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Estimating estuarine suspended sediment concentration through spectral indices and band ratios derived from Sentinel-2 data: a case of Umzimvubu Estuary, South Africa

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by
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DECLARATION

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work that I have not previously in its entirety or in part submitted for obtaining any qualification.

Signature:

Date: 24 November 2022

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Abstract

The current study was aimed at evaluating the reliability and efficacy of selected remote sensing band ratios and indices in accurately estimating the spatial patterns of suspended sediment concentration level in Umzimvubu Estuary, Eastern Cape, South Africa. Sentinel-2 imagery was acquired on the 29th of March 2022. Band reflectance values were extracted from Sentinel -2 imagery, and laboratory measurements of suspended sediment concentration were obtained from samples collected from fifty (50) sampling points in the estuary on the 29th of March 2022. Sentinel-2 imagery was then validated with the field data in estimating and mapping the suspended sediment concentration. Several remote sensing band ratios Red/(Green + Near-Infrared), Near-Infrared/Green, Red + Near-Infrared/Green, Blue*(Green + Red)/Blue and Green + Near-Infrared)/Blue and indices, that is the Normalised Difference Turbidity Index (NDTI), Normalized Difference Suspended Sediment Index (NDSSI) and Normalized Suspended Material Index (NSMI)) were then used to predict the suspended sediment concentration from Sentinel-2 imagery. The accuracy of band ratios and indices was evaluated by correlating the prediction against the observed suspended sediment concentration from Sentinel-2 imagery. A total of 50 points were randomly surveyed in the Umzimvubu estuary for analyzing suspended sediment concentration. Results indicate that the Blue*(Green + Red)/Blue, the Green + Near-Infrared)/Blue and NMSI performed well based on their R-squared. The Blue*(Green + Red)/Blue and Green + Near-Infrared)/Blue band ratios had 0.86 and 0, 94, respectively. While NSMI yielded an R-squared of 0,76 and RMSE of 19,2 mg/L.

The results in the current study indicate that Sentinel-2 imagery can reliably estimate the concentration of suspended sediment level in the Umzimvubu Estuary using band ratios and indices.

Keywords: *Suspended sediments; estuary; remote sensing; band ratios; spectral indices*

Contents

LIST OF ACRONYMS AND ABBREVIATIONS

DEA	Department of Environmental Affairs
DEM	Digital Elevation Model
EPA	Environmental Protection Agency
ESA	European Space Agency
DWAF	Department of Water Affairs and Forestry
GIS	Geographic Information Systems
GPS	Global Positioning System
L1C	Level-1C
MODIS	Moderate Resolution Imaging Spectroradiometer
MSI	Multispectral Imager
NDSSI	Normalized Difference Suspended Sediment Index
NDTI	Normalised Difference Turbidity Index
NSMI	Normalized Suspended Material Index
OLI	Operational land Imager
R	Correlation coefficient
RMSE	Root Mean Square Error
SPOT	Systèm Pour l'Observation de la Terra
SRTM	Shuttle Radar Topography Mission
R^2	R Squared
TOA	Top of Atmosphere
USGS	United States Geological Survey
WGS84	World Geodetic System of the year 1984

CHAPTER 1

INTRODUCTION

1.1. Introduction

The color of water is a significant variable that reveals information regarding the condition of the water environment. It is associated with physical and chemical properties, and changing status of water, particularly the suspended sediment, which has long been a major environmental issue of concern in many freshwater systems. Suspended sediment is regarded as one of the most commonly known water quality indicators (Qu, 2014; Ritchie, 2003); it serves as a transport agent to several water contaminants, semi-volatile organic compounds, and various pesticides (EPA, 2000). In coastal environments, suspended sediment is one of the most common water quality variables (Cai *et al.* 2015). This is because coastal ocean waters are frequently characterized by a high concentration of suspended sediment (Nguyen *et al.* 2020). In these environments, the geomorphic dynamics of estuarine waters is critically reliant on a balance between sediment inflow from rivers and sediment outflow due to wind-wave erosion and tidal waves (Volpe *et al.* 2011). In fact, the primary characteristic of estuarine waters rests on the dynamics of suspended sediments. Therefore, suspended sediment concentration in estuarine waters is not only the problem affecting economic activities and the sustainable development of human society such as coastal zone planning and ports and waterways construction (Feng *et al.* 2014; Mao *et al.* 2012).

In general, suspended sediments comprise organic and inorganic particles suspended within the water column (Droppo, 2001; Fryirs & Brierley, 2013). They are a natural and critical element of hydrological, environmental, and geomorphic functioning of the estuarine water system. Suspended sediments are defined as “very fine soil particles that remain suspended in water without being in contact with the base of a water body for a considerable period of time”. Suspended sediments are characteristically non-dissolving matters; they exhibit physical and chemical characteristics of water. These sediments come in a form of silt, clay, sand, and organic matter, characterized by a diameter of less than 62 µm (Bilotta & Brazier, 2008). Suspended sediment in an estuarine system may come from three main sources namely the sea, inflowing rivers and material generated within the estuary (Allanson and Baird, 2008). Therefore, spatial variations of suspended sediment in any water systems may exhibit a wide range of hydrological and ecological processes, such as up-stream erosion and topsoil loss, sediment transportation, nutrient and toxic loading, and contaminant accumulation (Pham *et al.* 2018).

High concentration of suspended sediment has the capacity to reduce the functionality of many water bodies such as estuaries (Karabulut & Ceylan 2005). Suspended sediment concentration also has the ability to alter the biological life in an estuary. High levels of suspended sediment concentration can also reduce the quantity of solar radiation penetrating through the estuarine water columns. As a result, photosynthetic potential by aquatic plants and phytoplankton becomes altered and, subsequently, living aquatic animals fed on these plants suffer. Increased suspended sediment concentrations also hinder normal functioning of aquatic ecosystems; suspended sediment can alter estuarine water chemistry such as temperature and dissolved oxygen (Branigan 2013; Qu 2014). Increased level of suspended sediment concentration in an estuary leads to both physical and chemical alterations. Physical alterations include the decrease in water clarity, obstruction of radiation to reach submerged aquatic plants, smothering of aquatic organisms, clogging navigational channels and changes of temperature (Cohen *et al.* 1993). Reduction of light and transparency also have a serious impact on the visual ability of predators, particularly birds and some fish (for instance snapper), during their attempt to catch their prey. High level of suspended sediment in estuarine waters can also affect the quality of irrigation, recreational and industrial water, due to its nature of being transport and storage agent of various types of pollutants such as nitrogen and phosphorus (Julien, 2002). Therefore, analyzing suspended sediment concentration is very critical for understanding water quality and environmental protection. This is also critical for the implementation of the effective environmental management of estuaries (Duan *et al.* 2013).

Analysing spatial variability in suspended sediment concentration in estuarine waters requires enhanced understanding of appropriate methods that are capable of reliably estimating that variability. Therefore, correct estimates of suspended sediment concentration can be achieved if appropriate techniques are employed (Bisantino *et al.* 2011). Since the early 1980s, studies conducted to address suspended sediment concentration level significantly relied upon traditional methods such as laboratory measurements (Kineke & Sternberg, 1992; Richie & Schiebe, 1980). Traditional method that was used to collect and analyze suspended sediment concentration data includes water sampling, filtering, and measuring dry weight. However, these were designed to perform under carefully controlled conditions using a handheld spectroradiometer (Clifford *et al.* 1995; Gippel, 1995). Although these methods are considered to provide accurate estimates of suspended sediment concentration, they also had restrictions with respect to in-situ collection and measurement of samples for subsequent laboratory analyses; they were labor intensive, time-consuming, weather sensitive, space discrete and coverage limited (Panda *et al.* 2004; Wu, 2015). As such, they provide only point-based data; measurements are taken at numerous survey points and used to estimate patterns across the study area (Pavelsky and Smith, 2009). Utilization of data acquired through these traditional methods for local analysis and large-scale suspended sediments quantification could lead to high uncertainties and potential errors (Peterson *et al*. 2018), especially over a large area where high density of surveys may be required to improve estimates. Moreover, it is difficult to quantify the sediment fluxes of large water bodies though field-based measurements, particularly less accessible areas. Exacerbating this is the fact that suspended sediment is highly spatially heterogeneous, and its spatial estimates are not easy to attain using the routine in-situ monitoring method alone (Hossain *et al.* 2010).

The advent of remote sensing technology has enabled rapid, timely and more easy monitoring of suspended sediment. This technology provides a reliable practical alternative way for attaining information pertaining to suspended sediment. The evidence of the association between the suspended sediments and reflectance within a specific channel of electromagnetic spectrum and/or the combination of spectral bands have made remote sensing technology more viable for suspended sediment monitoring (Ritchie *et al.* 2003). Satellite remotely sensed data has been extensively utilized in detection and characterization of suspended sediment at local, regional and global scale (Bisantino *et al.* 2011; Pereira *et al.* 2018; Sutari *et al.* 2020). In recent years, the rate in which applications of multi-sensor satellite data in estimating suspended sediment in coastal environments and ocean waters is fast growing in environmental and marine studies (Nezhad *et al.* 2019). Remote sensing techniques offer numerous advantages over traditional methods because of their spatial and temporal coverages, availability at no cost, ability to obtain immediate coordinate data for a specific area (Keiner & Yan, 1998; Peterson *et al.* 2018), and ability to collect data from inaccessible areas. Another advantage of employing remote sensing techniques in monitoring suspended sediment concentration is that the information relating to suspended sediment concentration in the entire estuarine waters can be obtained over a short period of time (Oyama *et al.* 2009). It is also easy to update remote sensing data, which allows continuous monitoring of watercourses. Resource managers are therefore interested in water quality using such data for informed decisions because of this method.

