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Assessment of Spatial-temporal Lake Victoria Shoreline Variations using Synthetic Aperture Radar

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Abstract

In the context of their dynamic and linear character, shorelines feature as among the most important features on the earth's surface. They change shape and position over multiple spatial and temporal scales, with their water levels serving as a key indicator to characterize the expansion or shrinkage of the water body in question. In the context of Lake Victoria, the central focus of this article, there has been an uncontrolled increase in its water levels which has ultimately contributed to variations in the lake shoreline. This variation has in turn led to unpredictable flooding along the shores of the lake, claiming human property. Therefore, environmental management authorities, such as NEMA, require accurate and up-to-date information about shoreline changes. The main objective of this study was to assess the spatial-temporal variations of the Lake Victoria shoreline in the Southern Buganda sub-region for the period 2015 - 2021, by employing microwave remote sensing. Sentinel 1 and Sentinel 2 imagery were used. The study also assessed the performance of HH and VH polarizations in shoreline delineation. Different image processing techniques such as thresholding and band math were used in both SNAP and ArcGIS software. Based on the DSAS evaluation statistics, VH polarization performed a better delineation of the shoreline than HH polarization. The study also found that the lake shoreline in the Southern Buganda sub-region was subject to entirely low erosion rates, ranging from 0.5m/yr to 2m/yr, as observed in the sub-counties of Buwunga, Kyanamukaaka, and Kabira. High erosion rates of above 5m/yr were observed in some areas in the Bukakata and Kyebe sub-counties. This study recommends that VH polarization be used. Further studies could integrate predictive analytics to attain future shoreline positions.

Keywords: *Shoreline, Synthetic Aperture Radar data, VH polarization*

1. Introduction

Although lakes comprise a small portion of the earth's surface, they are not only an important component of the global hydrological, biogeochemical and ecological processes, but also critical water sources for supporting and sustaining terrestrial ecosystems, human welfare, agricultural production, and industrial consumption (Verpoorter *et al.*, 2014). Water levels observed over a given epoch serve as a key indicator to characterize either the expansion or the shrinkage of lakes (Williamson *et al.*, 2009). In recent years, many lakes have experienced remarkable changes caused by natural factors (e.g., river discharge, precipitation, and evaporation) and human activities (e.g. the demands made on water bodies by, for example, agriculture) (Pekel *et al*., 2016). Hence, estimating the change in the global lake water level offers a crucial method in scientific research to assess lake shoreline variations, and is, therefore, important in water resource management, in maintaining ecological sustainability, and in engaging in relevant decision-making in this context.

Some studies have assessed the water levels (and water volumes) of large lakes on a global scale (Crétaux *et al.*, 2011; Busker *et al.*, 2018). This research did not, however, include research into numerous small lakes, especially lakes smaller in area than one square kilometre. However, consistent and accurate information on water level changes in global lakes remains scarce across the spatial-temporal scale (Xu *et al.*, 2020). Data derived from satellite altimeters has been widely used to monitor lake level change. This is because such data covers a large spatial area/extent, has a long temporal span, and, compared with traditional water level gauges, can be collected at a relatively low cost. In a study conducted by Xu *et al*., (2020) on the rising water levels of global lakes, it was concluded that based on estimations of 14,981 lake levels, 58.68% of global lake levels increased, while 41.32% decreased between 2003 and 2009. The average increase in the lake water level was found to be 0.013m/year. For the six-year period, most of the lakes experienced an increase in their water levels and, rather than shrinking, an expansion in their area was realized.

In Uganda, the economic and agricultural opportunities in the Lake Victoria basin support and sustain about 30 million people, with the population in the catchment still growing rapidly (Daniel-Erasmus, 2013). Owing to this increasing population, the forest cover surrounding the lake has been cleared for settlement, business, and agricultural purposes. The clearing of the vegetation in the lake's surroundings has contributed to the erosion of the lake's shoreline. Although perennial horticultural areas are well-managed, with perennial vegetational cover and runoff control measures well in place, many other areas with annual crops (such as maize) have not retained an adequate ground cover. Similarly, large areas have been exposed to extreme soil erosion as a result of poor land management practices (Daniel-Erasmus, 2013). Also, there has been an uncontrolled increase in the water levels in Lake Victoria. This increase has been influenced by the large amount of rainfall received over the area, with 80% of the lake`s refill coming from direct rainfall over the lake surface, and only 20% from basin recharge. Recent studies, however, attribute the rising lake water levels and shoreline variation to climate change, rapid population growth and urbanization (Mugume et al., 2024). A combination of these factors has left the surface bare, exposing the soils, and subjecting them to erosion by the lake water. This has further led to the occurrence of unpredictable flooding along the lake shore and the bursting of the shoreline, claiming properties (e.g., homesteads, business structures and crops); and hence, causing distress to the communities living along the shores of Lake Victoria.

In most of these instances, the environmental management authorities have no accurate and up-to-date information on these shoreline variations, and can, as such, not identify flood risk areas, the result being severe effects such as destruction of property. The impact of these hazards can be mitigated by assessing the variability of the shoreline to identify those vulnerable areas, where prior impact planning should be implemented to minimize the adverse effects. The provision of reliable and up-to-date information on the level of spatial change is a requirement for the efficient management of these environmentally sensitive areas. This research, therefore, aimed at accessing information on the spatial-temporal variation in the Lake Victoria shoreline by employing microwave remote sensing to identify vulnerable areas along the shoreline. The study also sought to assess the performance of HH (Horizontal-Horizontal) and VH (Vertical-Horizontal) polarizations in shoreline delineation.

In the broader context, the study contributes to the existing body of knowledge on the spatial temporal variation of the shores of the largest lake in Africa and inevitably in Uganda, the country, where diverse research is being done in a bid to protect the lake's existence.

2. Study Area

The Southern Buganda Lake Victoria shoreline was selected as the study area. This portion of the Lake Victoria shoreline is the most deeply indented and is in the Southeast Region of Uganda. Its geographical coordinates range from longitude 31º43'45" E to longitude 33º17'11" E and from latitude 0º58'02" S to latitude 0º25'16" S. The shoreline is covered by six sub-counties in the Masaka and Kyotera Districts. As shown in Figure 1, these sub-counties include Bukakata, Buwunga, Kyanamukaaka, Kyesiiga, Kabira, and Kyebe.

