Long-term morphological evolution of the Volta-Delta River mouth in Ghana using satellite images

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Abstract

The Volta-Delta River mouth at Ada, Ghana drains one of the largest river basins in West Africa. The river mouth sandspits have undergone enormous morphological changes due to both natural and human activities. Before the construction of a groyne system from 2012-2017 on the western side of the river mouth, cyclic sandspit elongation and breaching events were observed. To fully understand these cyclic events, satellite imagery from Landsat, Sentinel-2 and Google Earth were acquired from 1984-2020 and analyzed to depict the morphological processes occurring at the river mouth. The study examined the river mouth morphology before and after the construction of the groyne system.

Keywords: Breaching, Elongation, Erosion, Groyne system, Sandspit, Volta River mouth.

1. INTRODUCTION

Globally, deltaic coastlines are subjected to alarming rates of vulnerability with respect to erosion and shoreline retreat. Human engineering works in the drainage basin of deltas have influenced the destabilization of deltaic coastlines by impeding sediment supply to these areas (Syvitski et al., 2009). The presence of well-developed sandspits at the mouth of river deltas provides massive benefits with regards to urbanization, floodplain inundation prevention and biodiversity which requires the study of changes ensuing at such locations (Pradhan et al., 2015). Inadequate studies in relation to morphological changes at river mouths exposes them to huge vulnerabilities.

The Volta River mouth is geographically located at Ada in the Greater Accra Region of Ghana between latitudes 5°46'15.06" to 5°46'28.44" North and longitudes 0°39'46.03" to 0°41'31.46" East. The river mouth drains the Volta basin with a catchment area of approximately 400,000 km^2 and a total river network of about 1,500 km (Fig. 1(a)). The river mouth is characterized by two well defined sandspits which are highly morphological in nature (Fig. 1(b)).

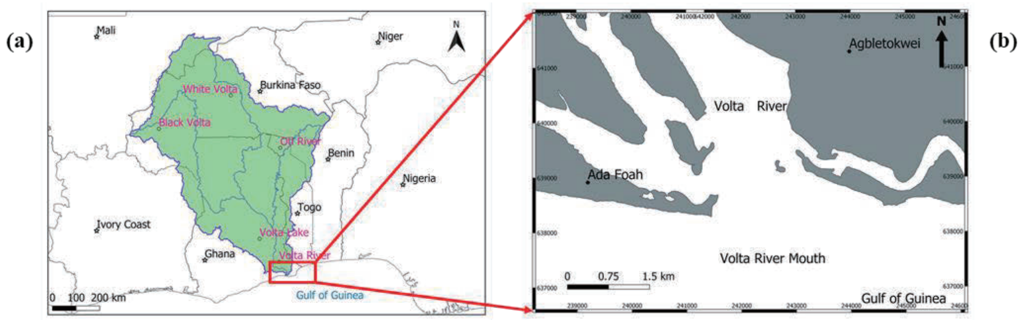

Figure 1: Map of study area (a) Volta River basin (b) Volta River mouth, Ada, Ghana.

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Upstream of the river mouth are two hydro-electricity dams which have influenced the reduced river discharge and sediment load by 23.23% and 92.32% respectively (Amenuvor et. al., 2020). Another engineering structure in the vicinity of the river mouth is a groyne system on the western side of the river mouth which was constructed between 2012-2017. The groyne system protects a total stretch of 16km of the coast against the intense erosion rates and displacement of coastal communities (Roest, 2018). Before the two-phased construction of the groyne system, erosion rates were estimated at about 6m/year which justified the urgent need for protection measures for Ada and its environs (Bollen et al., 2010). The goal of this study is to analyze observed morphological trends at the Volta River mouth using remote sensing images and highlight the driving forces for these processes.