There are relationships that exist among the radiation scattered out of water, the inherent water column absorption and scattering properties, and the type of water quality parameter and its concentration that absorb and/or scatter radiation (Vertucci, 1989). The suspended sediment concentration is no exception in this regard. Several studies that monitored suspended sediment in the estuary through remote sensing technology have based their models on empirical relationships between suspended sediment and spectral reflectance properties of water across different channels of electromagnetic spectrum (D'Sa *et al.* 2007; Montanher *et al.* 2014; Onderka & Rodný, 2010; Wang & Lu, 2010). These models have been invented in accordance with the field measured concentration of suspended sediment and specific wavelengths of satellite sensors such as Landsat, MODerate Resolution Imaging Spectroradiometer (MODIS), Sentinel, Systèm Pour l'Observation de la Terra (SPOT) (Katlane *et al.* 2020). Several spectral indices and spectral band ratios, coupled with field data, have demonstrated their capability in retrieving concentration of suspended sediment. In view of the background provided, the current study was aimed at assessing spatial patterns in suspended sediment concentration level in the Umzimvubu Estuary by employing various spectral indices and spectral band ratios.

1.2. Problem statement

Just like in any other estuary, suspended sediment is a common water quality issue experienced in the Umzimvubu Estuary. Proper assessment of this issue is critical if ecological and environmental functioning of this estuary is to be well understood. If assessment of this issue is not properly carried out, the effective ecological and environmental management of this area may continue to remain a challenge. The ability of empirical models generated from the relationship between spectral reflectance patterns of suspended sediment concentration and in-situ measured suspended sediment presents an economically viable way to monitor this issue in the study area. Several remote sensing based empirical models for estimating suspended sediment concentration in the estuary are available. For these empirical models, spectral indices and spectral band ratios were used as the base from which spectral reflectance characteristics of suspended sediment concentration were obtained. However, these empirical models are only reliable when applied in the areas where they were generated; they cannot be developed on one area and applied on another area. Moreover no study has developed empirical models for use in evaluating the physical quality of water in Umzimvubu estuary.

It is against this background that the current study also develops empirical models for monitoring suspended sediment concentration in the Umzimvubu Estuary.

1.3. General hypothesis of the study

The general hypothesis of the current study is that “empirical models generated from the relationship of in-situ suspended sediment concentration with spectral indices and spectral band ratios can provide invaluable information about concentration of suspended sediments”.

1.4. Main aAim of the study

The aim of the study is to develop empirical models to estimate the suspended sediment concentration in the Umzimvubu Estuary based on the relationship of field based suspended sediment concentration with spectral indices and spectral band ratios derived from Sentinel-2 imagery.

1.5. The objectives of the study

The following objectives are formulated to attain the main purpose of the study:

- To quantify the inherent optical properties of suspended sediment in estuarine waters;
- To develop empirical models to determine suspended sediment from Sentinel-2 data using the optical properties obtained from the first objective; and
- To validate empirical models’ performance using estuarine suspended sediment measurements.

1.6. The structure of the dissertation

Chapter 1, the introductory chapter, provides a background to suspended sediments, which include sources, causes and effects of suspended sediment concentrations on the estuarine. A brief summary of the methods that are used to estimate the suspended sediment concentration is stated. The main research problem, aim, the objectives, and the research questions are also stated. This chapter also provides the chapter overview of the dissertation. Chapter 2 (Literature review) offers reviews of the literature pertaining to estuarine suspended sediments, their sources and their environmental impacts on estuarine ecosystems. It also reviews the role of remote sensing technology in monitoring and estimating the suspended sediment concentration in an estuarine ecosystem. Ultimately, the literature review pertaining to the applications of statistical methods in determining the relationships between/among variables is also provided in this chapter.

Chapter 3 (Research methods) outlines various methods and techniques employed in the research to ensure that the aim and objectives are accomplished. The methods employed in this study include GIS, remote sensing, and field-based methods. In Chapter 4 (Results), a presentation of results that were obtained through the methods and techniques outlined in Chapter 3 are presented. The indication of the presence of suspended sediments in an estuary is presented in the form of maps. The relationship between the field-based suspended sediment concentration and the remote sensing based suspended sediment concentration is presented by the linear regression analysis in the form of graphs. Chapter 5 (Discussion and conclusion) provides the discussion of the research findings obtained in chapter 4 using the methods explained in Chapter 3. The discussion is based on the remote sensing spectral indices and band ratios utilized to obtain the concentration level of suspended sediment in the study area. Recommendations concerning the use of remote sensing and field-based methods to estimate the concentration of suspended sediments are made. Directions for future research are proposed and conclusions are drawn based on the results of the study.

The subsequent chapter (Chapter 2) provides the characteristics of the study area.

CHAPTER 2

CHARACTERIZATION OF THE STUDY AREA

2.1. Background and location of the study area

Umzimvubu Estuary is known to be a river mouth type of estuary that is approximately 14.5 kilometers long, with its mouth located in the north of Port St. Johns. The estuary lies between 31˚34’46.74” South 29˚28’57.32” East and 32˚37’19.39” South 29˚33’8.22” East. The estuarine is also situated in the Umzimvubu River catchment, which is classified as vulnerable due to rapid rates of soil degradation in the watershed (Snow, 2016). The Umzimvubu Estuary connects the Umzimvubu River and the Indian Ocean. Soil erosion and degradation of vegetation in the Umzimvubu River catchment have increased over the last century. As such, it can be envisaged that there is a strong association between increase in soil erosion and increase in estuarine sedimentation. Figure 2.1 shows the geographical location of the study area in relation to the Eastern Cape Province and South Africa.

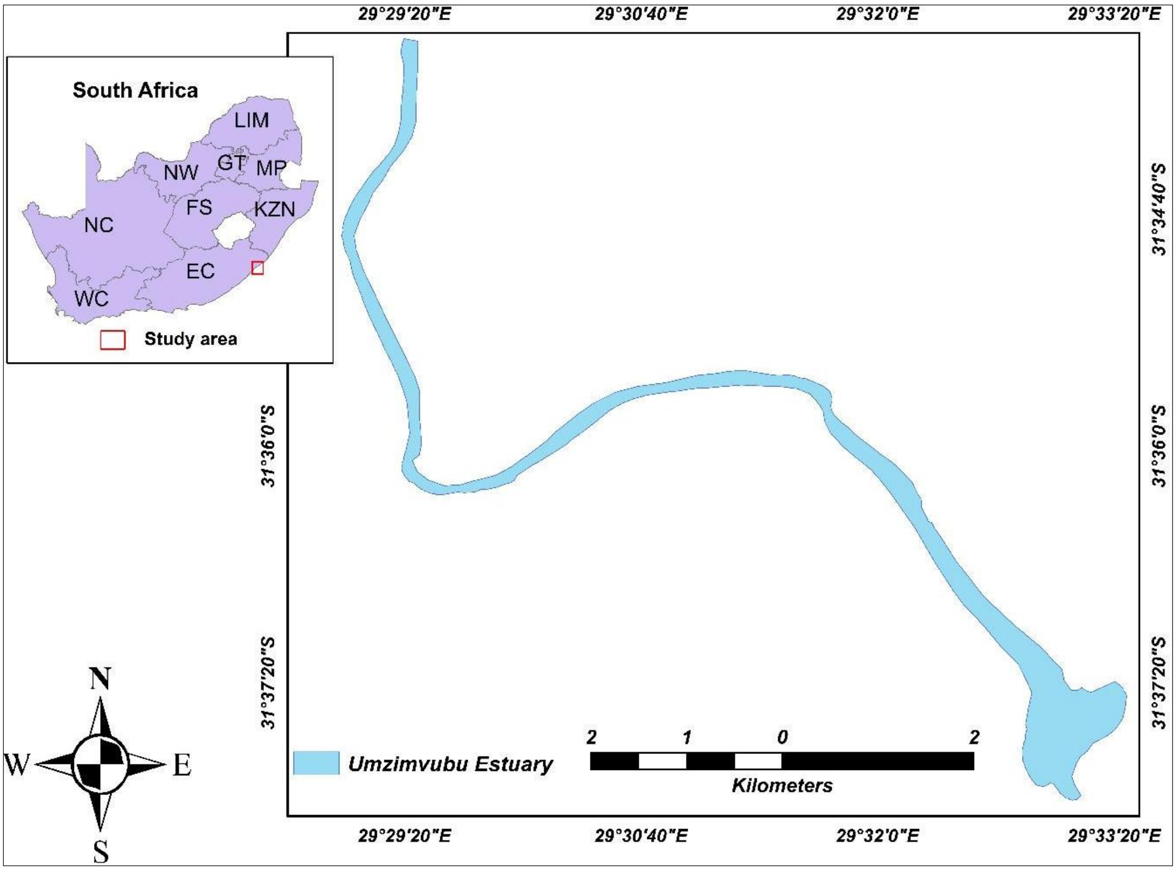

Figure 2.1: Location of the study area in the Eastern Cape Province of South Africa.

2.2. Climate and topography

Port St. Johns has a moderate, humid, and subtropical coastal climate. The summers in Port St. Johns receive the most rainfall with temperatures that vary from an average maximum of about

25°C to an average minimum of 20°C, while winter temperatures range from an average maximum of 21°C to an average minimum of 8°C. The annual rainfall varies between 1100 and 1400 ml per annum with the minimum and maximum rainfall received in June and March, respectively. Port St. Johns has reasonably good weather conditions during the course of the year, but extremes in climate and local variation are common as evidenced by the reports of drought, floods and the impacts of adverse meteorological phenomena such as tornadoes. The temperature extremes can increase the movement of sediments within the estuary (Stryker *et al.* 2018) due to accelerated weathering and stream bank erosion (Lintern *et al.* 2018). The topography of the study area was described using two elements, namely slope and elevation.

2.2.1. Elevation

The high mountain rivers whose headquarters drain elevations above 3000 meters yield sediments that are two to three orders of magnitude greater than lowland similar size rivers (Ruddiman, 2013). Furthermore, estuaries are the collection points for suspended sediments coming from the rivers (Beck, 2005). The Umzimvubu Estuary falls under South Africa's estuaries that do not have detailed topographical surveys (Van Niekerk & Turpie, 2012). Umzimvubu Estuary is distinctively described by mountainous terrain with hills, cliffs, beaches, and sandy dunes. The lower part of the estuary is characterized by a lesser gradient, which makes it vulnerable to floods. The elevation surface of the area surrounding the study area was generated from a 30 meters Shuttle Radar Topography Mission Digital Elevation Model (SRTM DEM) and was found to range from 77 to 381 meters above sea level. Figures 2.2 provide the elevation distribution in the study area.