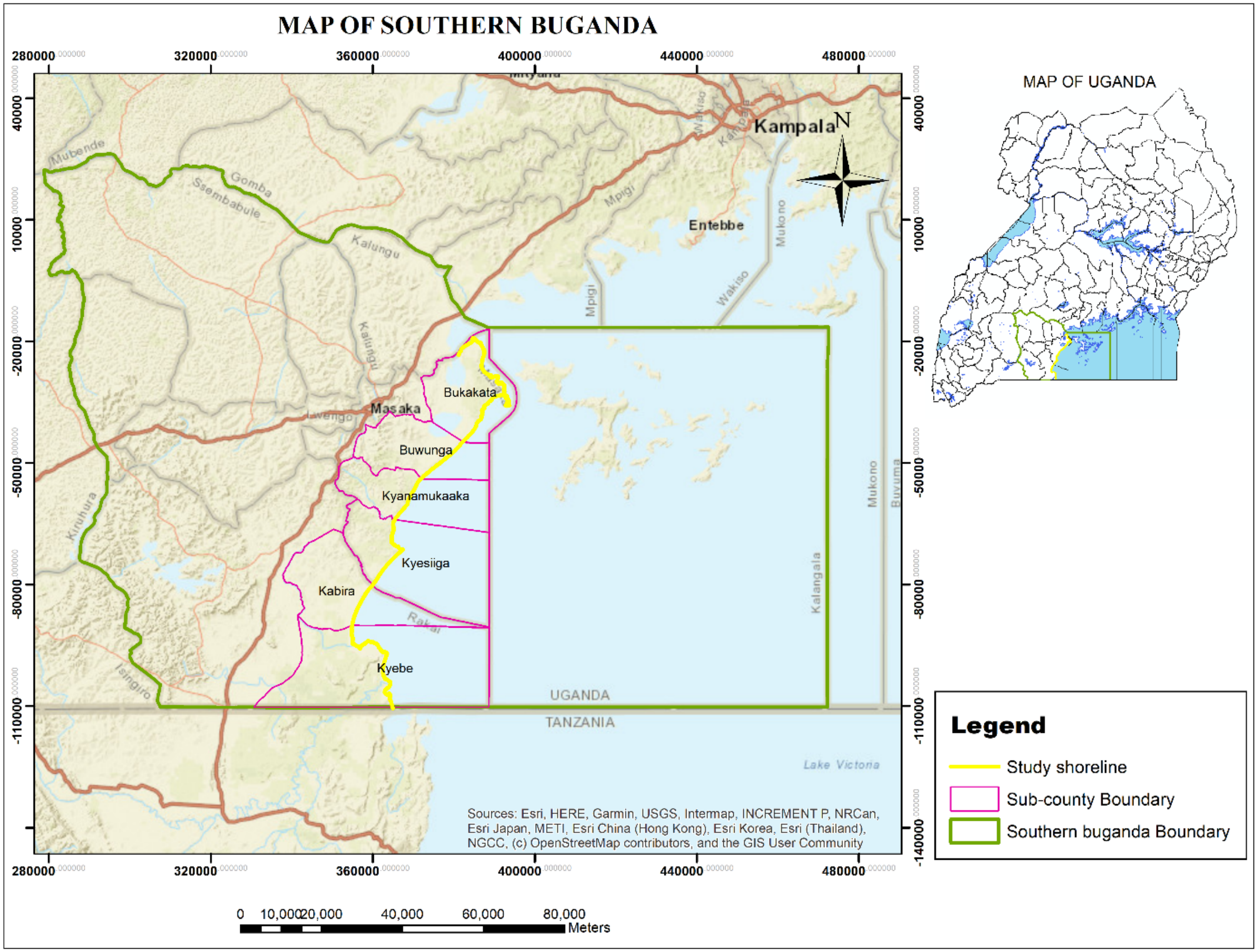


Figure 1. Study Area Location

3. Methodology

Phase 1 of the methodology was executed first, and the results of the evaluation served as a guideline as to which polarization to consider while downloading the other images in the second phase.

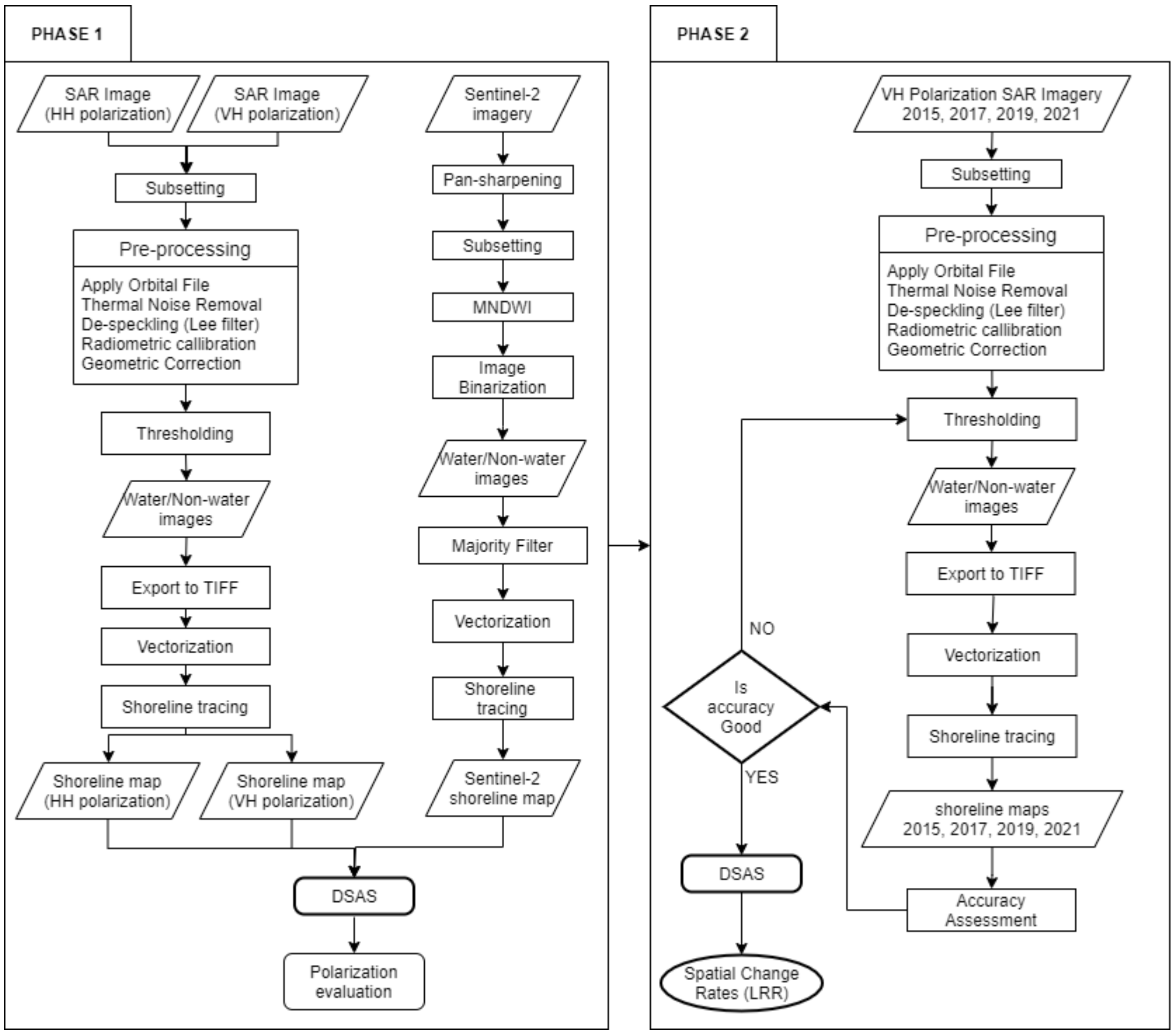


Figure 2. Methodology Flowchart

3.1. Phase1

3.1.1. Data Acquisition

The datasets used in Phase 1 (*Table 1*) involved space-borne images, including two Sentinel-1 SAR images, with single polarizations (HH and VH) for 2021. These were provided by the European Space Agency (ESA) and cover the study area considered for the shoreline assessment. Polarization states, which account for the orientation of the radar wave`s electric field, enable the enhancement of image quality, reduction of noise and speckle, as well as increased sensitivity to specific surface properties. A cloud-free satellite optical image collected by Sentinel-2 was also acquired to form the basis for the evaluation of the Sentinel 1 polarizations.

