of this area. In this study, satellite data are used to estimate the TSM concentrations in the studied area.

Materials and methods

Study area

Morocco country, as part of the Atlantic Ocean, is an important region in the local ecological system (DPDPM 2007). This region experiences strong currents in some coast and various tidal elevations. The area harbors several major and minor ports and is subject to intensive industrial activities and urban growth (DPDPM 2008). Thus, as many other coastal region, environmental change, inland processes including sediment, nutrient fluxes (riverine flux), and anthropogenic activities in the area threaten its water quality (Bennasser et al. 1998; Bouasria et al. 2007; Alaoui et al. 2008; DPDPM 2011b). An increasing level of sand mining,

for example, has stirred up heavy metals in the sediment load from some lake's mouth like Sebou river in Kenitra city (DPDPM 2007; METL 2014; Jaaidi and Cirac 1987). The study area is situated in the North Atlantic Ocean (Fig. 1). It is part of Africa on the northwestern. It has bordered by Spain to the north and Western Sahara to the south. The Morocco coast extends approximatively over 3500 km. Along the coastline, a different landforms types (or geomorphology) have been recognized and described depend on topography, elevation, shape, and composition characteristics (e.g., depends on rock types, unconsolidated materials, etc.). Wherever, freshwater rivers, estuaries, lagoons, and deltas drain into this larger body of water. The longshore drifts associated with the waves are the principal agents responsible for the sedimentary transport and the sand distribution along the coast. Many researchers concluded that this area along the coast have a potential coastal erosion (Moussaid et al. 2015; Azidane et al. 2017). A variety of the present erosion could be associated with coastal response to river sediment sources, river sediment transport, and sea-level rise and dune destruction. Indeed, the higher dredging intensity that occurs along the Moroccan coast and illegal sand extraction can minimize sediment volumes. These marine activities are mostly distributed in the northern and western parts of a test area (Fig. 2).

Datasets and image processing

The TSM measurements were made from 2007 to 2012 are based on Moderate Resolution Imaging Spectroradiometer (MODIS). MODIS is a big platform aboard the Aqua (EOS PM) satellites and Terra (EOS AM) orbit; and used in many research papers (e.g., Singh et al. 2021; Shen et al. 2021; Yang et al. 2021; Huang and Huang 2020). Three types

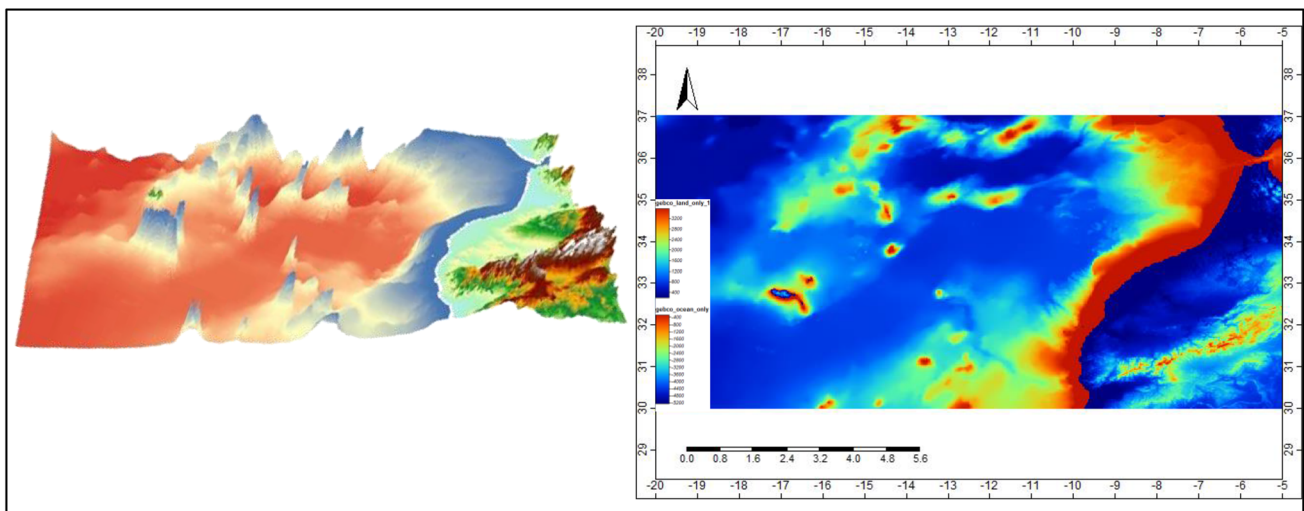


Fig. 1 Surface map of the North Atlantic Ocean, Morocco (right). A digital elevation model of the study area (left)