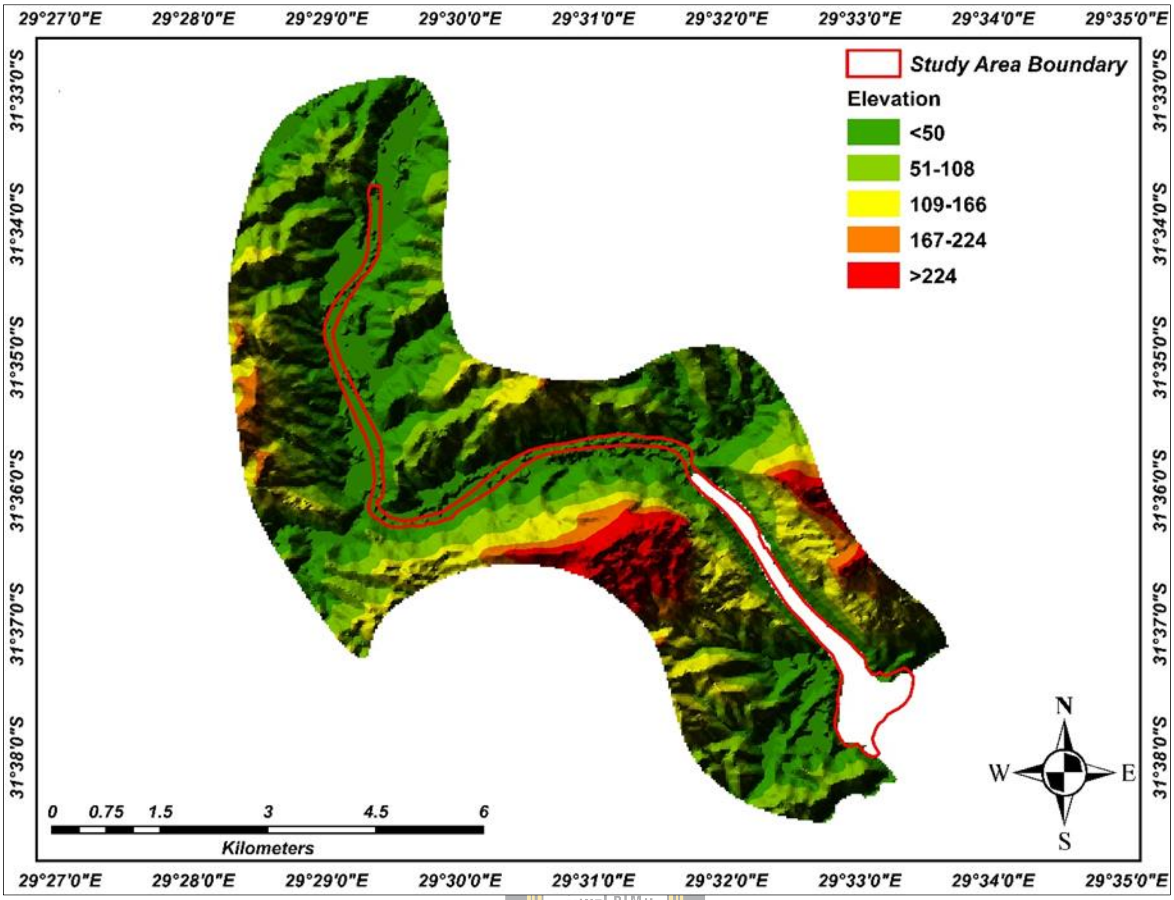

Figure 2.2: Elevation map of the study area.

It can be noted that the elevation class less than 50 m occupies 34% of the study area. Moreover, the elevation classes of 51m to 108m, 109m to 166m, 167m to224m, and over 224m occupied the area of 26%, 20%, 14% and 6% respectively. Table 2.1 illustrates the frequency of elevation classes of the area surrounding the study area.

Table 2.1: Area covered by each elevation class

Elevation class (meters asl.)	Area covered (%)
<50	34
51 – 108	26
109 -166	20
167 – 224	14
>224	6

2.2.2. Slope

Slope gradient replicates the steepness/gentleness of the land surface, and it is classified as one of the most topographic variables influencing soil erosion (Liu *et al.* 2001), resulting in a sediment yield increase with a slope length increase (Liu *et al.* 2001). The slope surface of the study area was calculated from a 30-meter Aster DEM and was classified into five classes in

ArcGIS. It was found that the slope surfaces range from 0^0 (gentle slope) to 78^0 (steep slope). Figures 2.3present the slope characteristics of the study area.

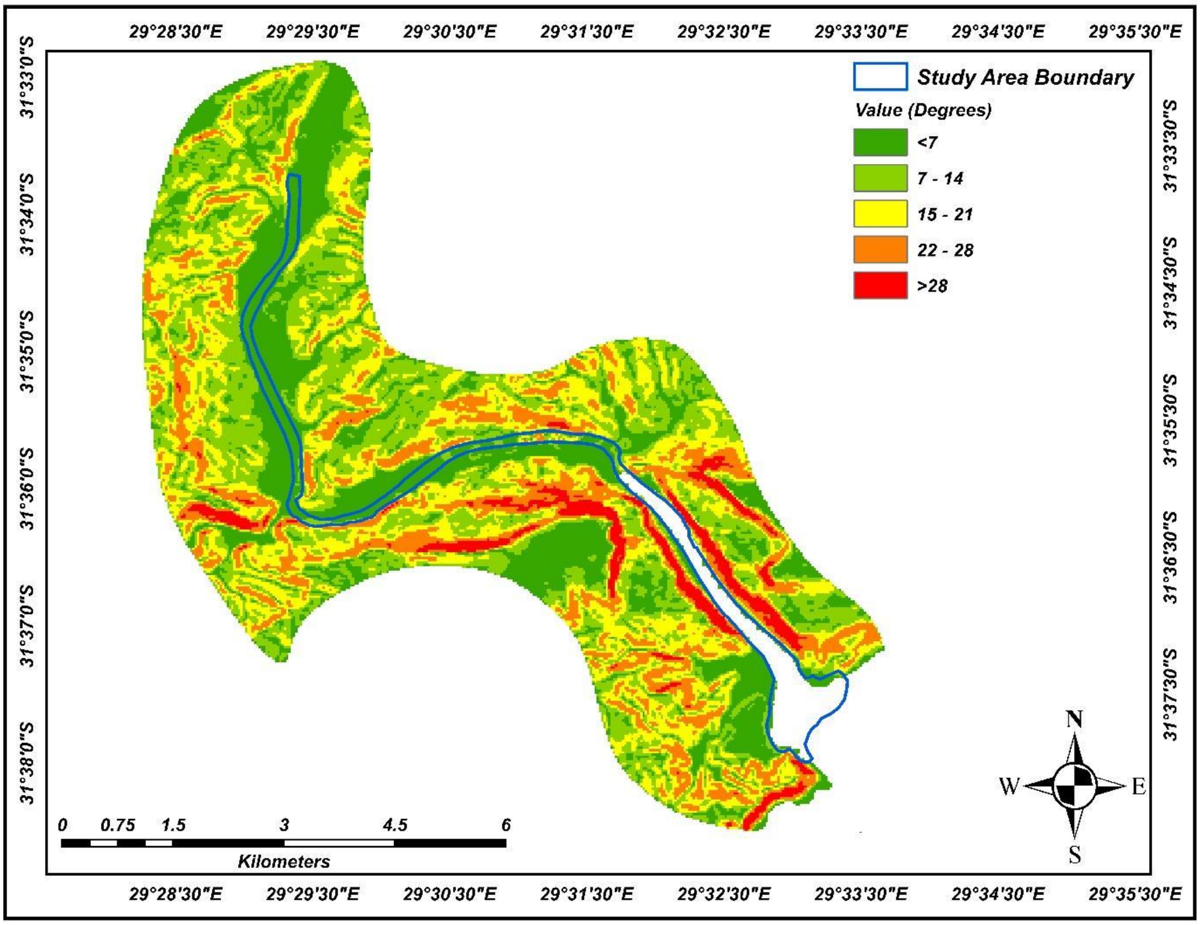

Figure 2.3: Slope map of the study area

It can be noted that the slope class of less than 7˚ covers an area of 25% in the study area. It is observed that the slope classes of 7˚ to 14˚, 15˚ to 21˚, 22˚ to 28˚ and over 28˚ covered an area of 30%, 26%, 15% and 4% respectively.

Table 2.2: Slope classes of the area surrounding the study area

Slope angle class (in º)	**Area covered (%)**
<7	25
7 – 14	30
15 – 21	26
22 – 28	15
>28	4

2.3. Vegetation type

The loss of vegetation cover through several factors such as overgrazing, ploughing or fires causes the soil to be vulnerable to being transported by either wind or water (Shit *et al.* 2012). This eventually contributes to the introduction of sedimentation in estuaries. The study area is characterized by two vegetation types, namely Coastal Forest and Thornveld and Pondoland Coastal Plateau Sourveld. Both vegetation types were classified under the grassland biome based on the Tainton (1984) veld types. The Coastal Forest and Thornveld vegetation type are situated along the coastal area and they cover most of the study area. Figures 1.6 and 1.7 present the vegetation characteristics map and classes of the area surrounding the study area, respectively.