Table 1. Summary of datasets used in Phase 1

Mission/satellite	Date	Polarization	Source
Sentinel 1A	10th/07/2021	HH	Copernicus Open Access Hub
Sentinel 1A	12th/07/2021	VH	Copernicus Open Access Hub
Sentinel 2	9th/07/2021	……	United States Geological Survey (USGS)

3.1.2. Sentinel 1 Data Pre-processing

This was conducted in the SNAP software (Sentinel Application Platform) since it is easy to integrate with other systems and scale operations at a low cost of computation. The level 1 Ground Range Detected (GRD) data provided by Sentinel 1 covers a large area which can lead to a waste of time when processing; therefore, the subset of the image was first obtained by clipping. This narrowed the spatial extent of the study area of interest. Orbital files were applied to the SAR data. The SNAP application enables the automatic download and update of orbit state vectors for each SAR scene in its product metadata, providing accurate satellite position and velocity information (Filipponi, 2019). Radiometric calibration was carried out, the object being to convert the digital values of the raw images which represent the pixel values of the ground scene into a backscattering coefficient (dB**)** (Bousbih *et al.*, 2017)**.** Speckles[1] were removed from the images by filtering; a Lee filter with a 3 x 3 window size was used. The Range Doppler terrain correction was applied to the SAR data. This was intended to compensate for the distortions so that the geometric representation of the image would be as close as possible to that of the real world.

3.1.3. Sentinel 1 Data Processing

This was conducted in SNAP software. For all the SAR data, pixel values were converted from their raw units to decibels. A thresholding technique that segments images based on the intensity of values was employed in the generation of water/non-water images from pre-processed Sentinel 1 data. The selection of the threshold value was an iterative process which was performed while analyzing histograms of the backscatter. The binarized images were exported to a GeoTIFF format for further

[1] Speckles are not noise; but they appear as physical phenomena on radar images which degrade the SAR imagery. This phenomenon is caused by random fluctuations of radar signals from objects.

processing in ArcGIS software. The ArcGIS platform was selected because of its availability and the advanced spatial analytics that it offers.

The generation of shoreline maps was conducted in ArcGIS software. Binarized images were converted to vectors using the raster-to-polygon tool in the ArcGIS toolbox. By using the trace tool in the editor toolbar, the Lake Victoria shoreline was delineated to generate shoreline maps.

3.1.4. Sentinel 2 Data Pre-processing

This was conducted in ArcGIS software 10.5. Pan-sharpening was applied to downscale the 20-m SWIR band to 10 m by using the 10-m NIR band as the PAN-like band. This was carried out to match the SWIR band to the 10-m green Band 3. To allow for collocation, a subset of the study area was obtained and re-projected to the same coordinate system as Sentinel 1 (WSG84 UTM Zone 36N). Radiometric and atmospheric corrections were also applied to enhance the Sentinel 2 images.

3.1.5. Sentinel 2 Data Processing

The modified Normalized Difference Water Index (MNDWI) technique was applied to extract water areas from the Sentinel-2 image using the green and SWIR bands. MNDWI is defined in equation [1] as:

$$MNDWI = \frac{\rho_{Green} - \rho_{SWIR}}{\rho_{Green} + \rho_{SWIR}} \quad [1]$$

Where: ρ_{SWIR} is the reflectance of the SWIR band;

ρ_{Green} is the reflectance of the green band.

Binarization of Sentinel 2 images was conducted in ArcGIS software to generate water/non-water images using the thresholding technique, with 0.2 as the threshold value for the MNDWI products. The binarized images were filtered using a majority filter to eliminate the isolated pixels. The filtered images were converted to vectors using the raster-to-polygon tool in the ArcGIS toolbox. By using the trace tool in the editor toolbar, the Lake Victoria shoreline was delineated to generate Sentinel 2 shoreline maps.

3.1.6. Polarization Evaluation

Digital Shoreline Analysis System (DSAS) version 5.0 was used to generate the valuation statistics for the two polarizations. Shorelines extracted from both the HH and VH polarized Sentinel 1 images for the year 2021 were input as shorelines. The shoreline extracted from the Sentinel 2 optical imagery for the year 2021 was input as the baseline, from which deviations were measured. Transects were cast at an interval of 150m. Statistics such as minimum deviation, maximum deviation, mean deviation and standard deviation were generated.

3.2. Phase 2

Data used in Phase 2 (*Table 2*) were based on the evaluation results in Phase 1. Three more Sentinel 1 images for the years, 2015, 2017, and 2019 were downloaded in the VH polarization from the European Space Agency (ESA) for the temporal rates of change. Sentinel 2 images for the years, 2015, 2017, and 2019 were downloaded from the USGS to assess the accuracies of the shorelines extracted from the Sentinel 1 data.

Table 2. Summary of datasets used in Phase 2

Mission/satellite	Date	Polarization	Source
Sentinel 1A	12th/07/2021	VH	Copernicus Open Access Hub
Sentinel 2	9th/07/2021	……	United States Geological Survey (USGS)
Sentinel 1A	10th/07/2019	VH	Copernicus Open Access Hub
Sentinel 2	8th/07/2019	……	Copernicus Open Access Hub
Sentinel 1A	8th/07/2017	VH	Copernicus Open Access Hub
Sentinel 2	11th/07/2017	……	United States Geological Survey (USGS)
Sentinel 1A	10th/07/2015	VH	Copernicus Open Access Hub
Sentinel 2	5th/07/2015	……	Copernicus Open Access Hub

3.2.1. Sentinel 1 Data Pre-processing

Sentinel 1 data pre-processing was performed in SNAP software. The pre-processing operations included sub-setting, applying orbit files, radiometric calibration, de-speckling and geometric correction.

3.2.2. Sentinel 1 Data Processing

Pixel values were converted from their raw units to decibels and water/non-water images were generated in SNAP software by using a thresholding technique. The selection of the threshold value was an iterative process, which was performed while analyzing histograms of the backscatter. The binarized images were exported to a GeoTIFF format for the generation of shoreline maps in ArcGIS software. The generation of shoreline maps was carried out by converting the binarized images to vectors using the raster-to-polygon tool in the ArcGIS toolbox. By using the trace tool in the editor's toolbar, the Lake Victoria shoreline was delineated to create the shoreline maps.

3.2.3. Accuracy Assessment

The Sentinel 2 data for the years 2015, 2017, and 2019 were pre-processed and shoreline maps were generated to form the basis for assessing the accuracy of the SAR-derived shorelines for the respective years. This was performed in ArcGIS using the Digital Shoreline Analysis System (DSAS) version 5.0.

3.2.4. Generation of Spatial Change Rates

The shoreline spatial change rates were generated using the DSAS version 5.0 extension and added to ArcGIS. The shorelines extracted from SAR data for the years 2015, 2017, 2019, and 2021 were merged into a single shapefile, which was input to DSAS. A buffer of 500m was created around the shorelines and the baseline was generated by tracing out one side of the buffer extents. The generated baseline was input to DSAS. A buffer distance of 500m was chosen for the purpose of visualizing the spatial rates of change at the sub-county scale. Transects were created at an interval of 150m. The change rates (LRR) were computed by DSAS and displayed on the maps. The rates were generated per sub-county.