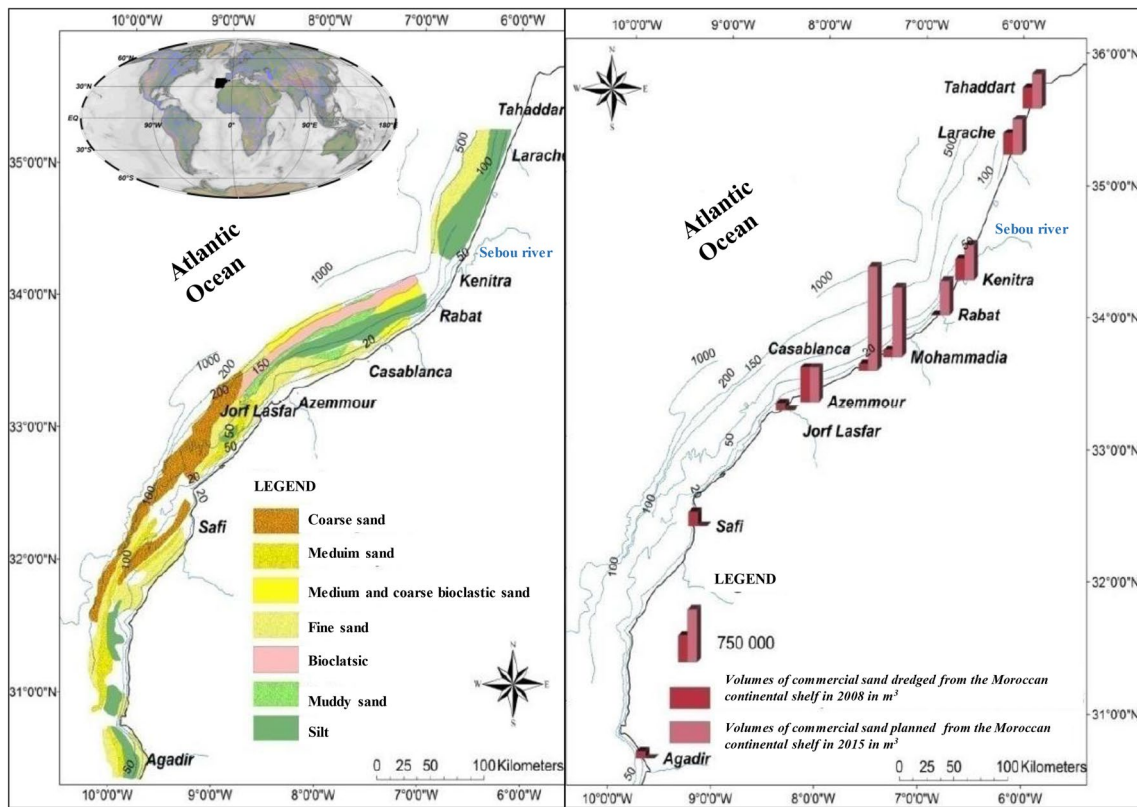


Fig. 2 Volumes of commercial sand dredged from the Moroccan continental shelf in 2008 and planned production in 2015 (right). Synthetic map of sedimentological data of the continental shelf of the Moroccan Atlantic (Jaaidi and Cirac 1987, modified) (left)

of data were used; TSM images between 2007 and 2012; wind speed data between 2007 and 2009; and ocean current speed data between 2007 and 2009 covering the Atlantic coast (Table 1).

Times series of good-quality MODIS 250 resolution products were downloaded from Glob Colour Merged (MODIS/MERIS/SEAWIFS) with the resolution of 4 km and daily datasets. The TSM values corresponding to our points of interest were geo-corrected, and land and cloud areas were masked out to obtain very precise TSM measurements. Upon extracting dataset to a local system, the data were displayed to access image quality and then processed using ESA Sentinel Application Platform (SNAP), and are available from the official website: <http://step.esa.int/main/download/snap-download/>.

Additionally, we chose two types of data, which were used to represent the meteorological conditions for the entire region: (1) monthly wind speed data that matched the date of acquisition for each satellite image from 2007 to 2009 were accessed from the website (<http://apdrc.soest.hawaii.edu/las/v6/constrain?var=13073>); (2) monthly ocean current prior to the acquisition date of each satellite image from 2007 to 2009 were accessed from the website (<http://apdrc.soest.hawaii.edu/las/v6/constrain?var=2776>).

The autumn period is defined here to include three months, September, October, and November. The winter period contains December, January, and February data. The spring period include Mars, April, and May. The summer season contains June, July, and August.

Table 1 TSM and meteorological data used in this study

Parameters	Resolution	Source
TSM	[2007–2012] daily; 4 km	Satellite data: http://hermes.acrr.fr/index.php?class=demonstration_products
Wind	[2007–2009] monthly	Model: http://apdrc.soest.hawaii.edu/las/v6/constrain?var=13073
Ocean current	[2007–2009] monthly	Model: http://apdrc.soest.hawaii.edu/las/v6/constrain?var=2776

Results and discussion

Seasonal variability of satellite TSM concentration

Different seasons (autumn, winter, spring, and summer) have been studied. Figure 3 shows the seasonal distribution of TSM concentration in North Atlantic Ocean from MODIS images.

From Fig. 3, the TSM in 2007 to 2012 distributed in wide area. High concentration of TSM accumulated around the coast represented by red color. December, January, and February represent winter which is wet season in Morocco. Wet season characterized by high rainfall, in which will increase the debit of rivers. TSM of coastal area is varying in range of 9 until max 10 g m^{-3} . June, July, and September represent summer which is dry season in Morocco. Pattern of TSM distribution is spread compared with pattern of TSM in winter season, but the concentration of TSM in this period is lower than winter season. The rate of flow of rivers during dry season is lower and the TSM is about 3 g m^{-3} . The dataset from 2012 has very high turbidity condition. This high turbidity is mainly concentrated near the river mouths.

On the other hand, Fig. 3 is a snapshot of the TSM pattern, and so, it cannot represent the mean TSM for each year in the season; in addition, it clearly shows the spatial patterns in each derived TSM snapshot and the main differences and changes in TSM patterns.

To view the changes of TSM patterns in coastal area, an alternative method for examining the annual variability in TSM concentration is used to examine the maps of the mean in each pixel box. For that, the pixel information values (Pins) were used. The Pins locations in coastal area are displayed in Fig. 4.

Furthermore, Fig. 5 shows TSM time series at the pixels. The TSM had significant spatial variability between 2007 and 2012. Overall, the mean TSM of each season varied widely, from 2 g m^{-3} in summer to 18 g m^{-3} in winter. A higher mean of TSM observations in these years is evident in the autumn and winter seasons, with both models given very comparable results.

However, it is clear from Fig. 6 that the maximum TSM concentrations appear in winter, and the minimum in summer, with lower concentration peaks arising in spring and autumn.

The seasonal difference in satellite TSM concentrations was estimated by subtracted winter and summer TSM concentrations, winter and spring TSM concentrations, and winter and autumn TSM concentrations for each pixel box over the entire area (Fig. 7).