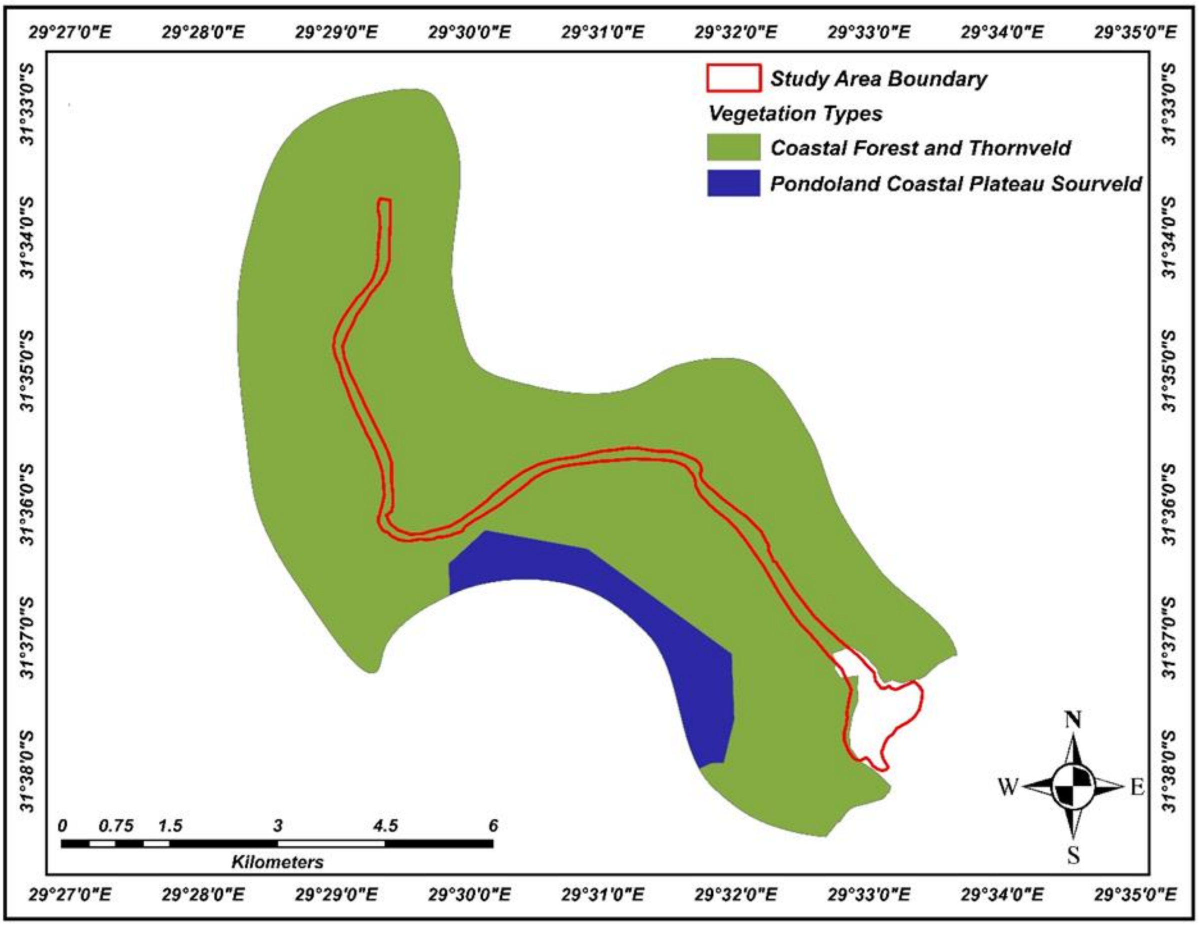

Figure 2.4: Vegetation types of the study area (Source: Tainton, 1984)

It is noted that the Coastal Forest and Thornveld and Pondoland Coastal Plateau Sourveld vegetation types occupy 91% and 9% of the study area respectively. Table 2.3 shows the area covered by each vegetation type in the study area.

Table 2.3: Vegetation classes of the area surrounding study area

Vegetation class	**Area covered (%)**
Coastal Forest and Thornveld	91
Pondoland Coastal Plateau Sourveld	9

2.4. Biodiversity

The Umzimvubu Estuary is ranked 35th out of South Africa's 265 estuaries in terms of its conservation importance in relation to biodiversity (DWS, 2014). This estuary was given a high conservation importance rating, forming part of the 15% of South African estuaries that are healthy (DWAF, 2002b). This is because Umzimvubu Estuary is an important nursery for fish species that are endemic to the region. These fish species such as white Steenbras and spotted grunter form an important part of commercial and recreational fishing in South Africa. Particularly, Umzimvubu Estuary contributes approximately R6 783 215 per annum to marine fisheries. The white Steenbras and spotted grunter fish species use the estuary for different activities such as recruitment for juveniles, facilitating growth and protection of annual cohorts, and feeding areas for adults.

2.5. Land-use types

Land-use is one of the most significant factors that influences soil erosion (Zhang *et al.* 2015), and soil erosion is one of the primary sources of suspended sediments (Vercruysse *et al*. 2017). Soil erosion is primarily due to the removals of vegetation that eventually lead to the altered sites with exposed or loosen topsoil (Issaka & Ashraf, 2017). The study area is characterized by several land use types that include commercial irrigated land, semi-commercial/subsistence dryland, degraded forest and woodland, mines & quarries, thicket & bushveld, unimproved grassland, built up areas, barren rock and waterbodies. The study area is dominated by thicket & bushveld in the upper part of the study area with 41%. Figure 2.5 presents the land-use types of the area surrounding the study area.

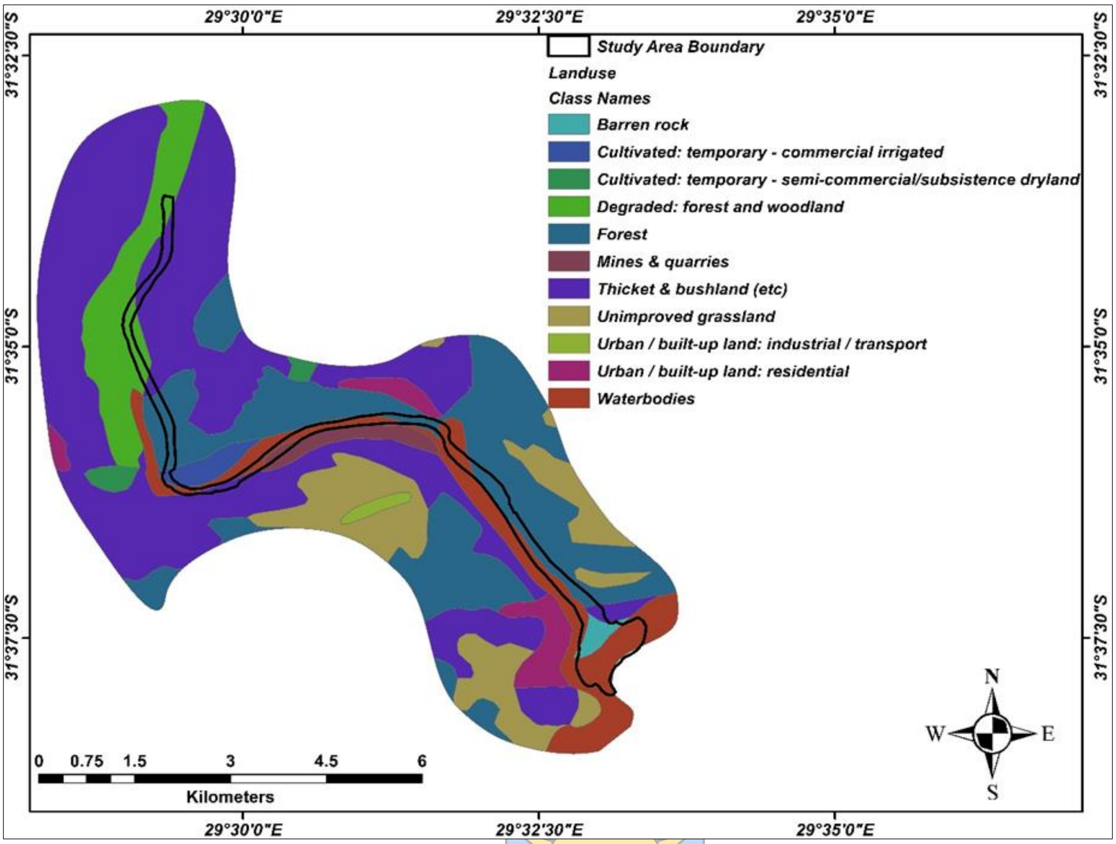

Figure 2.5: Land-use map of the study area (Source: GeoTerraImage, 2015)

From Table 2.4, it is observed that thicket and bushland class covers a region of 41% in the study area. It is also noted that water bodies, degraded forest and woodland, forest, unimproved grassland and semi-commercial/subsistence dryland covers an area of 9%, 7%, 24%, 11% and 0.8% respectively. Moreover, residential urban/built up land, mines and quarries, commercial irrigated land, industrial/transport built up land and barren land occupies an area of 4%, 1%, 0.8%, 0.7% and 0.7% respectively.

Table 2.4: Land use classes of the area surrounding the study area

Land use/cover type	**Area covered (%)**
Thicket & Bushveld	41
Waterbodies	9
Degraded forest and woodland	7
Forest	24
Grassland	11
Semi-commercial/subsistence dryland	0.8
Built up land	4
Mines and Quarries	1
Commercial irrigated land	0.8
Industrial/transport built up land	0.7
Barren land	0.7

A literature review pertaining to the estuarine suspended sediments and the role of remote sensing in monitoring and estimating the suspended sediments is in the following chapter.

CHAPTER 3
LITERATURE REVIEW

3.1. Introduction

This chapter reviews the literature regarding estuarine suspended sediments, their sources, and environmental impacts on estuarine ecosystems. The literature regarding the nature and significance of estuaries is also reviewed in this chapter. The South African national policies and legislation that govern the management and protection of estuaries are also reviewed in this chapter, as well as literature pertaining to the role of remote sensing technology in monitoring estuarine suspended sediment concentration. Ultimately, the literature review pertaining to the applications of statistical methods in determining the relationships between/among variables is also provided.

3.2. The nature and value of estuary

An estuary refers to a partially enclosed coast of a water body that is either permanently or temporally linked to the sea with less salty waters than that of adjacent sea, as a result of freshwater contributions (Potter *et al.* 2010). Estuaries can be highlighted as being the focal points for the establishment and carrying out of community and commercial activities because of the opportunities and benefits they provide (Breen and McKenzie, 2001). The benefits and opportunities that an estuary provides include being a vital location for cultural and recreational activities for coastal occupants and tourists. The estuaries are widely recognised for their ability to produce food, through the production of shellfish and fish, which are often harvested through aqua cultural processes (Miththapala, 2013; Thrush *et al.* 2013). Residents dwelling near an estuary often utilize it for various activities, such as fishing, water sports and for cultural activities (Breen and McKenzie, 2001). Commercially and recreationally, the fish species, such as snapper and blue cod, utilize the estuary as either their permanent residing place or temporary breeding place (Potter *et al.* 2015). The aesthetics of an estuary are visually attractive with scenic qualities that are highly valued. This can increase human well-being and, subsequently, have a positive impact on adjacent land and property values (Thrush *et al.* 2013). Therefore, it is of utmost importance that the estuaries are conserved and protected for best estuarine ecosystem functioning and improved human wellbeing.