4. Results and Discussion

4.1. Evaluation of the performance of the HH and VH polarizations in shoreline extraction

As shown in Table 3 below, the shoreline from the SAR data in VH polarization produced a mean deviation of 1.1m from the reference shoreline, with a standard deviation of 1.8m, while the shoreline from the SAR data in HH polarization produced a mean deviation of 2.1m from the reference shoreline, with a standard deviation of 2.3m.

Table 3. Comparative analysis of shorelines from VH and HH polarization

Statistics	VH Polarization Shoreline	HH Polarization Shoreline
Minimum deviation (m)	0.5	1.2
Maximum deviation (m)	2.9	2.8
Mean deviation (m)	1.1	2.1
Standard deviation (m)	1.8	2.3

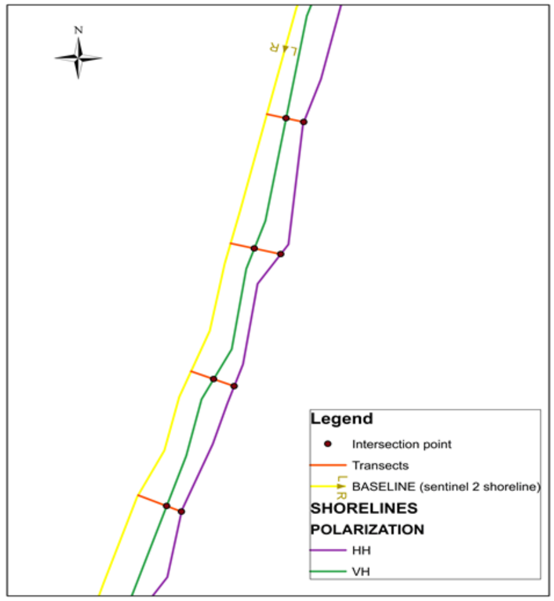


Figure 3: A Segment of DSAS Output

From the results obtained, as opposed to the shoreline from the HH polarized Sentinel 1 image, the shoreline from the VH polarized Sentinel 1 image was closer to the shoreline from the Sentinel 2 optical data, and with low deviation. Therefore, in this case, the SAR data in VH polarization is much more reliable in shoreline delineation than the SAR data in HH polarization.

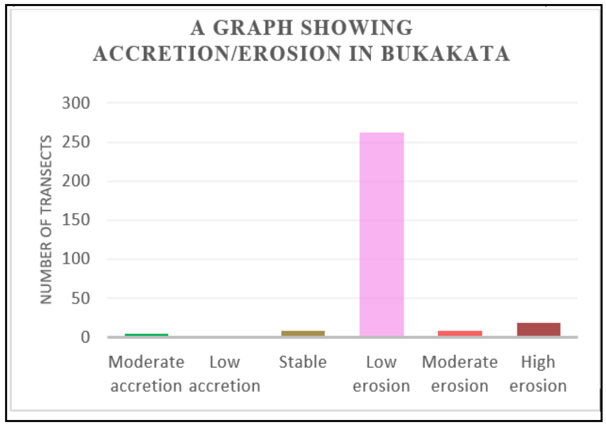
4.2. Spatial annual rates of change of the shoreline

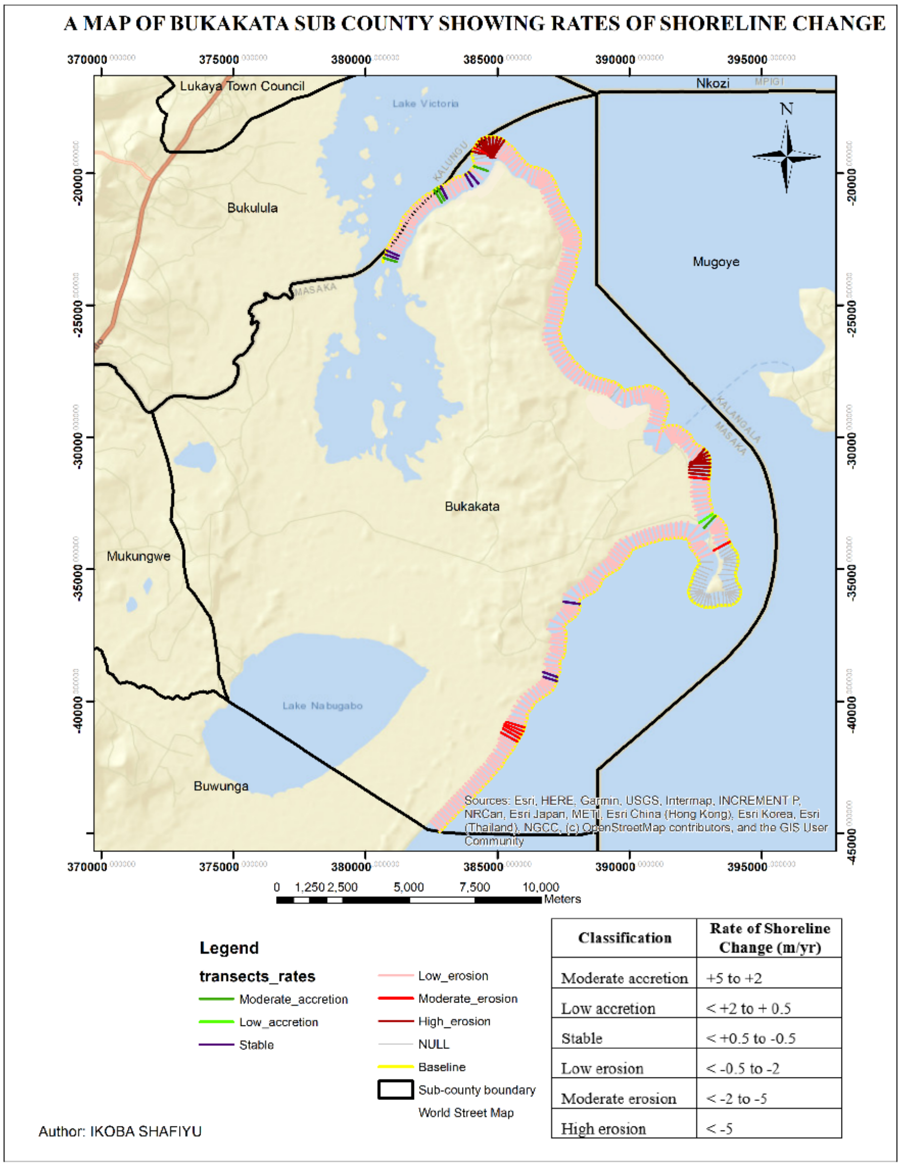
The results that were generated are based on the six counties in the districts that cover the study shoreline which include Bukakata, Buwungu, Kyanamukaaka, Kyesiiga, Kabira, and Kyebe.

4.2.1. Bukakata sub-county

As shown in Figure 4, Bukakata sub-county had 344 transects in total. The largest portion of the Bukakata shoreline underwent low erosion at 262 transects with a percentage of 76.16%. Low erosion was followed by high erosion, with 18 transects, and with a percentage of 5.23%, 2.33% of its shoreline remained stable over the years.