Interannual variability

The inter-annual variability is calculated separately for coastal stations from satellite data, which demonstrates the fact of annual mean TSM values tend to fluctuate more smoothly from 5 to 80 g m^{-3} . Considerable inter-annual

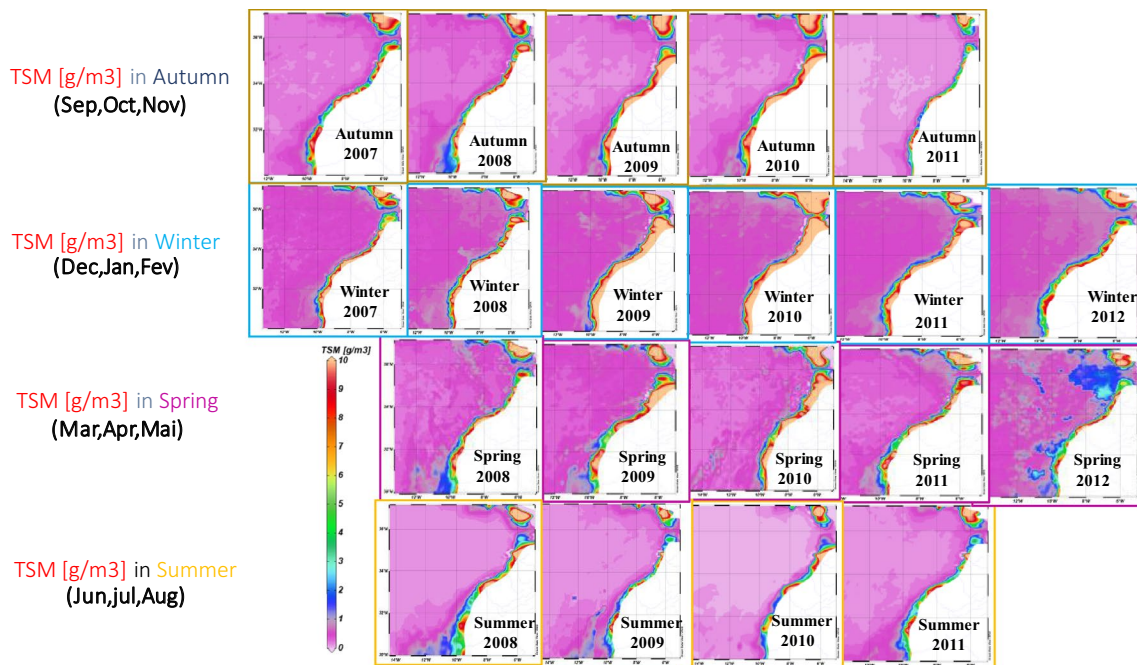


Fig. 3 Derived-TSM pattern distribution snapshot map from 1978 to 2013 in North Atlantic Ocean