The proper functioning of an estuary is reliant on several factors such as size and length of the river catchment, tidal and freshwater flushing time, nature and degree of the intertidal area, and climatic settings that yield a variety of estuarine systems (Underwood and Kromkamp, 1999).

An estuarine ecosystem is made up of biologically diverse variables, such as mud and sand flats, salt marshes, water column, bivalve reefs and beds, plants such as sea rush, jointed rush, marsh ribbonwood shrub, saltwort, native succulents, cordgrass and so on (Niering *et al.* 1978). These variables are interconnected by moving animals and tidal water flows, which play a significant role in the geomorphological structure of creeks and channels that together determine the productivity of natural systems of the biosphere (Dame, 2008). Estuarine ecosystems are amongst the majority of productive systems on earth, due to long water residence times and the cycling of nutrients several times before they are flushed to the sea (Sharifinia, Daliri, and Kamrani, 2019; Finkbeiner, Oleson, and Kittinger, 2017; Miththapala, 2013). They are generally principal points of influence both from the side of the land and sea, mainly due to their ability to create a transition corridor of steep slope, with physio-chemical form at a point where land and sea intersect (Jennerjahn and Mitchell, 2013).

3.2.1. Economic value

This marine life found within the estuarine system provides many non-consumptive and consumptive values to people, including nature observation and photography, and commercial and recreational fishing (Bergstrom, *et al.* 2004). This is because estuarine system provides highly productive aquatic habitat such as seagrass and kelp beds, shellfish beds and coral reefs, hard-bottom communities of sponges and outcrops, soft-bottom communities with mud and sand, rocky intertidal zones, fringing mangrove forests, and vegetated marshes/wetlands (Lellis-Dibble, Mcglynn, and Bigford, 2008). These aquatic habitats then provide important forage, spawning, refuge, and nursery habitat for commercial, recreational, and forage fish species during one or more of their life history stages. Many species of commercially important fish and shellfish use estuaries as nurseries to spawn and allow juveniles to grow. South Africa's coastal areas generate substantial capital through their ecosystem services including tourism, recreation and fishing, for instance estuaries generate nearly R65 million a year from subsistence harvesting and fishing. Estuaries contribute R 4.2 billion per annum to the South African economy (Janisch *et al.* 2020).

3.2.2. Biological value

The natural mixing of freshwater and saltwater in an estuary creates an ecologically rich ecosystem that provides unique habitat for a wide diversity of marine life (Bergstrom *et al.* 2004). The biological importance of estuaries relates especially to their function as nursery areas for a wide variety of marine organisms such as fish, birds, shellfish, mammals and other wildlife (Blaber, 2000). Many species of fish and shellfish use estuaries as nursery ground to spawn and allow juveniles to grow. Thousands of birds, mammals, fish and other wildlife use estuaries as places to live, feed and reproduce. Migratory birds use estuaries to rest and gain food during their journeys. In developing countries, such fisheries often constitute the main source of both food and income for people living along the coast (Blaber, 2000).

3.3. Estuarine ecosystem alteration

Estuarine ecosystems have been subject to alteration in recent years (Borja *et al.* 2010). The estuarine ecosystem has been vulnerable both to natural and anthropogenic processes. Natural influences are forces of nature including tidal currents, waves and winds, while human-induced factors include expansion of coastal zones, pollution, and the presentation of non-native species to the region (Thompson *et al.* 2002). Commonly, ecosystem alteration and depletion are attributed to by lack of understanding and appreciating benefits associated with such systems (Crooks & Turner, 1999). The degradation of estuaries results in loss of habitat, species loss, water quality deterioration, reduction of water supply and storage, introduction of algal blooms and sedimentation into the system and the reduction of recreational opportunities (Kennish, 2002). Reduced water quality, specifically because of an increase in suspended sediments, has been linked to several factors such as decline in fish abundance and changes in gill structure (Bilotta and Brazier, 2008). The presence of suspended sediments in an estuary results in an increase in resting oxygen consumption. Therefore, the presence of suspended sediments ultimately results in loss/decline of fish species occupying the estuarine environment (Hess *et al.* 2017). Implications of estuarine condition on marine ecosystems.

Marine ecosystems are found in the ocean site, some of which are functional in the near shore regions. Among these ecosystems are salt marshes, estuaries and mangrove forests, with others appearing to be very unproductive, such as the ocean floor. A marine ecosystem is characterized by organisms and their species, predators, competitors, mating, temperature, concentration of nutrients, sunlight, turbulence, salinity and density (Airame *et al.* 2003). The high salinity content and global circulation distinguishes marine ecosystems from other aquatic ecosystems. It is then defined as an adaptive complex system that is made up of separate agents that interact among themselves towards producing collective effects, integrating scales from individual behaviors to the dynamics of whole systems (Levin & Lubchenco, 2008). The significance and value of a marine ecosystem comes from the benefits that it delivers to humans, which is known as ecosystem services (Hattam *et al.* 2015). These services play a fundamental part in human wellbeing because they provide goods, services and cultural benefits to the earth's developing population. Examples of these ecosystem services are fish harvests, recreation and tourism, transportation, breeding and nursery habitats, shoreline stabilization and erosion control, flood control, and scientific and educational opportunities (Barbier, 2017). The ecosystem services derived from estuaries range from food production to recreational opportunities (Thrush *et al.* 2013).

3.4. The nature and sources of estuarine suspended sediments

Suspended sediment are micro-particles in a flowing stream, held in suspension by the eddy currents and which only settle out once the stream water flow rate drops, such as when the streambed gets flatter, or the stream feeds into a pond or lake (Parsons *et al.* 2015; Cantalice *et al.* 2015). These particles are suspended, playing a fundamental role in elemental cycling in coastal ecosystems, rivers and lakes (Kjelland *et al.* 2015). One characteristic of suspended sediment is its diameter of 62 µm, which does not allow sediment to pass through a 0.45-micrometer membrane filter (Bartram & Ballance, 1996). The quantity of sediment suspended is influenced by the strength of turbulence and/or size of sediment particles. (Bishop *et al.* 2011). The sediments suspended in the water column are typically less than 0.1 mm in diameter and are mostly silt- and clay-sized particles (Kemker, 2014). These particles are transported by flowing water, until they settle out when flow is insufficient to keep them in suspension (Van Rijn, 2013).

A huge portion of suspended sediment is produced by soil erosion where land slope, land use, soil type and rainfall all have important influences on the spatial pattern of sediment generation (Bhatti *et al.* 2007). However, a certain amount of sediments come from the beds and banks of rivers, through the weathering process. This sediment is in the form of fine particles, transported in water paths as a suspended load (Bhatti *et al.* 2007). Suspended sediment is normally transported with the same speed as that of the surrounding water. The nature and amount of sediments transported by rivers depends on the weathering regime of the catchment area (Viers *et al.* 2009). Sedimentation through soil erosion is triggered by land use activities such as deforestation, overgrazing, other poor farming practices and urbanization (Stronkhorst *et al.* 2009). For example, whenever the land is cleared for various developments, roads and buildings are established on the site that exposes soils. Then, the soils become susceptible to erosion and eventually cause large quantities of sediments to be transported into nearby water bodies through surface runoff, especially after rain (Chin & Gregory, 2001). The livestock that grazes along the riverbanks, cleared trees and lack of riparian vegetation also lead to high sediments in the nearby streams and rivers (O’Callaghan *et al.* 2019).

3.5.Effects of suspended sediments on estuarine functioning

The proper functioning of an estuarine ecosystem is affected by the loss and modification of natural locale, changes in mouth conditions, water flow, natural resource use, sedimentation and turbidity, loss of system variability, recreational disturbances, changes in salinity, changes in nutrient status and pollution. However, sedimentation remains one of the main threats to estuarine ecosystems universally (Tundu *et al.* 2018). Sediments deposited into the estuarine system reduce water quantity, quality and accessibility for different uses, while equally increasing the costs associated with water purification (Tunde *et al.* 2018). High-suspended sediments can considerably decrease the aesthetic quality of water bodies, leading to negative impact on recreation and tourism (Bilotta & Brazier, 2008). Suspended sediments significantly reduce the visibility, reduce the depth of the photic zone, and modify the vertical stratification of heat in the water column because of amplified light attenuation (Wilber & Clarke, 2001).

An increased/decreased concentration of suspended sediments affects the estuarine ecosystem through the loss and modification of natural locale (Kjelland *et al.* 2015). Furthermore, suspended sediments affect the estuarine ecosystem through the loss and modification of natural locale by burying it (Kjelland *et al.* 2015). The loss of natural habitat in an estuarine ecosystem reduces nursery and feeding for fish, which directly affects the contribution to coastal fisheries (Whitfield & Cowley, 2010). Increased concentration of suspended sediments also has detrimental physical impacts such as fish egg abrasion, reduced bivalve pumping rates, and direct mortality of fish (Yang *et al.* 2017). Suspended sediments are not necessarily harmful to aquatic and estuarine ecosystems; for instance, various fishes grow well in turbid estuarine environments, most probably benefiting from a reduced risk of predation (Adams *et al*. 2015). Suspended and bedded sediment loading imbalance in aquatic systems can be considered one of the greatest factors leading to a reduced water quality (Berry *et al.* 2003; Kjelland *et al.* 2015). Therefore, it is imperative to understand the impacts of sedimentation on estuarine ecosystems' sustainable development if management of estuarine resources is to be attained.

3.6. Impacts of suspended sediments on estuaries

Estuarine flora and fauna are directly and indirectly affected by suspended sediments through various mechanisms in various ways, leading to possibly physiological alterations of habitat. Increase/decrease in the concentration of suspended sediments above threshold level in an estuarine system result in environmental effects on the aesthetics, water quality and biota (Bilotta & Brazier, 2008). It smothers marine communities or completely buries them resulting in asphyxiation of seagrass beds, corals and mangrove stands (Simcock, 2017). It further decreases the amount of sunlight that enters the estuary, which, in turn, limits the production of algae and *macrophytes*, increases water temperatures and reduces growth of in situ natural vegetation. The taxonomic group which is greatly affected by the reduction of sunlight entering the estuary include *Periphyton* and *Macrophytes* (Bilotta & Brazier, 2008; Davidson, 2000).