BUKAKATA SUB COUNTY		
Accretion/erosion	**No. of transects**	**Percentage**
Moderate accretion	5	1.45
Low accretion	1	0.29
Stable	8	2.33
Low erosion	262	76.16
Moderate erosion	8	2.33
High erosion	18	5.23
Total number of transects	**344**	



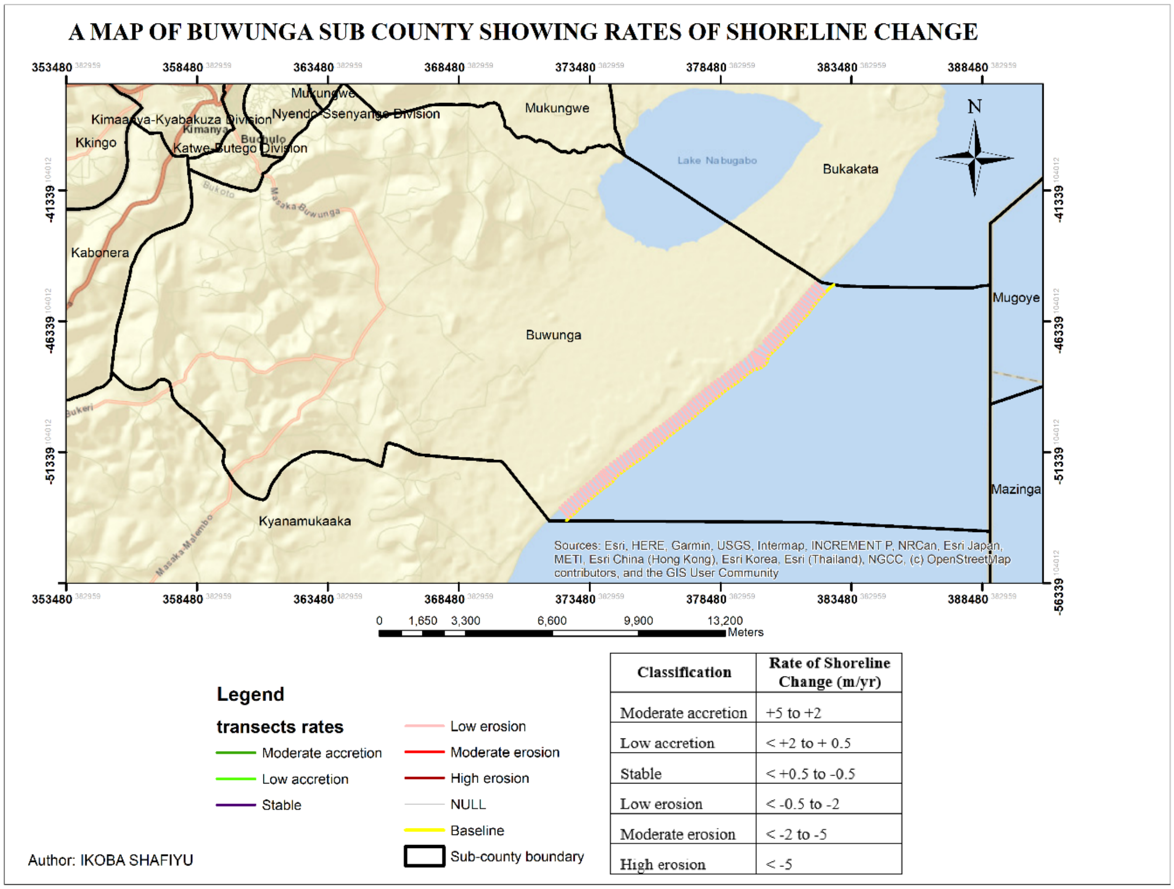


Classification	Rate of Shoreline Change (m/yr)
Moderate accretion	+5 to +2
Low accretion	< +2 to + 0.5
Stable	< +0.5 to -0.5
Low erosion	< -0.5 to -2
Moderate erosion	< -2 to -5
High erosion	< -5

Figure 3. Bukakata Sub-county Rates of Change

4.2.2. Buwungu sub-county

As shown in Figure 5, Buwunga sub-county had a total of 89 transects. At all these transects, low erosion, ranging from 0.5 m/y to 2m/yr, was recorded; and there was no high erosion, moderate erosion, low accretion or moderate accretion.



Classification	Rate of Shoreline Change (m/yr)
Moderate accretion	+5 to +2
Low accretion	< +2 to + 0.5
Stable	< +0.5 to -0.5
Low erosion	< -0.5 to -2
Moderate erosion	< -2 to -5
High erosion	< -5

BUWUNGA SUB COUNTY		
Accretion/erosion	**No. of transects**	**Percentage**
Moderate accretion	0	0
Low accretion	0	0
Stable	0	0
Low erosion	89	100
Moderate erosion	0	0
High erosion	0	0
Total number of transects	**89**	

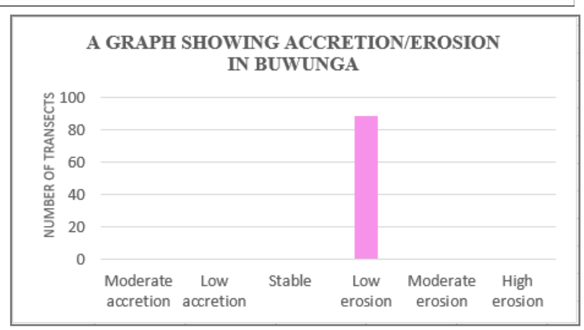
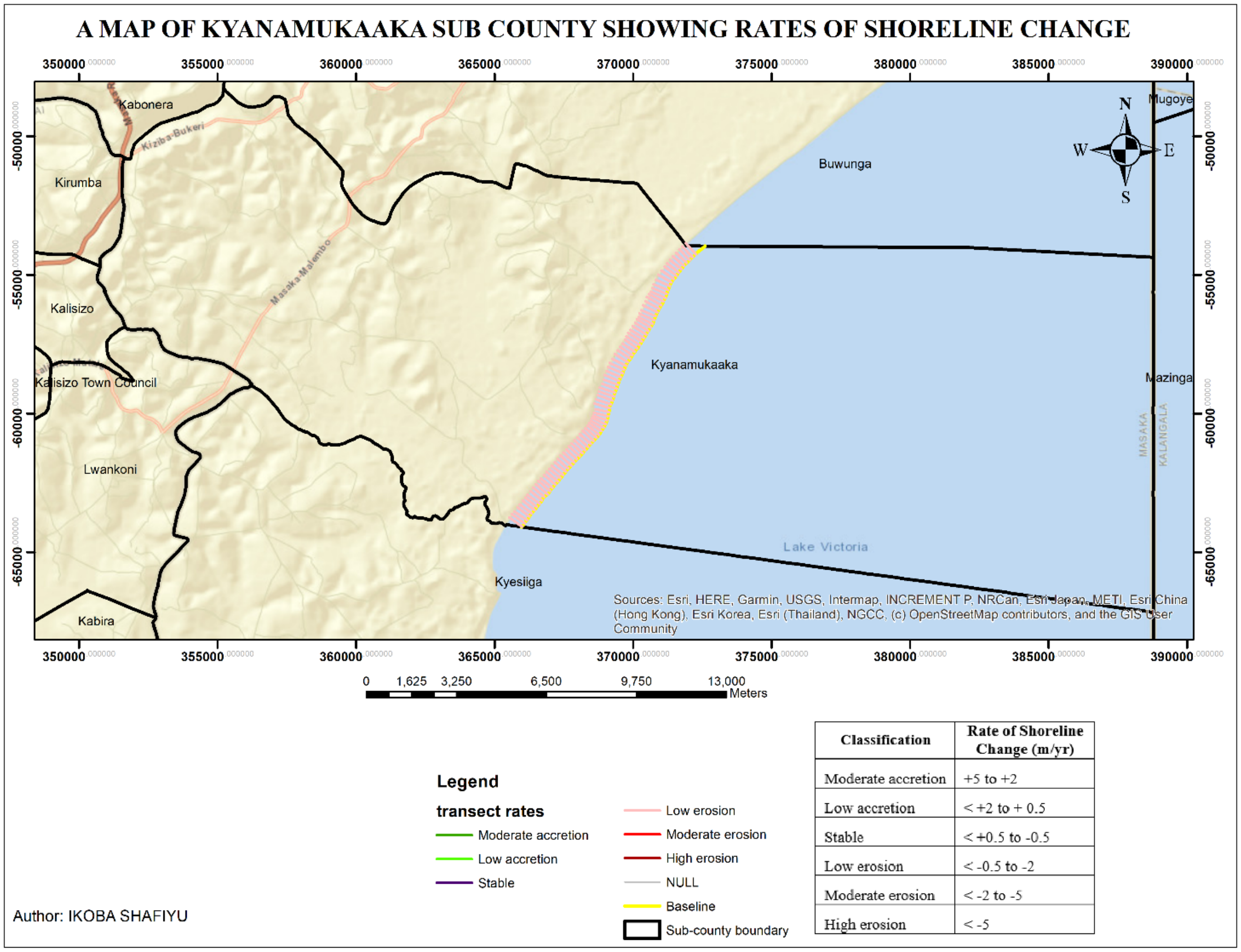