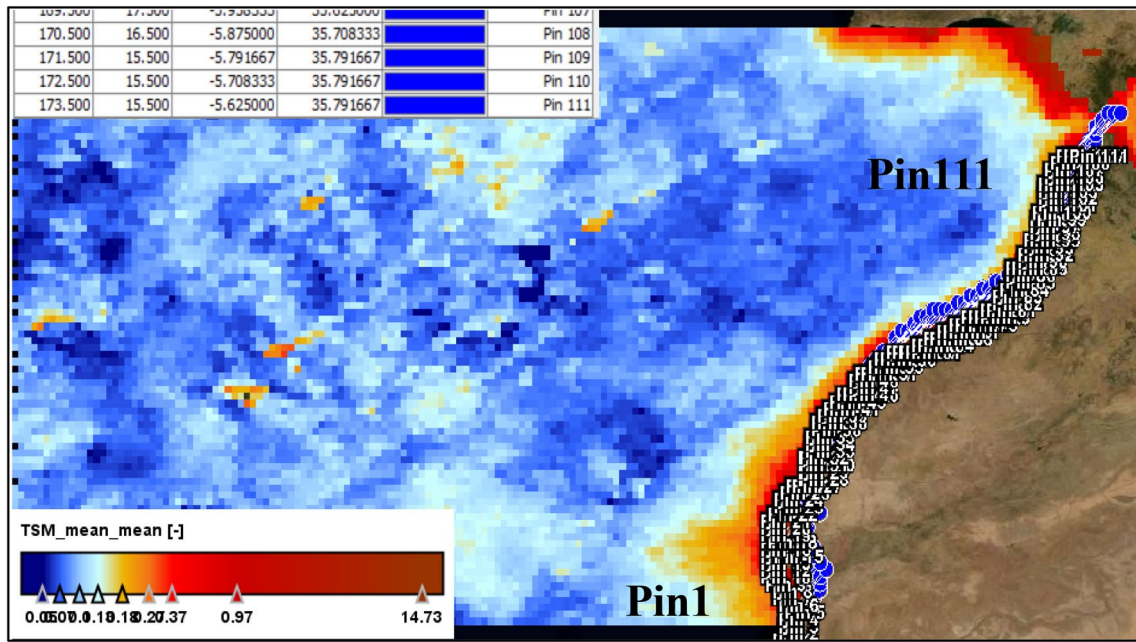


Fig. 4 Distribution of TSM measurement stations using 111 pins in coastal area

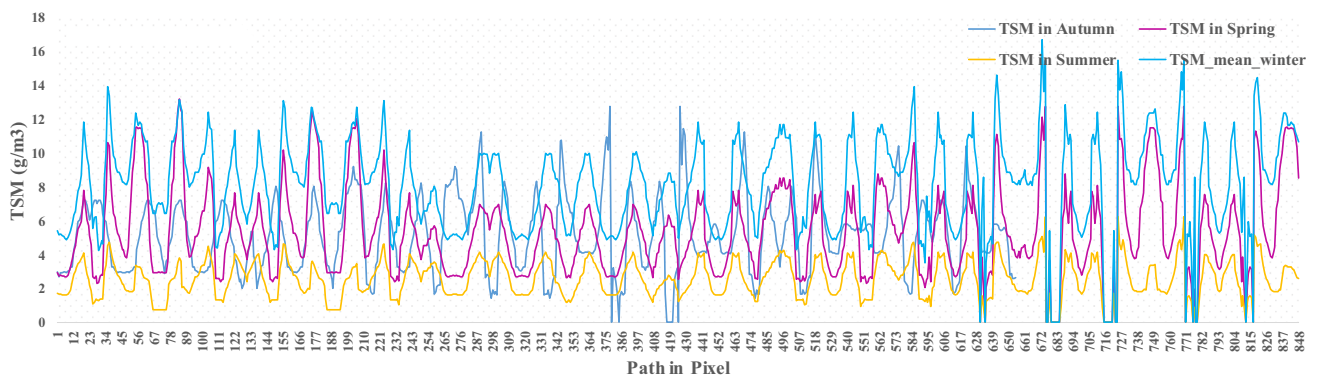


Fig. 5 Total suspended matter time series extracted from 111 pins for the period 2007–2012

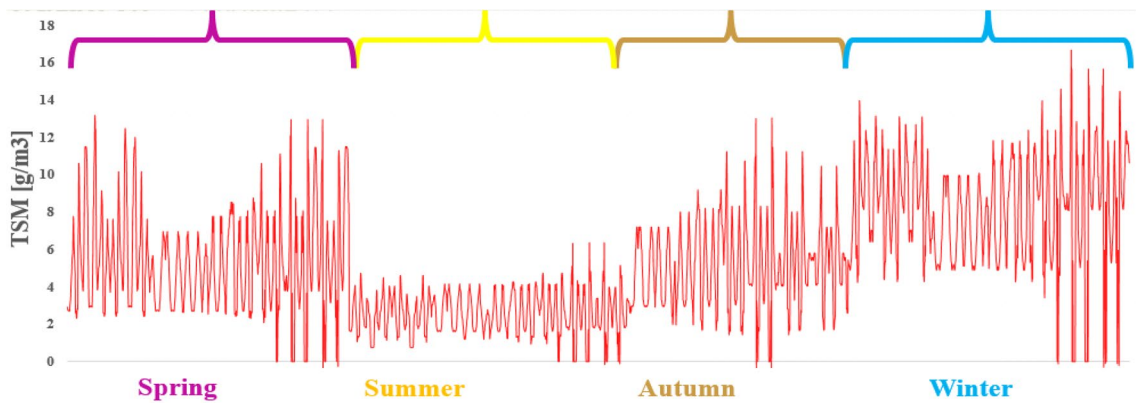


Fig. 6 Derived mean TSM for four season, from 2007 to 2012

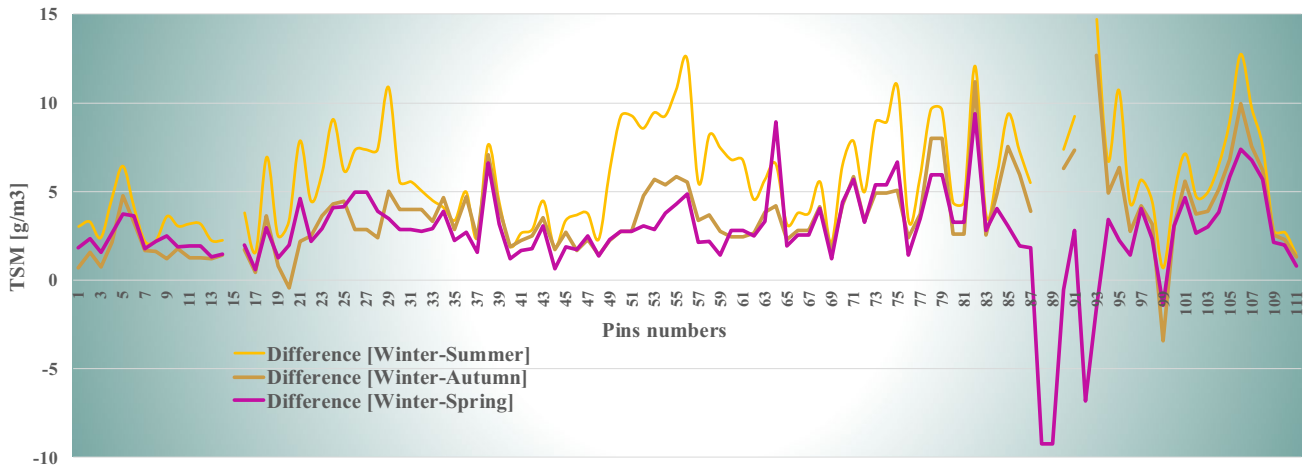


Fig. 7 TSM concentration seasonal differences between summer and winter, winter and autumn, and winter and spring

variations of TSM are typical for the northern Sahara, western Morocco on the Atlantic Ocean and northern Morocco.

The greater peak of TSM concentrations took place in northern Morocco in the 6-year period. This maximum

appears in 2007, 2008, 2009, and from 2010 to 2012. Nevertheless, peak of TSM concentrations occurs twice in 2012 in the northern Morocco. As mentioned earlier, the discharge of TSM concentrations propagates in the whole northern part in 2012, as shown in Fig. 8.