The increase of suspended sediment in an estuary may degrade fish habitat areas that contain buried eggs. These areas become filled with sediments, and this leads to a reduction in the amount of available oxygen (Bekic, 2013). The negative effects that suspended sediments impose on the fish community are from the individual level such as spawning success and fry emergence to the system level such as decreased richness of species (Kjelland *et al.* 2015). Furthermore, the sediments reduce fish feeding and respiratory efficiency and cause physiological stress (Cavanagh, 2014). Suspended sediment increase also decreases feeding activity, rates and success by damaging the visual cues that fish or predators use to spot prey, and this normally occurs in species such as salmon (Cavanagh, 2014). This is because these predators require clear waters in order to easily locate their prey. Therefore, the health of the ecosystem becomes prone to risks because of the prey-predator relationships being disrupted (Kjelland *et al.* 2015). Suspended sediments tend to physically and chemically have toxic organic chemicals, heavy metals and nutrients absorbed to them (Hacısalihoğlu & Karaer, 2016). Therefore, a rise in the amount of suspended sediment increases these toxic substances, which results in eutrophication (Simcock, 2017). Decreased suspended sediments in estuarine systems lead to degradation of the system by starving it of the elements required to withstand production since sediments normally carry various minerals, nutrients and organic matter (Bekic, 2013). Therefore, a reduction or a rise in suspended sediment concentration above threshold may cause a degradation of an ecosystem (Shahzad *et al*. 2018).

3.7. Suspended sediment monitoring

Efficient estuarine and coastal water quality monitoring is a fundamental exercise for safeguarding and rehabilitation of marine freshwater resources for local and state government agencies (Nukapothula *et al*. 2019). Monitoring of suspended sediments in estuarine systems is imperative for monitoring the effects of terrestrial inputs and anthropological activities on the offshore water environment (Shang & Xu, 2018). It is also vital for the development of aquatic ecosystems because suspended sediments present a variety of nutrients, minerals, and organic matter. Generally, the purpose of monitoring aids in providing the decision makers with keeping track of the project, a strategy to plan for sustainability and guidance for future endeavors (Biwott *et al.* 2017). Monitoring of spatial patterns of suspended sediments in an estuarine system comes in handy with industrial, monitoring urban and agricultural runoff and any other environmental modifications that take place because of increased suspended sediments (Larson *et al.* 2018).

Monitoring of suspended sediment at both spatial and temporal scales through conventional techniques has proven to be challenging. One of the traditional methods that has been used to estimate suspended sediments in an estuary is based on collecting water from a point within an estuary, where the collected sediment contained in a measured volume of water is filtered, dried and weighed (Reisinger, 2015). With this traditional method, the suspended sediment concentration is measured only point by point in space and time at the sampling stations (Greb *et al.* 2018). As such, it is not easy to achieve accurate estimates of suspended sediment concentration at spatial context; high density of points is required if precise estimates of such are to be attained. Moreover, the number of sampling points can be limited due to accessibility of sites (Bhatti *et al.* 2008), therefore making it hard to accurately build the spatial distribution map of suspended sediment concentration. This is because spatially extrapolating data over a large area with limited point-based suspended sediment concentration data may bring about significant errors (Jian-Jun, 2009).

Sampling numerous points in an estuary can also become laborious, time-intensive, and labor-intensive; the amount of data collection time and labor may increase as the number of sampling points increases (Park *et al.* 2020). The point-based measurements are not only expensive but can also result in biases by sampling logistics (Reisinger, 2015). Moreover, the measurements are biased to fair weather conditions because boats are commonly deployed during fair weather conditions (Greb *et al.* 2018). Whereas these measurements deliver much desired data, the inadequacy in the spatial and temporal contexts elicits challenges when trying to characterize the complexity and heterogeneity of an estuarine system (Reisinger, 2015). This is because estuaries are ever-changing environments; the conditions perceived at a single point can be the outcome of several compounded and interconnected processes. As such, the observational evidence might not replicate the system in space or throughout time.

3.8. Role of remote sensing in monitoring suspended sediments

The advent of remote sensing technology has provided an effective, efficient, and reliable way of monitoring suspended solid concentration (Ritchie *et al.* 2003; Gholizadeh *et al.* 2016). Over the past decades, remote sensing techniques have played a prominent part in water quality studies, mainly because of their technical advances in terms of instrument/sensor and algorithm/image processing improvements (Dube *et al.* 2015). Remote sensing technology offers advantages over conventional techniques for suspended sediment monitoring due to its ability to measure bio-geophysical variables over different surfaces of coastal waters to a considerable spatial extent (Nukapothula *et al.* 2019). Generally, remote sensing plays a major role in estimating suspended sediments because it provides synoptic views of water properties for larger spatial coverage with a high resolution of temporal and spatial coverage (Bhatti *et al.* 2011). However, natural resource management agencies have been slow to embrace the power of remote sensing technology; even though vital water quality parameters such as *c-phycocyanin*, *chlorophyll-a*, *suspended solids*, light attenuation, Secchi Disk transparency, coloured dissolved organic matter and turbidity have been quantified with necessary accuracies (Greb *et al.* 2018).

The role of remote sensing in estimating/monitoring water quality variables is based on the investigation of the inherent optical properties of the water-leaving reflectance, following the removal of environmental effects (Zheng & DiGiacomo, 2017). Inherent optical properties quantitatively define the absorbing and scattering constituents of ocean water (Werdell & McKinna, 2019). Water-leaving reflectance describes the nature in which scattering and absorption of radiation by dissolved and suspended materials in the water body influence the spectrum and radiance spread (light field) of the light from the water body (Lee, 2006). Therefore, the spectral pattern and extent of the corrected water-leaving reflectance are of interest from a remote sensing perspective. The observed signal comprises the signal from the optically active elements of the water and surface reflected glint, along with the bottom reflectance in shallow waters (Shahzad *et al.* 2018). Removal of environmental effects plays a major role in remote sensing because materials in surface waters and atmosphere change radiation and reflectivity characteristics of the surface water, which ultimately changes the spectral signature backscattered from the water surface (Ahmad, 2006). Absorption and the scattering mechanism play a prominent part in changing the intensity and direction of the signal in the atmosphere. This is not always the case unless corrections that consider scattering and absorption are applied (Hadjimitsis *et al.* 2010). Therefore, retrieval of water constituents based on surface water reflectance requires an accurate atmospheric correction. To understand the biosphere of the ocean without atmospheric and oceanic surface effects, processing of satellite ocean color imagery known as atmospheric correction is required. A dependable and stable atmospheric correction method forms the foundation for ocean color products of the required high quality (Muller *et al.* 2015).

2.8. Spectral characteristics of suspended sediments

Suspended sediments have a serious effect on the penetration of sunlight into the estuarine aquatic ecosystem. Sediment properties such as particle size, organic matter, color, and mineral composition have an impact on the reflectance volume of estuarine waters (Jian-Jun, 2009). Small detrital or non-algal particles mostly contribute to the backscattering, whereas phytoplankton contribute to absorption and scattering (Nechad *et al.* 2003). Particle size distribution influences suspended sediment concentration reflectance relations; smaller-sized sediments normally give rise to higher spectral reflectance for similar suspended sediment concentration (Bhargava and Mariam, 1991). Moreover, it provides greater insights with regard to the contribution of seawater constituents to the remote sensing reflectance signal or ocean color in both coastal and oceanic waters (D'Sa *et al.* 2007). This was also evident as an increase in albedo was observed with a decrease in sediment particle size (Myers *et al.* 2015). Therefore, their concentration level can be determined by analyzing their optical properties, such as scattering, absorption and backscattering coefficients, the nature of the particles, and wavelength (Bowers & Binding, 2006). Figure 3.1 shows the spectral reflectance characteristics of suspended sediments across the visible and near-infrared regions of the electromagnetic spectrum. As the concentration of suspended sediment increases, the spectral signature of the suspended sediment concentrated water increases for all wavelengths when compared to spectral signature of clear waters, with the peak signal typically occurring in the red and near infrared regions of electromagnetic spectrum (Pereira *et al.* 2018). This is in line with the study by Bhatti *et al* (2011), who noted that the suspended sediment or organic materials in the water results in an increase in the spectral reflectance in the visible region of the electromagnetic spectrum and the peak shift toward longer wavelength. The study conducted by Choubey (1994) noted that, as the level of concentration of suspended sediment rises, the reflectance in the visible region (0.4-0.7 nanometer) and near infrared region (0.8-0.9 nanometer) also rises. As such, the visible and near-infrared wavelength channels can be explored with the view to quantify the suspended sediment concentration.

The presence of algae in water plays a significant role when estimating the concentration of suspended sediment from remote sensing platforms; in the presence of algae, the suspended sediments are always characterized by low spectral reflectance, regardless of the concentration levels (Han *et al.* 1994). In the study conducted to investigate the spectral reflectance responses of water with different levels of suspended sediment in the presence of algae by Karabulut and Ceylan (2005), it was noted that even if the concentration level of suspended sediment is significantly increased, the spectral reflectance properties of algae always stand out. This was evident in the results, where the spectral pattern of algae was visible even after increasing the concentration of suspended sediments. It was also observed that between 400 and 900 nanometer wavelengths there are distinct differences in reflectance values corresponding to different suspended sediment concentration level values (Karabulut & Ceylan, 2005). Therefore, it is of importance to take note that the spectral reflectance of suspended sediments slightly deviates from its normal patterns because of the presence of algae in the water.