Figure 4. Buwungu Sub-county Rates of Change

4.2.3. Kyanamukaaka sub-county

Just like Buwunga sub-county, the entire Kyanamukaaka sub-county shoreline underwent low erosion of 0.5m/yr to 2m/yr over the period of six years. As shown in Figure 6, Kyanamukaaka had a total of 80 transects, which all indicated a change rate ranging from 0.5m/yr to 2m/yr.



KYANAMUKAAKA SUB COUNTY		
Accretion/erosion	**No. of transects**	**Percentage**
Moderate accretion	0	0
Low accretion	0	0
Stable	0	0
Low erosion	80	100
Moderate erosion	0	0
High erosion	0	0
Total number of transects	**80**	

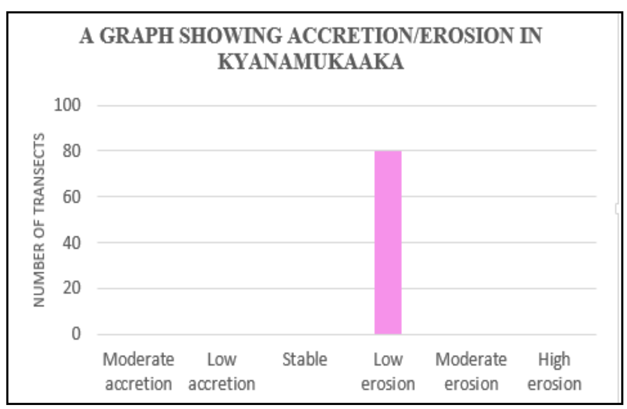
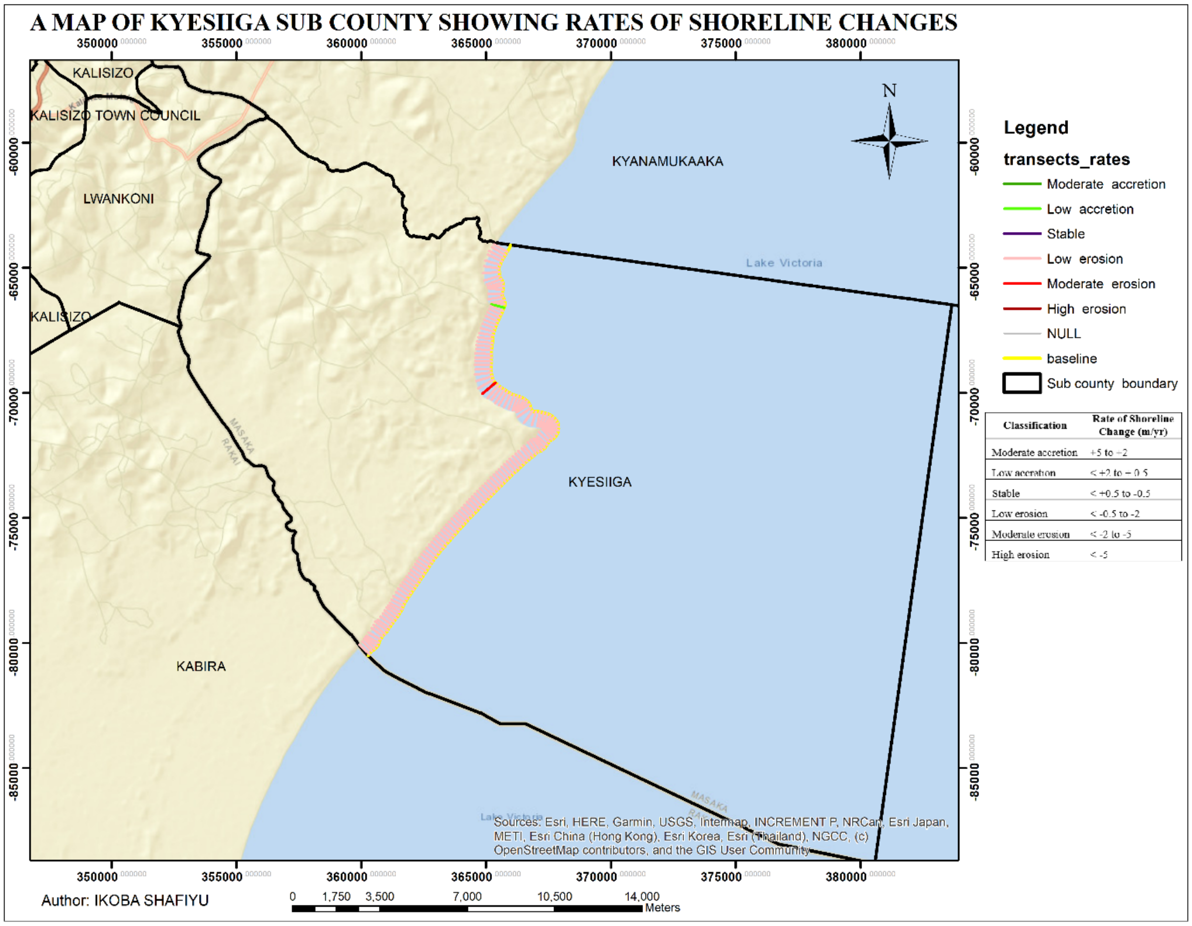


Figure 5. Kyanamukaaka Sub-county Rates of Change

4.2.4. Kyesiiga sub-county

As shown in Figure 7, a total of 140 transects were recorded along the Kyesiiga shoreline, and of the 140 transects, 138 reflected low erosion rates − a percentage of 98.57%. Moderate erosion and low accretion were also recorded in two transects, which both indicated 0.71%.