2. MATERIALS AND METHODS

2.1 Data Collection

In this study, historical satellite imagery was acquired from Landsat (5, 7, & 8) and Sentinel-2 satellite missions from 1984-2020 which served as the main source of images. These images were supplemented with Google Earth images to fill the no-data gaps from the Landsat and Sentinel-2 sources. A total of 164 images were acquired for the study period and used to perform the long-term morphological analysis. The Landsat and Sentinel-2 images which originally have a spatial resolution of 30m/pixel and 20m/pixel respectively, were down-sampled to 15m/pixel and 10m/pixel respectively using bilinear interpolation to improve the accuracy of detected shorelines (Vos et. al., 2019). Furthermore, the resolution of supplementary images from Google Earth were 2m/pixel and 20m/pixel. A summary of images acquired for the study are presented in Table 1 below.

Table 1: Details on acquired satellite images for the study area.

Image Source	No. of Images	Resolution	Down-sampled Resolution
Landsat (5,7 & 8)	50	30m/pixel	15m/pixel
Sentinel-2	80	20m/pixel	10m/pixel
Google Earth	34	2m/pixel & 20m/pixel	-

2.2 Image Processing

Shoreline detection was carried out using two approaches for the main and supplementary sources of images. For the Landsat and Sentinel-2 images, the water-land boundary was defined using the Modified Normalized Difference Index (MNDWI) developed by Xu (2006). The MNDWI values range between -1 and 1 with negative values corresponding to water pixels and positive values corresponding to land pixels. In the case of the Google Earth images, all images were rectified into a single coordinate system (World Geodetic System-84) using an affine transformation with the baseline 271 degrees from the North. The shorelines were then detected using the difference in colour intensity of the wet and dry sand.

2.3 River Mouth Sandspit Analysis

To conduct detailed studies on the morphological evolution of the of the Volta River mouth, quantitative analysis was conducted using the acquired satellite images. Parameters of the sandspit used to achieve this include the alongshore coordinate of the updrift (x_1) and downdrift (x_2) sandspits and their corresponding y-coordinate values (y_1 and y_2 respectively). The areas of the updrift (A_1) and downdrift (A_2) sandspits were also defined. Definition of these parameters are shown in Fig. 2.

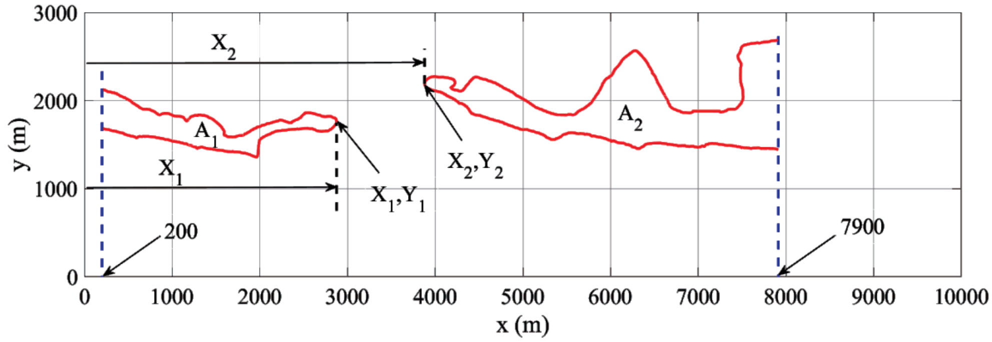

Figure 2: Definition of sandspit parameters used in sandspit analysis.

3. RESULTS AND DISCUSSIONS

3.1 Pre-Groyne Construction Morphological Trends (1984 – 2012)

Visual inspection of remotely acquired images in the pre-groyne construction period gives an indication of the morphological processes at the Volta River mouth (Figs. 3 and 4). As shown in Figs. 3(a) and 3(b), development of the western sandspit (updrift) is sustained by the accumulation of the longshore sediment transport and elongates in the eastward direction. This confirms the direction of longshore sediment transport coming from the west to the east and makes the western sandspit the dominant sandspit at the river mouth.

Upon reaching an equilibrium length, the western sandspit undergoes breaching events which leads to the transfer of sediment from the breached sandspit to the eastern sandspit (downdrift) and other downdrift areas (Figs. 3(c) to (d)). Once this cycle ends, the natural morphological process is repeated (Figs. 3(e) to (g)). This natural process has been halted through the stabilization of the western sandspit. This was done by the construction of the groyne system to ensure efficient tidal exchange, facilitate navigation through the channel and trap the incoming longshore sediment transport to alleviate the intense erosion experienced at coastal communities around the river mouth.