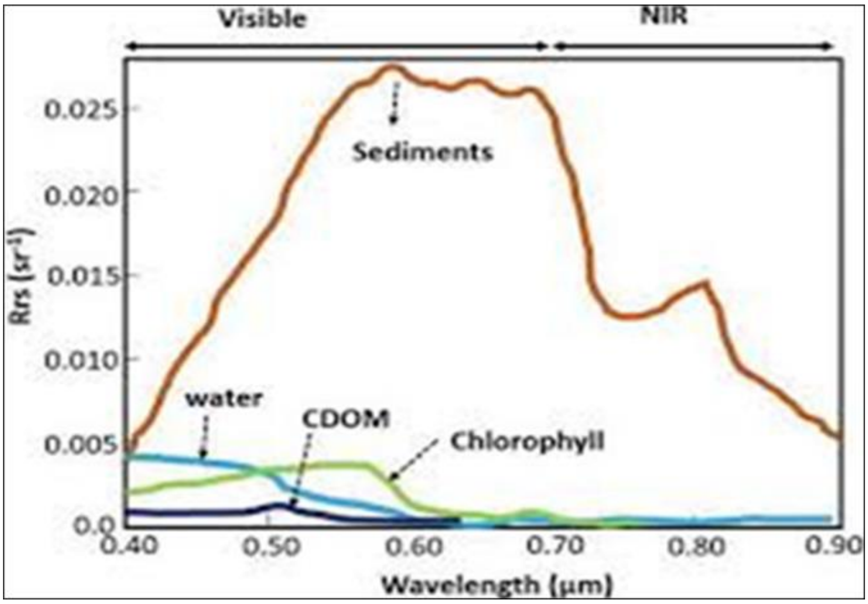

Figure 3.1: Spectral characteristics of suspended sediments across visible and near infrared regions of the electromagnetic spectrum (Source: Hafeez et al. 2018).

3.9. Remotely sensed data for mapping suspended sediments

Several satellite sensors were initially built, designed, and launched for the purpose of terrestrial or ocean remote sensing applications (Dekker *et al.* 2018) which included recording data for freshwater, estuarine and other oceanic environments. In the estuarine environment, suspended sediment concentration has been widely studied across different geographical areas, using different remote sensing satellite sensors such as Landsat, MEdium Resolution Imaging Spectrometer, MODIS, and Sea-viewing Wide Field-of-view Sensor, SPOT, IKONOS, Sentinel and WorldView-2. A wide range of Landsat imagery has also been used in several studies to estimate and monitor suspended sediments (Doxaran *et al.* 2006; Olmanson *et al.* 2008; Onderka and Pekarova, 2008; Yepez *et al.* 2018; Chelotti *et al.* 2019). Landsat-8

Operational Land Imager (OLI) has the potential to record information on landscape features in visible, near infrared, and short wave infrared spectral bands as well as a panchromatic band with a spatial resolution of 30 meters. The 30-meter spatial resolution of Landsat satellite is higher than most ocean color satellite's spatial resolution, allowing it to resolve the fine-scale distribution of suspended sediments in estuarine environments (Yepez *et al.* 2018). The spatial resolution then becomes an influencing factor for the use of Landsat OLI imagery in estuarine environments (Min *et al.* 2012; Vanhellemont & Ruddick, 2014; Zheng *et al.* 2016). Landsat-8 OLI has shown potential to record detailed and precise spatial patterns of suspended sediments as a result of advancements such as 12-bit quantization, spectral coverage, and improved signal-to-noise ratio (Wu *et al.* 2015). However, it lacks the suspended sediment temporal coverage variation because Landsat acquires and records data for a specific area every 16 days, and cloud cover on the specific acquisition date may result in a lower temporal resolution of usable images, particularly in areas susceptible to overcast weather (Brezonik, Menken, and Bauer, 2005), such as coastal areas. Therefore, integrating Landsat-8 OLI data with other satellite data of high temporal resolution, such as daily MODIS or sentinel imagery may enhance the Landsat-8 OLI monitoring capacity for suspended sediments (Wu *et al.* 2015, Yepez *et al.* 2018). Several studies have used Landsat-8 OLI imagery to estimate and monitor the suspended sediment concentration level (Vanhellemont & Ruddick, 2014; Wu *et al.* 2015*;* Yepez *et al.* 2018; Chelotti *et al.* 2019; Hernandez-Cruz *et al.* 2019).

Although ocean color satellite sensors (such as SeaWiFS, MODIS, MERIS, and Geostationary Ocean Color Imager) have spectral bands that are specifically configured for observing bio-optical characteristics of aquatic environments, their low spatial resolutions (250 m to 1 km) limit their abilities to observe river channels or areas close to the river mouth (Li *et al.* 2019). As a result, Sentinel-2 has piqued the interest of the remote sensing community, due to its open access and free imagery. However, one of Sentinel's distinguishing features is its ability to provide an unprecedented combination of capabilities, representing a significant advancement over current multi-spectral missions, with the potential to meet the satellite data requirements for fine-scale mapping (Marinho e*t al.* 2021). Furthermore, the mission is close to Landsat-8 local times, allowing for the seamless integration of Sentinel-2 data with historical images to create a long time series (Li *et al.* 2019). Sentinel-2 Multispectral Imager (MSI) is a constellation of two satellites in sun-synchronous polar orbit that monitors land and coastal zones by providing high spatial (10-60 m) and temporal (2-5 days) resolution images (Malenovský *et al.* 2012). MSI has 13 bands ranging from visible to shortwave infrared (SWIR) spectral regions, making it an ideal data source for documenting variations in suspended sediment in coastal and inland waters (Hansen & Hansson, 2017).

Furthermore, MSI has four (4) additional Near-Infrared Radiometer (NIR) bands with higher spectral resolution than Landsat-8's Operational Land Imager (OLI) instrument (bands 5-8a) (Chetty, 2020). As a result, in optically complex coastal and inland seas, these additional NIR bands optimize bio-optical characteristic retrieval accuracy (Qing *et al*. 2021). In particular, they improve retrievals of bio-optical parameters in highly turbid and hypertrophic waters, such as suspended sediment concentration, turbidity, and Chlorophyll-a (Liu, *et al.* 2017, Gernez, *et al.* 2015, Kutser, *et al.* 2016). Sentinel imagery has been deployed in several studies for estimation and estimation of suspended sediment concentration (Kanga *et al.* 2020, Marinho *et al.* 2021, Zhang *et al.* 2020, Zhang *et al.* 2022). This is evident from the results obtained in Kanga *et al.* (2020) study, which showed that the prediction accuracy based on Sentinel-2A was adequate for suspended sediment concentration (R^2 of 0.8).

3.10. Remote sensing algorithms for mapping suspended sediments

Various remote sensing algorithms have been devised to estimate the concentration of suspended sediment, consisting of empirical and semi-analytical models (Shang and Xu, 2018). Semi-analytical algorithms are based on bio-geo-optical approach, which relates the water-leaving radiance, biogeochemical constituents, and inherent optical properties (Matthews *et al.* 2010; Greb *et al.* 2018). Semi-analytic algorithms are more applicable to various water bodies as opposed to empirical models. However, they have challenges with regard to obtaining model initialization parameters or limited accuracies (Wu *et al.* 2015). Volpe *et al* (2011) presented a method that estimates suspended particulate matter concentration in estuaries using a simplified radiative transfer model. The study used observations from multispectral satellite sensors such as Landsat, Advanced Spaceborne Thermal Emission and Reflection Radiometer, and Advanced Land Observing Satellite Advanced Visible and Near-Infrared Radiometer (ALOS AVNIR). The method produced accurate, robust and repeatable results based on the uncertainty. Chen *et al.* (2013) developed a three-band-semi-analytical model to derive total suspended matter. The validation of total suspended matter between the derived model and the field-measured total suspended matter concentration produced 29% of uncertainty. Therefore, the total suspended matter concentration model can be applied when estimating total suspended matter in coastal waters even though the model has the limitations of sensitivity to errors from atmospheric correction procedures (Matthews, 2011).

In-contrast to semi-analytical models, empirical algorithms directly relate the remote sensing signal to suspended sediments using statistical techniques (Matthews, 2011; Greb *et al.* 2018). Based on the studies conducted in estuarine waters, empirical algorithms demonstrated their capability to provide reliable information on suspended sediments. Examples of these models include the red-to-near infrared ratio adopted, which has been deemed capable for deriving suspended sediments from the imagery (Greb, Dekker, and Binding, 2018). Empirical algorithms are generated from in-situ measurements with undefined single suspended sediment unity, which is not fixed in natural environments, making the empirical algorithm become limited to regional applicability (Shang and Xu, 2018; Nukapothula, Chen, and Wu, 2019). Studies that have employed this approach revealed the empirical algorithm's capabilities to provide reliable information on inland and transitional waters (Vos *et al.* 2003; Miller & McKee, 2004; Odermatt *et al.* 2008; Doxaran *et al.* 2009; Petus *et al.* 2010). In their study to determine suspended sediment concentration level based on remote sensing reflectance measurements, Doxaranet *al.* (2002) noted the superiority of this model in reducing and eliminating the effects of sediment type and differences occurring in regular field reflectance measurements.

He *et al.* (2013) used Geostationary Satellite Ocean Colour imagery to assess the patterns in suspended particulate matter in coastal waters. In this study, a regional empirical algorithm was used to assess the concentration of suspended particulate matter in extremely turbid waters. Although the empirical algorithms provide reliable estimates of suspended sediment concentration levels, He *et al.* (2013) also noted that these models are regionally confined; their applications beyond a regional scale are an issue of concern. Nevertheless, the empirical algorithms for suspended sediments estimation are much simpler and more accurate (Rodrigues *et al.* 2018). Shang and Xu (2018) applied an empirical model based on the band ratio of R_{rs} 745 (near infrared) and R_{rs} 490 (blue). The model proved to be effective in estimating suspended particulate matter, with the results revealing a strong relationship between band ratio and in situ suspended sediment data ($R^2 = 0.9376$, RMSE = 89.32 mg/L). Pereira *et al.* (2019) also conducted a study to estimate suspended sediment concentration in an intermittent river using multi-temporal high-resolution satellite imagery. In their study, the results revealed that the near infrared spectral band was effective in retrieving suspended sediment concentration.

Among algorithms that are used for estimating and monitoring the concentration of suspended sediments, the potential of indices has been explored in several studies (Hossain, Jia, and Chao, 2010; Montalvo, 2010; Arisanty & Saputra, 2017). Remote sensing indices balance sensitivity to suspended sediments using a variety of spectral bands (Wilson *et al.* 2016). The indices that have been used to monitor suspended sediment concentration are Normalized Difference Turbidity Index (NDTI), Normalized Suspended Material Index (NSMI), Normalized Difference Suspended Sediment Index (NDSSI), by using the reflectance measurement combinations of different portions of electromagnetic spectrum (Hossain, Jia, and Chao, 2010; Arisanty & Saputra, 2017). The suspended sediment indices are used because of their simplicity and ease of computation (Fang, Liang, and Kuusk, 2003). The bands that suspended sediment indices use the most are the visible and near infrared bands due to their sensitivity to suspended sediments. The indices have been successfully used to monitor and estimate the concentration of suspended sediments, mostly in the absence of in situ measurements of suspended sediments (Hossain, Jia, and Chao, 2010; Montalvo, 2010; Arisanty and Saputra, 2017; Lacaux *et al.* 2017).