KYESIIGA SUB COUNTY		
Accretion/erosion	**No. of transects**	**Percentage**
Moderate accretion	0	0.00
Low accretion	1	0.71
Stable	0	0.00
Low erosion	138	98.57
Moderate erosion	1	0.71
High erosion	0	0.00
Total number of transects	**140**	

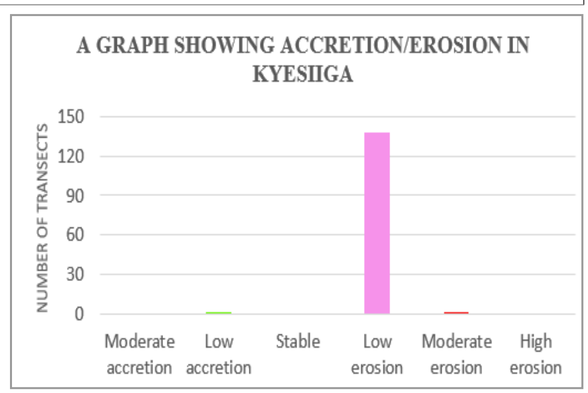
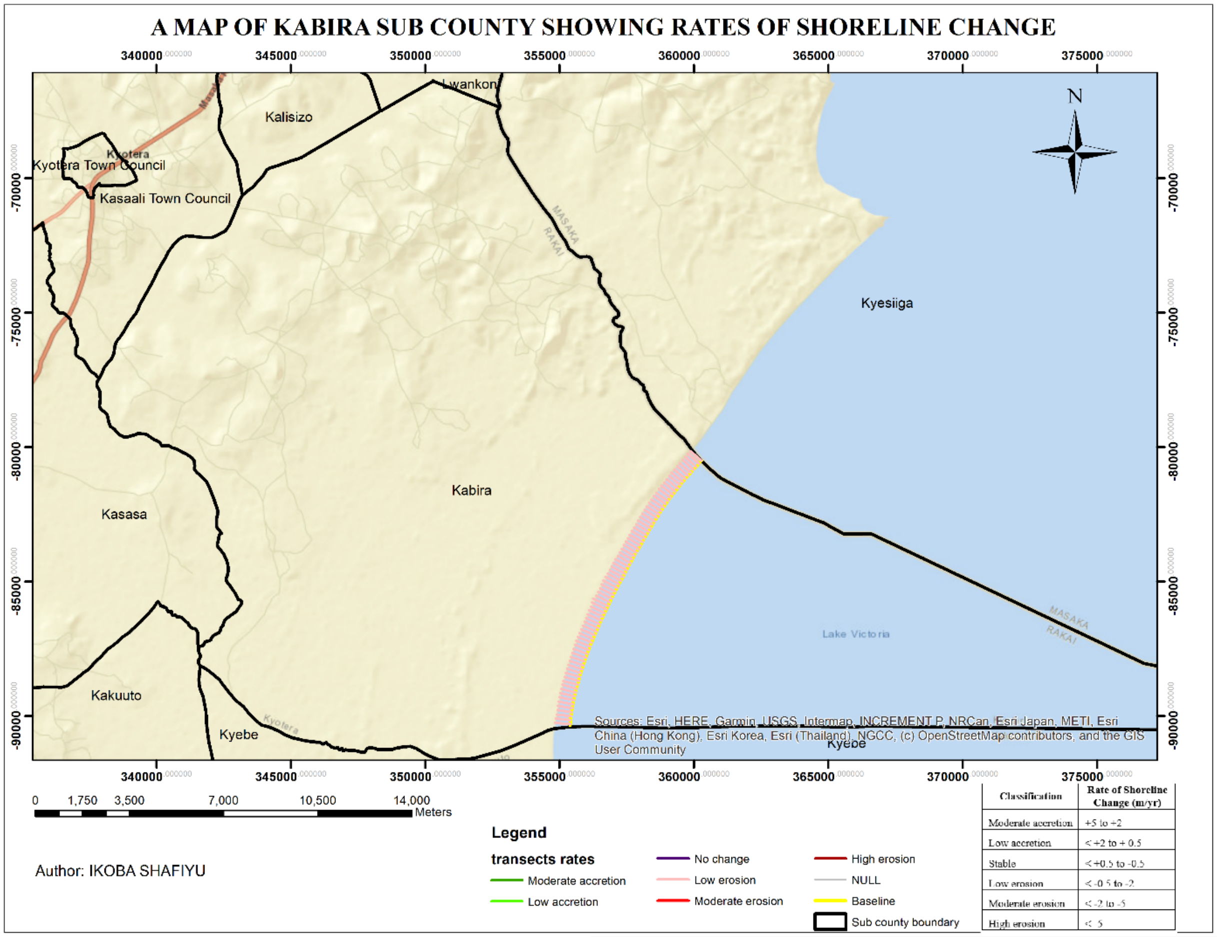


Figure 6. Kyesiiga Sub-county Rates of Change

4.2.5. Kabira sub-county

A total of 75 transects were recorded along the shoreline of Kabira Sub-county. As shown by the statistics in Figure 8, low erosion rates were detected for all these transects over the six-year period.



KABIRA SUB COUNTY		
Accretion/erosion	**No. of transects**	**Percentage**
Moderate accretion	0	0
Low accretion	0	0
Stable	0	0
Low erosion	75	100
Moderate erosion	0	0
High erosion	0	0
Total number of transects	**75**	