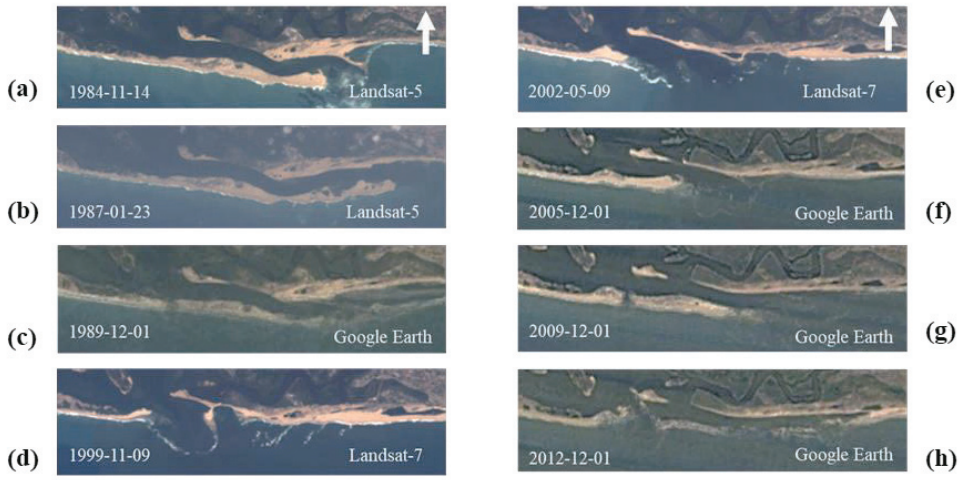

Figure 3: Pre-groyne construction morphological period (1984 – 2012).

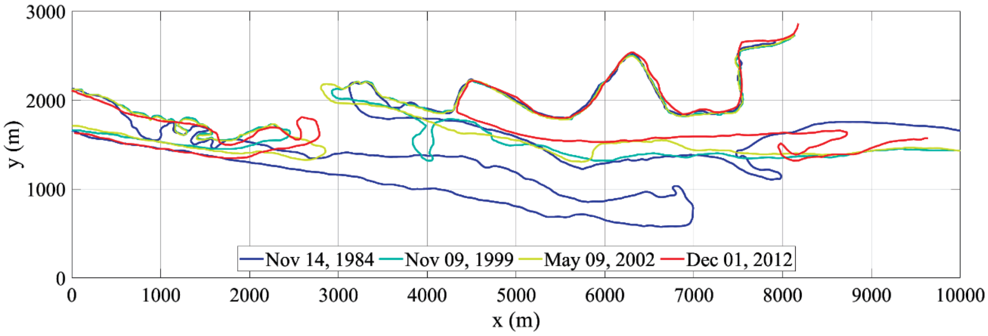

Figure 4: Volta River mouth shoreline variation (1984 – 2012).

3.2 Post-Groyne Construction Morphological Trends (2013– 2020)

Figures 5 and 6 show a change in morphological trends from the pre-groyne construction period with the most influential factor being the presence of the groyne system. Figures 5(a) and 5(c) shows the river mouth sandspit conditions after the first and second phases of groyne construction, respectively. Owing to the stabilization of the western sandspit, the formation and landward migration of shoals in the ebb delta is observed and its subsequent attachment to the eastern sandspit (Fig. 5(b) to (f)). This phenomenon has led to the intrusion of both sandspits into the estuary area of the river mouth.