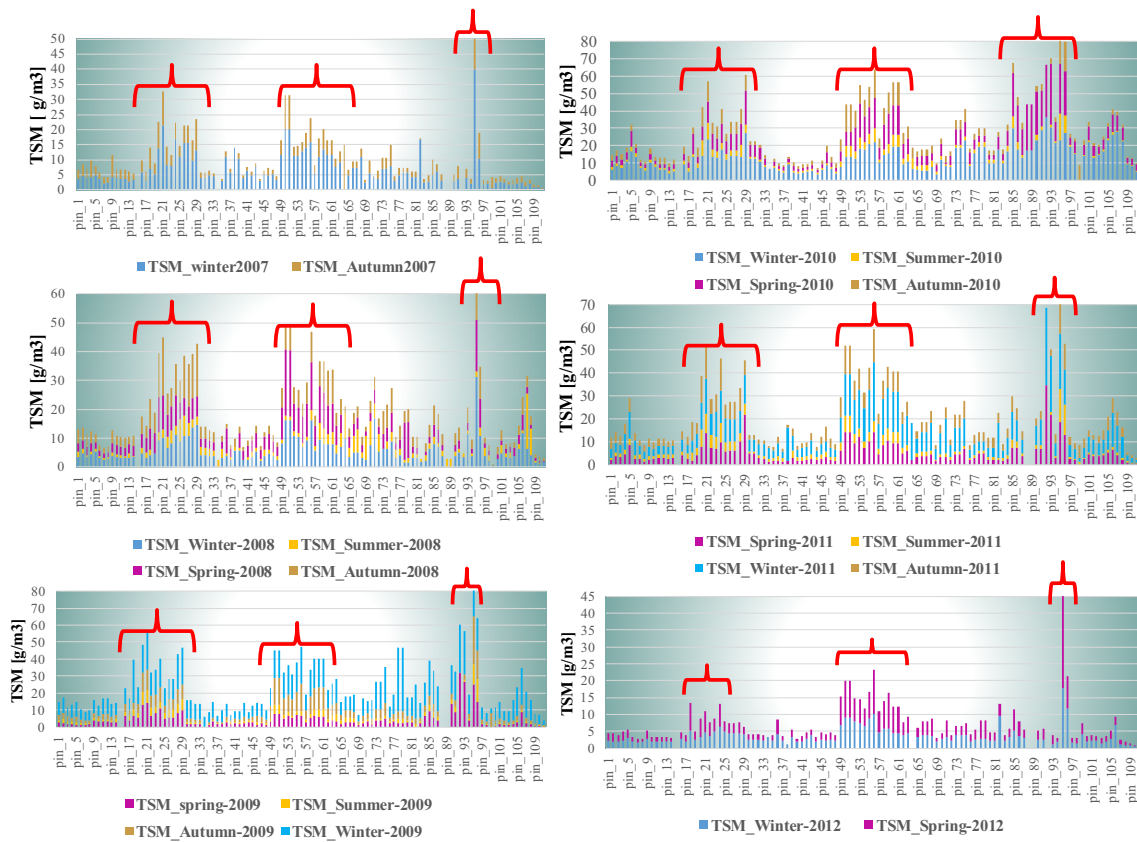


Fig. 8 Annual mean TSM concentration, calculated from satellite data

Factors affecting the spatial and temporal changes in TSM

To test the TSM variation, the relationship between mean TSM and the local potential affecting factors was evaluated. Various factors influence the significant annual and seasonal variation generally observed in TSM, including seasonal wind, freshwater input, sediment load, tidal cycle, and flocculation (Wang et al. 2007).

In this study, the spatial–temporal variability of TSM concentration was demonstrated using the seasonal wind, ocean current, and freshwater input. Figure 9 shows the distributions of annual average wind speed. The increased wind speed in summer favored the resuspension of sediment in the northern Sahara, and therefore, TSM was higher in summer

than in winter. Apparently, the maximum of TSM in the northern Sahara is provoked by increased wind storm activity resulting by air transfer in Sahara in 2007, 2008, 2009, 2010, 2011, and 2012. Strong winds and prevailing northern Sahara component affected coastal abrasion established resuspension of particulate matter along the coast where the major coastal stations are located.

An increase in water turbidity in the northern Morocco and western Morocco on the Atlantic Ocean does necessarily imply dredging. Especially that the dredging concentrated in these regions. The annual mean TSM from 2007 to 2012 confirm the aforementioned increasing trend in water turbidity. One argument indicating the presence of dredging was the observation that the clear waters turned turbid in 2012 in northern Morocco. Furthermore, dredging further increased