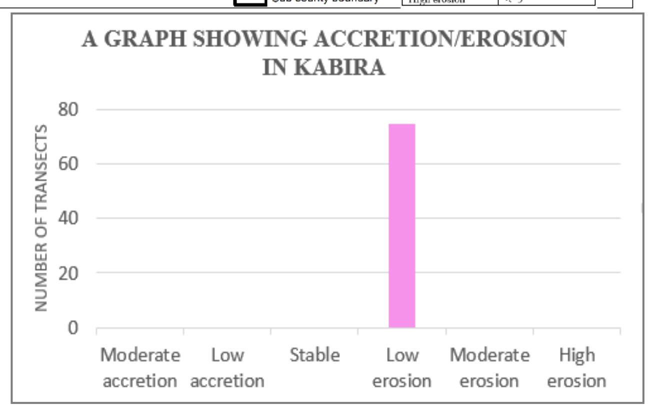
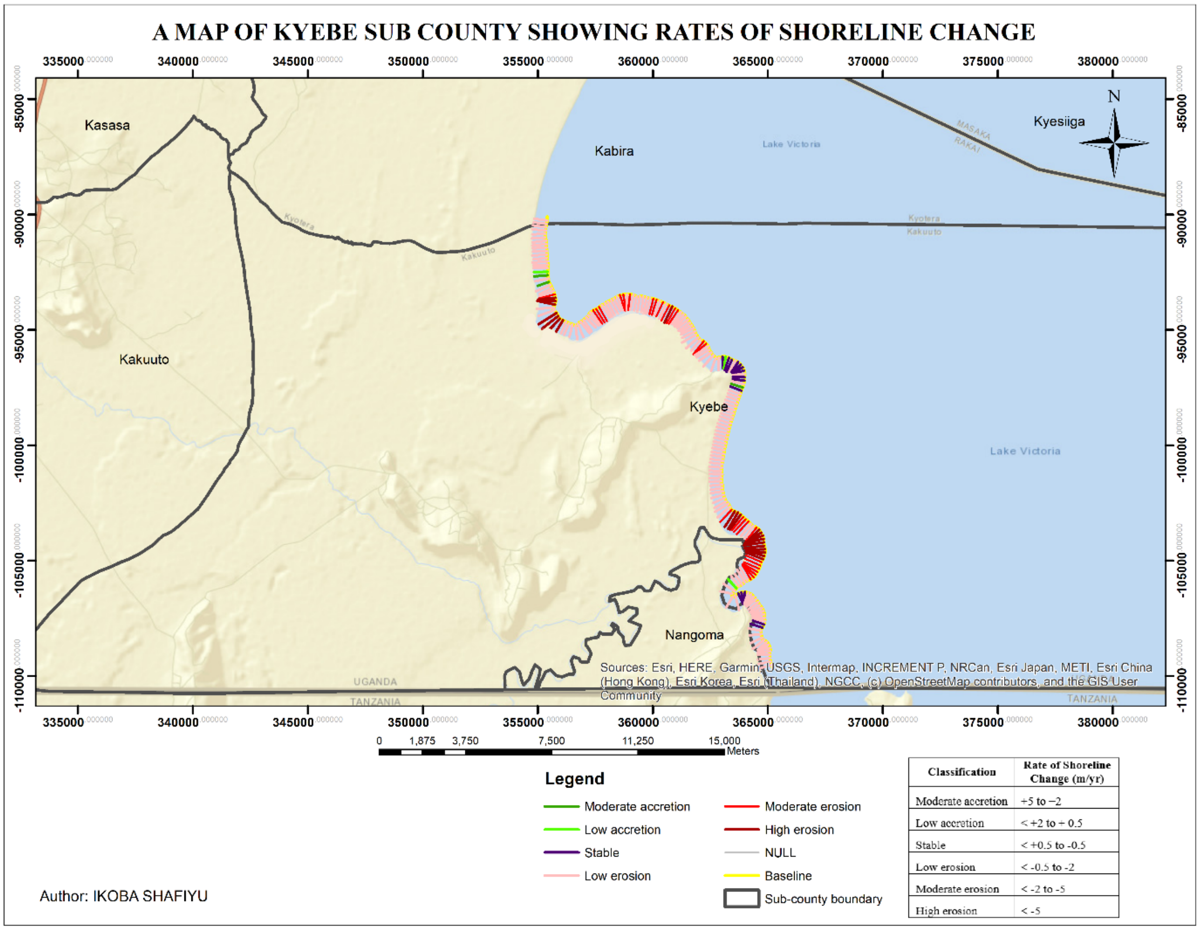


Figure 7. Kabira Sub-county Rates of Change

4.2.6. *Kyebe sub-county*

Kyebe sub-county shoreline had a total of 203 transects, making it the second longest after the Bukakata sub County shoreline. Of the 203 transects, 134 recorded low erosion and a percentage of 66.01%. This was followed by moderate erosion detected at 27 transects, with a percentage of 13.30%. Kyebe had the highest coverage of high erosion rates, recorded at 20 transects, indicating a percentage of 9.85%



KYEBE SUB COUNTY		
Accretion/erosion	**No. of transects**	**Percentage**
Moderate accretion	2	0.99
Low accretion	3	1.48
Stable	15	7.39
Low erosion	134	66.01
Moderate erosion	27	13.30
High erosion	20	9.85
Total number of transects	**203**	

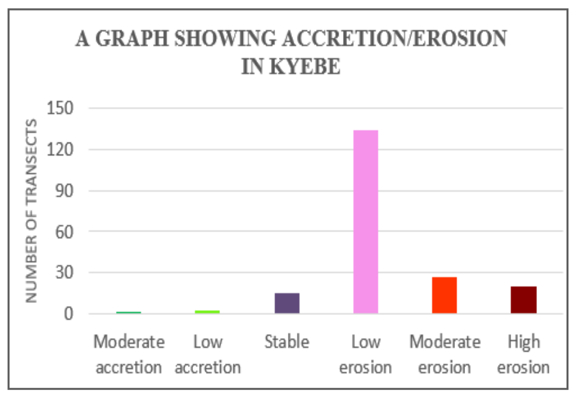


Figure 8. Kyebe Ssub-county Rates of Change

4.2.7. Discussion

This study used microwave remote sensing data with SNAP and GIS to quantify shoreline change in the Southern Buganda sub-region. It has been observed that the Southern Buganda shoreline underwent both erosional and accretional processes. The study has revealed that, generally, over the six years, 2015-2021, about 127.65km of the Southern Buganda shoreline underwent erosion, with the portion of the shoreline in the sub-counties of Buwunga, Kabira, and Kyanamukaaka subjected entirely to low erosion. As observed in the sub-counties of Bukakata and Kyebe, about 3.30km of the shoreline was stable over the research period. Only 1.65km of the shoreline underwent accretion over the six years. The dominant shoreline erosion could be attributed to human activities, such as sand mining along the lakeshores, while the increasing water levels of Lake Victoria that have been recently reported have left many residents in settlement distress. The rise in water level, attributed to increased rainfall, has wrecked several homes, farms, and businesses. Section 107 of the Uganda National Environment Act Cap 153 stipulates that in terms of the regulations, the lakes specified in the Seventh Schedule (Lake Victoria inclusive) shall have a protected zone of two hundred meters (200m) measured from the low watermark. However, people still live within these protection zones and some of these are registered proprietors who hold valid certificates of title. Some people have obtained permission from the authorities to utilize the land situated in such areas, including that in the protection zones of the lake. Therefore, the Government should put more emphasis on the implementation of the existing regulations and provide more sustainable remedies for the permit holders and other people with legitimate legal interests on the shores of Lake Victoria.

5. Conclusions and Recommendations

In conclusion, as compared to the SAR data obtained in the HH polarization, the SAR data obtained in the VH polarization provide for the best delineation of shorelines. Thus, for shoreline studies intended to make use of Synthetic Aperture Radar data, VH polarization should always be adopted.

Over the past six years, the Lake Victoria shoreline in the Southern Buganda sub-region has generally undergone change rates ranging from 0.5m/yr to 2m/yr, thus indicating entirely low erosion of the shoreline, as observed in the sub-counties of Buwunga, Kyanamukaaka, and Kabira. The Government of Uganda should put more emphasis on enforcing the existing National Environment Regulations on the protection zones for lake shores as stipulated by the National Environmental Act of 2000, especially in the sub-counties of Bukakata and Kyebe, where high erosion rates of above 5m/yr were observed. Local leaders in these sub-counties could be specifically involved in policy and law formulations; furthermore, by virtue of their office, they should be assigned − as a matter of routine − to monitor the shoreline periodically. The National Environmental Management Authority could appoint officers and assign them to shoreline monitoring and management.

6. References

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