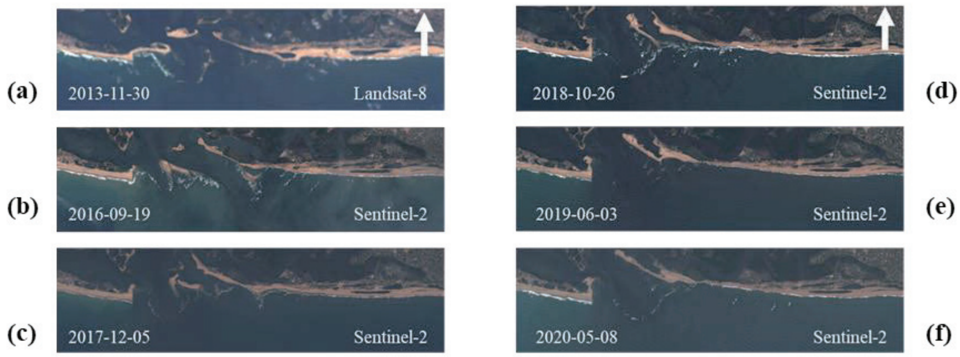

Figure 5: Post-groyne construction morphological period (2013 – 2020).

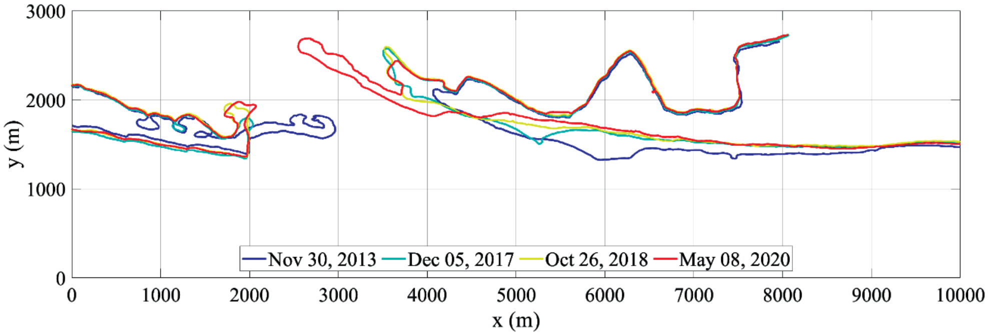

Figure 6: Volta River mouth shoreline variation (2013 – 2020).

3.3 River Mouth Sandspit Features

From the quantitative analysis of sandspit properties, a detailed explanation of the morphological processes at the river mouth can be performed. In Fig. 7(a), the elongation of the western sandspit is observed up until a maximum length of x_1 = 9672m (1988) where the sandspit was breached (BR-01). This cyclic process was once again repeated with the sandspit elongating to a length of x_1 = 5013m (2008) where it was breached (BR-03). With respect to the eastern sandspit, it is observed that no appreciable changes in terms of elongation trends occurred making it the non-dominant sandspit at the river mouth. However, a breach (BR-02) occurred after reaching a length of x_2 = 2810m (2003) (Fig. 7(b)).

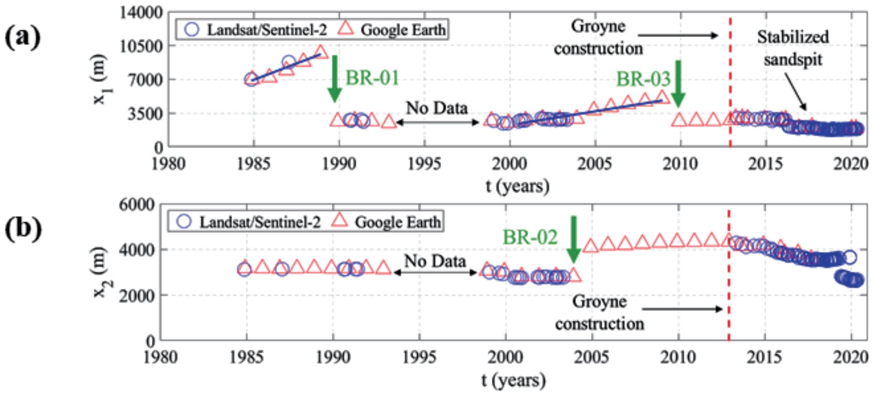

Figure 7: Alongshore x-coordinates of updrift and downdrift sandspits.