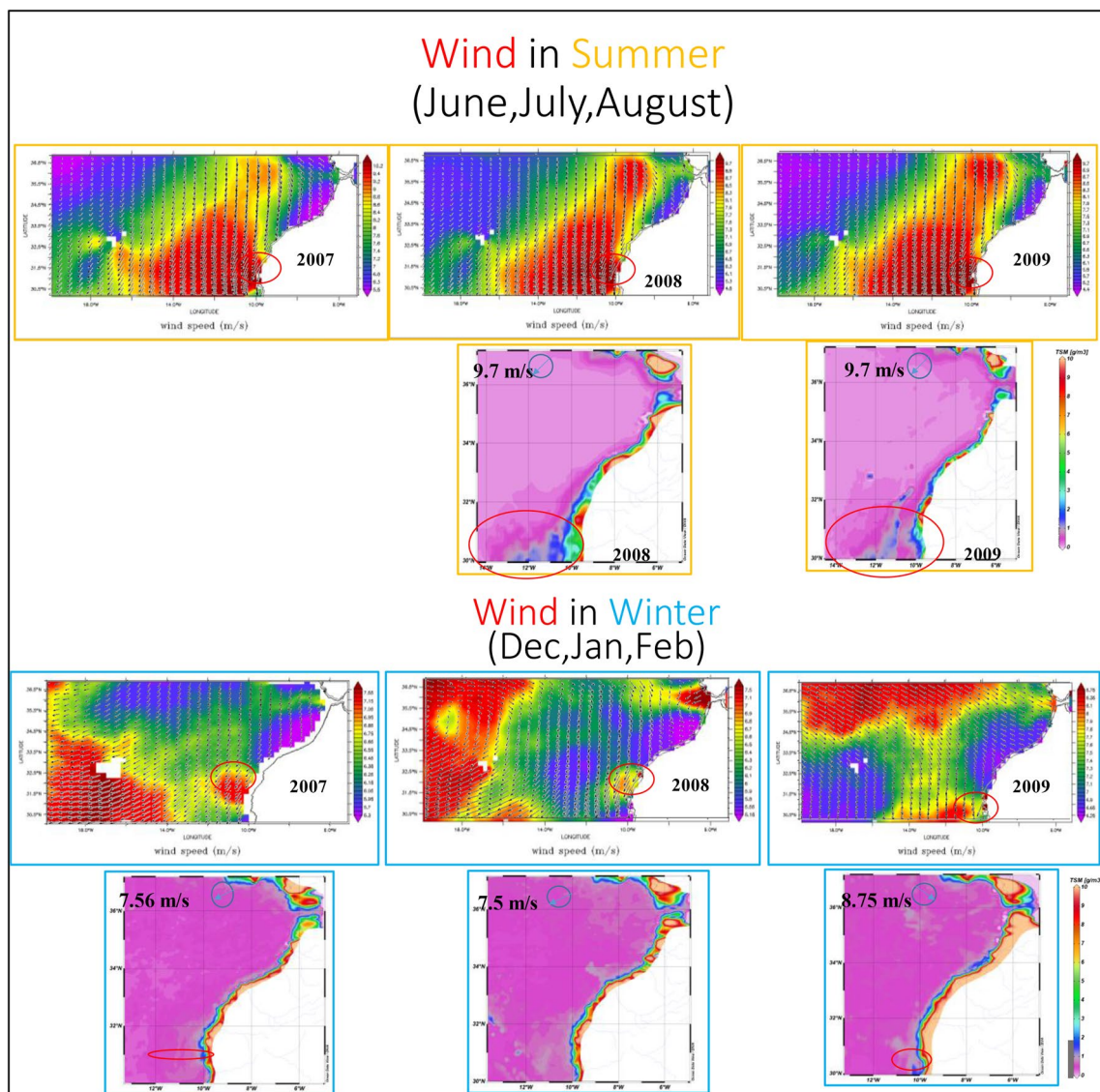


Fig. 9 Distributions of annual average wind speed in coastal waters in 2007, 2008, and 2009

due to the rapidly rising demand for sand to support construction. In 2012, 30 million m^3 of sand are dredged in the northern Morocco. The evidence extracted from MODIS images in 2012 in this area thus confirms this argument.

Many studies (e.g., Hakkou et al. 2015) have reported the impacts of dredging on littoral areas especially on the northern Morocco, including the effects of increased water turbidity, for instance, on aquatic plants and animals, and also noise, pollution. Hakkou et al. (2015) expressed that the noisy, oil pollution, turbidity, and decreased habitat caused by dredging could seriously affect the propagation, growth, and subsistence of fish in the area. DPDPM (2011a) reported that the population of some fish species have rapidly decreased with the rapid growth of fisheries, boating, traffic, and dredging activities in Kenitra city. Sand dredging might in fact become the main factor of TSM variation in Kenitra coast after 2012.

The relationship between mean TSM and other potential affecting factors, such as ocean current data, is also illustrated in Fig. 10. During winter events of strong wind, together with currents, it is responsible for increase in the bottom friction producing very efficiently sediment resuspension. Strong currents are concentrated along the northern coast of Morocco, and sediment concentrations are more pronounced.

These results coincide very well with sediment thickness distributions in the coastal and offshore area (Fig. 11). Sediment thickness increases dramatically toward the open sea in the Northern Morocco, western Morocco, and northern Sahara.

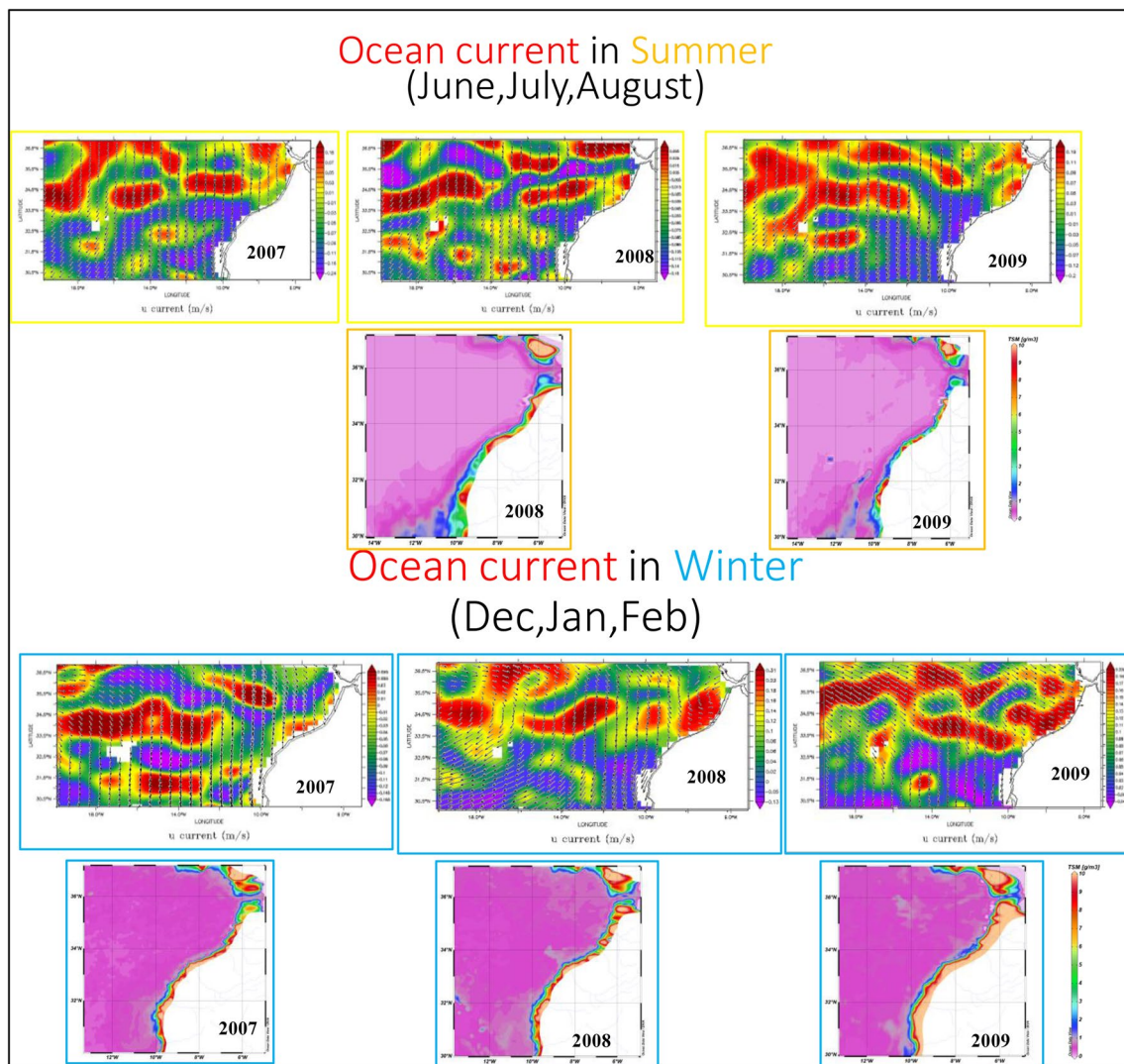


Fig. 10 Distributions of annual average ocean current in coastal waters in 2007, 2008, and 2009

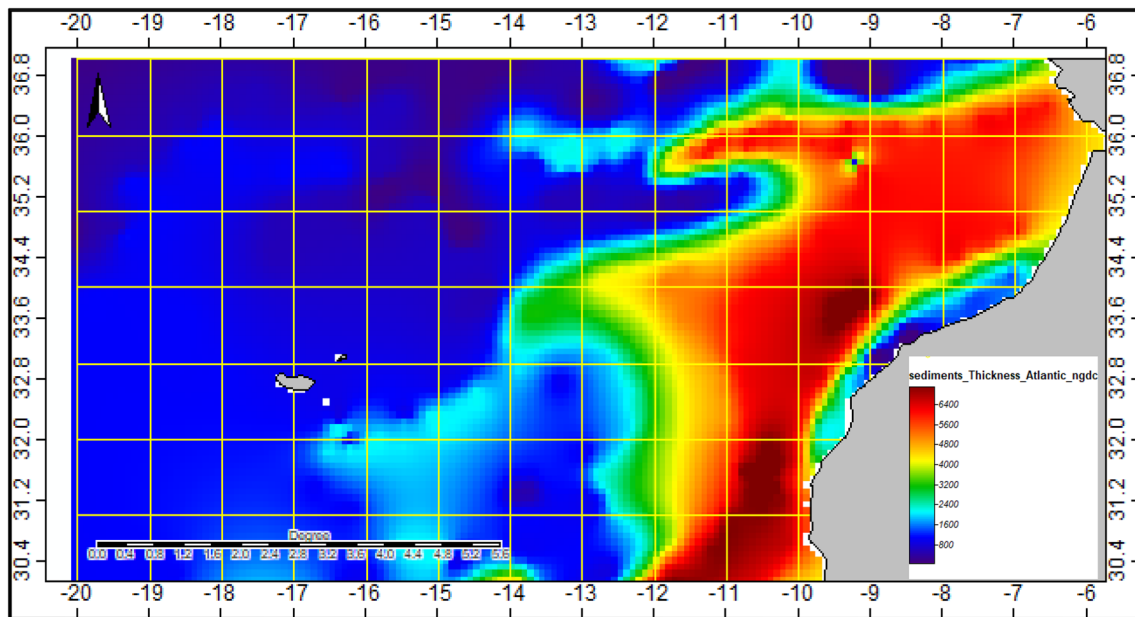


Fig. 11 Sediment thickness map

Conclusions

In this paper, we demonstrate how satellite images and time series analysis of TSM products may contribute to the understanding of process in marine environment, especially for shallow coastal areas. The spatial distribution and temporal variability of TSM concentration in the North Atlantic Ocean of Morocco coastal waters were investigated using satellite MODIS data for the period of 6 years (i.e., 2007–2012), leading to several key findings. It was first clearly established that higher TSM concentrations were observed in winter (December, January, and February), and lower TSM concentrations characterized summer (June, July, and August). The satellite data indicate similar patterns of TSM concentrations which may be divided accordingly into three different areas: at the north of Morocco, at the west of Morocco, and at the north of Sahara. The annual mean shows high turbidity in these regions. This distribution of maxima in the north and the west of Morocco affected by dredging operations, which could be a result of human activities such as an increased level of sand mining in response to the rapid economic growth occurring in Morocco that has resulted in increased sediment resuspension. On the other hand, the currents are strong in these areas, so the TSM distribution increase quickly.

The purpose of this paper is to demonstrate that capability of wind storm for monitoring the evolution of sediment resuspension processes in shallow coastal water environment in western Sahara. Our work offers new insight to

understand the impacts of dredging. Future improvements to the procedure include: conducting field sampling to better calibrate the image processing.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical approval I confirm that this work is original and have not been published elsewhere, nor is it currently under consideration for publication elsewhere.