Analysis of the alongshore sandspit y-coordinates (y_1 and y_2) revealed sandspit intrusion trends in the post-groyne construction period (2013-2020). As shown in Figs. 8(a) and 8(b), intrusion of both sandspits into the upstream section of the river mouth can be observed. This trend may tend to pose futuristic problems such as narrowing of the river mouth and hence, leading to an inefficient tidal exchange between the estuary and the ocean.

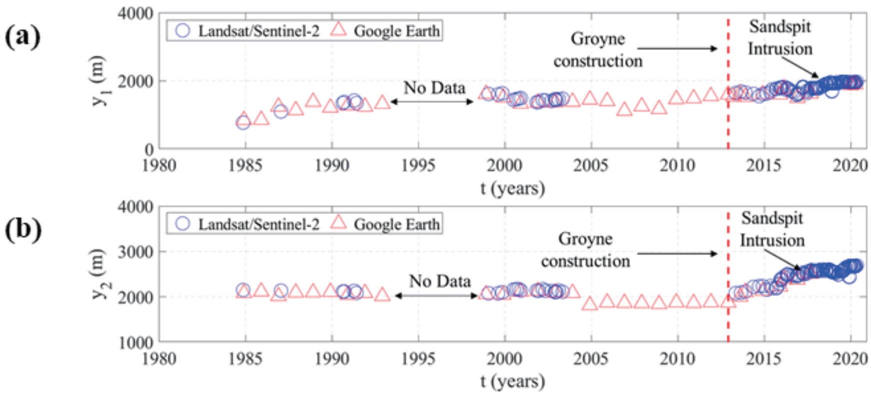

Figure 8: Alongshore y-coordinates of updrift and downdrift sandspits.

The final quantitative parameter investigated was the area of sandspits (A_1 and A_2). In Fig. 9(a), the area changes of the western sandspit follows a similar trend as the elongation trends which further supports the dominance of the western sandspit at the river mouth. Pertaining to the eastern sandspit, its unstable nature is depicted in Fig. 9(b). This is because of the deposition of sediment from the western sandspit when breaching events occur. This condition also leads to the formation of a small lagoon on the eastern sandspit.

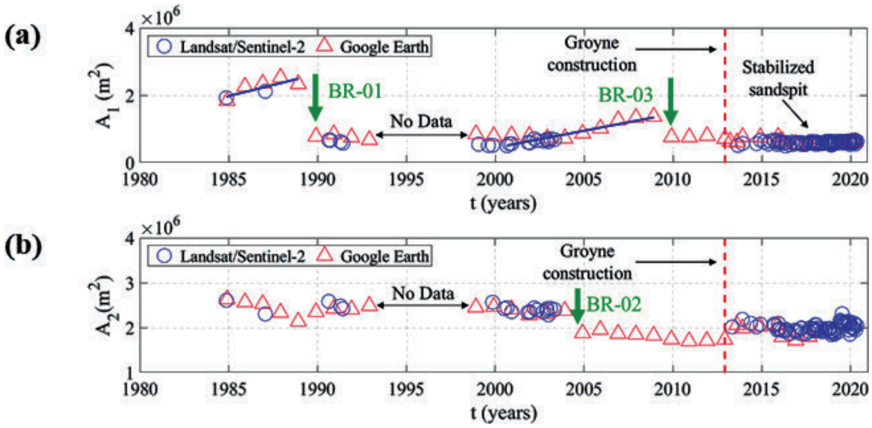

Figure 9: Sandspit area changes of updrift and downdrift sandspits.

4. CONCLUSION

From this study, the morphological evolution of the Volta River mouth has been outlined by utilizing freely available remote sensing images from 1984-2020. Analysis of river mouth morphological variations before and after the construction of the groyne system was performed. Results from image and sandspit analysis showed the natural morphological condition of the river mouth from 1984-2012 where the dominant sandspit was characterized by elongation and breaching events. After groyne construction (2013-2020), a new trend of morphology was observed with both sandspits intruding into the estuary. The sudden change in river mouth behaviour clearly highlights the response of a river mouth sandspit when the longshore sediment transport is trapped through engineering activities.

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