References

- Alaoui N, Mhammedi B, El Moumni A, El Hmadi A, Raissouni A, El Arrim A (2008) Mineralogical and geochemical study of mud volcanoes in north Moroccan atlantic margin. *Afr J Environ Sci Technol* 2(11):387–396
- Azidane H, Benmohammadi A, Haddout S, Hakkou M, Belghaba T, Boko M, Magrane B (2017) Evaluating the impacts of sea-level rise on the Moroccan coast: quantifying coastal erosion and inundation in a Atlantic alluvial plain (Kenitra coastal). *Epis J Int Geosci* 40(4):269–278

- Bennasser L, Fekhaoui M, Jean-Louis Benoit-Guyod GM (1998) Influence of tide on water quality of lower Sebou polluted by Gharb plain wastes (Morocco).
- Bouasria S, Sadki O, Hamoumi N (2007) Contamination in traces metals in superficial sediments at the exit of Tensift river-Souira Qdima (Moroccan Atlantic margin)
- DPDPM (2007) Etude de reconnaissance géophysique des gisements de sable en vue de la protection des plages de l'Atlantique. Rapport définitif. Mission 1 : Etude d'identification des zones potentiellement exploitables, 176 p
- DPDPM (2008) Etude de sédimentologie des ports et du littoral marocain. Mission 2 : identification des zones d'accumulations de sables et potentiellement exploitables. Rapport final, n°17124436-M2R1, 92 p
- DPDPM (2011a) Etude d'expertise sédimentologique de la plage de Mehdiya. Rapport final, n°1712781, 81 p
- DPDPM (2011b) Etude d'expertise sédimentologique de la plage de Mehdiya (Maroc). Rapport final, n°1712781, 81 p
- FAO (2014) The state of world fisheries and aquaculture, opportunities and challenges 2014. FAO Report, Rome
- Gutiérrez F, Teodoro AC, Reis E, Neto C, Costa JC (2016) Remote sensing technologies for the assessment of marine and coastal ecosystems. In: Seafloor mapping along continental shelves, pp 69–104
- Hakkou M, Benmohammadi A, Castelle B, Bertin X, Labraimi M, EL Hassani A, Layachi M (2015) Perspectives d'optimisation technique de la gouvernance environnementale des activités de dragage du sable marin au Maroc. Bulletin de l'Institut Scientifique, Rabat, Section Sciences de la Terre, n° 37
- Huang P, Huang Y (2020) Spatial–temporal patterns of total suspended matters (TSM) in the Yellow River Estuary. In: IGARSS 2020–2020 IEEE international geoscience and remote sensing symposium, IEEE, pp 5773–5776
- Jaaidi P, Cirac EB (1987) La couverture sédimentaire meuble du plateau continental atlantique marocain entre Larache et Agadir. Bulletin De L'Institut Géologique Du Bassin D'aquitaine 42:33–51
- Mendes R, Vaz N, Fernández-Nóvoa D, da Silva JCB, de Castro M, Gómez-Gesteira M, Dias JM (2014) Observation of a turbid plume using MODIS imagery: the case of Douro estuary (Portugal). *Remote Sens Environ* 154:127–138. <https://doi.org/10.1016/j.rse.2014.08.003>
- METL (2014) Ministère d'équipement, du Transport et de la logistique, M. Impact de la houle exceptionnelle du 6–7 janvier 2014 sur les infrastructures portuaires
- Moussaid J, Ait A, Zourarah B, Maanan M (2015) Using automatic computation to analyze the rate of shoreline change on the Kenitra coast, Morocco. *Ocean Eng* 102:71–77. <https://doi.org/10.1016/j.oceaneng.2015.04.044>
- NASA (2008) About Modis. Retrieved 16 Feb 2008. <http://modis.gsfc.nasa.gov/about/>.
- Ritchie JC, Zimba PV, Everitt JH (2003) Remote sensing techniques to assess water quality. *Photogramm Eng Remote Sens* 69(6):695–704
- Shen Q, Xing X, Yao Y, Wang M, Liu S, Li J, Zhang B (2021) Estimation of suspended matter concentration in manwan reservoir, lancang river using remotely sensed small satellite constellation for environment and disaster monitoring and forecasting (HJ-1A/1B), charge coupled device (CCD) data. *Int J Remote Sens* 42(14):5236–5256
- Singh RK, Sinha VSP, Joshi PK, Kumar M (2021) A multinomial logistic model-based land use and land cover classification for the South Asian Association for Regional Cooperation nations using moderate resolution imaging spectroradiometer product. *Environ Dev Sustain* 23(4):6106–6127
- Tang S, Larouche P, Niemi A, Michel C (2013) Regional algorithms for remote-sensing estimates of total suspended matter in the Beaufort Sea. *Int J Remote Sens* 34(19):6562–6576. <https://doi.org/10.1080/01431161.2013.804222>
- Teodoro AC (2015) Applicability of data mining algorithms in the identification of beach features/patterns on high-resolution satellite data. *J Appl Remote Sens* 9(1):095095. <https://doi.org/10.1117/1.JRS.9.095095>
- Teodoro AC, Gonçalves H (2012) A semi-automatic approach for the extraction of sandy bodies (Sand Spits) from IKONOS-2 data. *IEEE J Sel Top Appl 5(2):634–642*. <https://doi.org/10.1109/JSTARS.2011.2181339>
- Vahtmäe E, Kutser T (2013) Classifying the Baltic Sea shallow water habitats using image-based and spectral library methods. *Remote Sens* 5(5):2451–2474. <https://doi.org/10.3390/rs5052451>
- Vanhellemont Q, Ruddick K (2014) Turbid wakes associated with offshore wind turbines observed with Landsat 8. *Remote Sens Environ* 145:105–115
- Wang Z, Li L, Chen D, Xu K, Wei T, Gao J, Zhao Y, Chen Z, W., & Masabate. (2007) Plume front and suspended sediment dispersal off the Yangtze (Changjiang) River mouth, China during non-flood season. *Estuar Coast Shelf Sci* 71(1–2):60–67
- Yang M, Khan FA, Tian H, Liu Q (2021) Analysis of the monthly and spring-neap tidal variability of satellite chlorophyll-a and total suspended matter in a turbid coastal ocean using the DINEOF method. *Remote Sens* 2021(13):632
- Zhu W, Tian YQ, Yu Q, Becker BL (2013) Using Hyperion imagery to monitor the spatial and temporal distribution of colored dissolved organic matter in estuarine and coastal regions. *Remote Sens Environ* 134:342–354. <https://doi.org/10.1016/j.rse.2013.03.009>

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