3.11. Integration of field data into remote sensing methods for suspended sediments estimation

Traditionally, on-site sampling was the only mechanism for assessing the suspended sediment condition of coastal and inland waters by samples collected during cruises, which is expensive and time consuming (Shang and Xu, 2018). In situ sampling has the merits associated with its flexibility during measurements of a wide range of biological, physical and chemical parameters, which include nutrients, organic and inorganic micro pollutants, trace metals, optical properties and cyanobacteria. Furthermore, in situ monitoring offers a complete understanding of complex aquatic processes; it also has the ability to gather environmental data that cannot be detected from a remote sensing platform (Greb *et al.* 2018).

The complex and dynamic nature of landscape processes pose significant challenges for monitoring and assessment from satellite imagery (Greb *et al.* 2018). From the point of view of water resources, these also limit the opportunity to capture the dynamics of aquatic systems and responses adequately and accurately to pressures (Tyler *et al.* 2016). It is on this basis that remotely sensed data needs to be accompanied or be validated by field-based measurements. The question is not directed to the effectiveness of individual monitoring methods but to the combination of monitoring methods that can achieve the best results for proposed objectives. For short term monitoring, in-situ sampling might be the most suitable method to utilize and remote sensing might be more relevant for long term monitoring (Mayr *et al.* 2019). As a result, the combination of both remote sensing and field techniques presents the most effective way to monitor suspended sediments because both play complementary roles (Geller *et al.* 2017).

For example, in any given place and time, in situ sampling can offer precise measurements of suspended sediments.

However, achieving large-scale landscape data using in-situ techniques may be challenging, especially if there is a long distance between monitoring points (Peterson *et al.* 2018). As such, remote sensing technology compensates for these shortfalls. Furthermore, using either of these monitoring methods exclusively reduced the reliability of the results, as compared to when the two were combined (Greb *et al.* 2018). It is of the utmost importance to specify that the use of remote sensing does not remove the need for and use of in situ measurements because both systems deliver applicable and relevant information. This means that the use of remote sensing is not by any means to be a replacement for in situ measurements because both methods complement each other. It is against this backdrop that the satellite based suspended sediment patterns are verified by field measured suspended sediment patterns for validity and reliability purposes.

3.12. A review of statistical methods for validating remote sensing data with in-situ data

Validation or accuracy assessment is an integral component of most mapping projects incorporating remotely sensed data (Congalton, 2001). It is imperative to determine whether the results produced can be accepted with confidence or rejected, and to determine whether the method used is suitable for its intended use (Belouafa *et al.* 2017). The suspended sediment concentration data derived from the imagery is no exception. Similarly, it is more imperative to determine whether a certain statistical approach can be trusted in terms of its ability to ensure model validity. There are several statistical methods or approaches available and these include Pearson correlation and regression analysis, which are available and employed to validate remote sensing data by comparing the in situ measured and remote sensing derived concentration of suspended sediment.

3.12.1. Correlation analysis

Pearson correlation measures the direction and robustness of the relationship occurring between two variables on an interval scale (Obilor & Amadi, 2018). The relationship degree is determined by correlation coefficient represented by “r”. The correlation coefficient can be any value within the range of +1 and -1. The value is zero indicates no relationship existing between variables. The relationship is considered positive if r value is between +1 and 0 which ultimately means that an increase in one variable might lead to an increase in the other variable (Obilor & Amadi, 2018). If r value is less than 0 then the relationship is negative, meaning that an increase in one variable leads to a decrease in the other variable. Nevertheless, a positive relationship does not always signify the relationship between variables; it means that the data points fall along the line of best fit (Sakwe, 2015). Therefore, the strength of the relationship can be determined by how close the Pearson correlation coefficient is to +1 or -1, depending on whether the existing relationship is positive or negative (Sakwe, 2015).

Ouellet-Proulx *et al.* (2016) used the Pearson correlation test in their study to determine the strongest correlation between suspended sediment concentration and lagged water level. The highest correlation, i.e., r = 0.37, was obtained between lagged water level and suspended sediment concentration for a time lag of 240 h (10 days). Ellison *et al* (2010) also used Pearson's correlation test which indicated strong positive relations between turbidity and suspended sediment concentration (r = 0.96) and between streamflow and turbidity (r = 0.71). In the study by Sakwe (2015), the Pearson correlation results indicated no correlation between the suspended sediment and nutrients, but on the other hand, high correlation was obtained between the fecal coliform and the suspended sediment loads in the investigated rivers. The Pearson correlation analysis was not utilized in the study because it always concludes that linear relationships exist between variables, which might not always be the case. This may lead to misinterpretation because a high degree of correlation from large values of the correlation coefficient may not automatically imply a high linear relationship amongst the two variables and it is time consuming and tedious to calculate.

3.12.2. Regression model

The regression analysis method is also one of the statistical techniques available to establish the relationship between variables. Nau (2014) defines regression analysis as "art and science of fitting straight lines to patterns of data and in a linear regression model; the dependent variable is predicted from independent variables using a linear equation" (Nau, 2014). The linear regression technique applies the mathematical equation, $y = mx + c$, in describing the line of best fit for the relationship between y (dependent variable) and x (explanatory variable) (Kumari and Yadav, 2018). The purpose of regression analysis is to show whether independent variables have a significant relationship with a dependent variable or show the relative strength of different independent variables' effects on a dependent variable (Mooi *et al.* 2018). With linear regression technique, the nature and strength of the relationship is defined by the least square regression (r^2) value, ranging from 0 to 1, with value close to 0 indicating the absence of the relationship, and value close to 1 signifying a strong relationship (Nau, 2014). The regression coefficient value and sign define the strength and direction of a relationship respectively.

Linear regression model can be used for the following reasons:

- It helps in the analysis of the strength of the relationship between dependent and predictor variables
- It can adjust for the effect of covariates and/or the confounders
- It enables estimation of the significant risk factors that may have impact on the dependent variable
- It also important in the analysis of the extent to which a change in the explanatory variable by one "unit" would affect the dependent variable
- Ultimately, it is also important in the quantification of the new cases.

The principal advantage of linear regression is its straightforwardness, explicability, scientific acceptance, and unlimited accessibility (Chambers & Dinsmore, 2014). The linear regression analysis was successfully utilized in a study conducted by Jamison (2018) whereby a linear regression was used to predict the suspended sediment load as a function of water discharge; the former is a dependent variable, and the latter is an independent variable. High correlation coefficient values between the suspended sediment and river water discharge were obtained in the study. It is against this background that the current study views the linear regression techniques feasible in the validation of remote sensing derived suspended sediments with the field measured suspended sediment.

The subsequent chapter (Chapter 4) provides detailed information pertaining to the methods and techniques applied to attain the purpose of the current study.

CHAPTER 4

RESEARCH METHODOLOGY

4.1. Introduction

This chapter provides the methods and techniques that were applied to achieve the purpose of the research. The remote sensing approach was employed to determine the spatial patterns of suspended sediment concentration. Satellite imagery, in the form of the Sentinel-2 imagery, was employed as the base from which suspended sediment concentration was detected and characterized. Field-based suspended sediment concentration data were collected to evaluate the performances of remotely sensed data in estimating suspended sediment concentration level in the study area. Empirical models were generated based on the significant relationship between spectral indices, band ratios and field data.

4.2. Data acquisition

The following datasets were acquired for the purpose of the study:

4.2.1. GIS data acquisition and pre-processing

The current study employed remotely sensed data, in the form of Sentinel-2 imagery. The imagery (with the ID: L1C_T35JQF_A026430_20220329T080204), acquired on 29 March 2022, was downloaded from United States Geological Survey (USGS) website (*https://earthexplorer.usgs.gov/*). The Sentinel-2 imagery was chosen for the current study because of its improved spatial resolution when compared with other cost-free satellite imagery, such as Land Remote-Sensing Satellite (LANDSAT) and MODIS sensors (Immitzer, Vuolo, and Atzberger, 2016), a 12-bits radiometric resolution, and its availability at no cost. Launched on 23 June 2015 (Copernicus, 2015), Sentinel-2A contains a MSI instrument that samples 13 spectral channels. Managed by European Space Agency (ESA), Sentinel-2 MSI sensor offers high-resolution optical imagery in three spatial resolutions including 10m in four visible-IR bands, 20 meter in its six (6) VIR-SWIR bands, 60 meter in its three (3) bands in NIR (Richter *et al.* 2011), providing reliable data source for suspended sediment concentration in coastal waters (Hansen *et al*. 2017). Table 4.1 provides the characteristics of the Sentinel-2 image.

Table 4.1: Characteristics of the Sentinel-2 data

Band	Wavelength centre (nm)	Resolution (m)
1 – Coastal aerosol	443	60
2 – Blue	490	10
3 – Green	560	10
4 – Red	665	10
5 – Vegetation red edge	705	20
6 – Vegetation red edge	740	20
7 – Vegetation red edge	783	20
8 – Near infrared	842	10
8A – Vegetation red edge	865	20
9 – Water vapour	940	60
10 – SWIR –Cirrus	1375	60
11 – SWIR	1610	20
12 – SWIR	2190	20

4.2.2. Field-based data

The field-based data collected for the purpose of this study to collect samples regarding the concentration level of suspended sediments. These surface samples provide an exceptional comparison with remote sensing optical properties, which serve as the representative of suspended sediment concentration. Fieldwork was conducted on the 29th March 2022, with a view to coincide with the Sentinel-2A satellite overpass. The field survey was also conducted in cloudless weather to obtain the concentration of suspended sediments that coincides with the cloudless satellite-based concentration of suspended sediments. The Garmin® eTrex 22x Handheld GPS was used to record the absolute locations on which the water samples were collected. A simple random sampling technique was employed to select the sites on which the water samples were obtained. The main reason for employing the random sampling method was based on its ability to remove human bias involved in the selection process (Sharma, 2017). Prior to collection of water samples, the sample-holding containers were rinsed twice with clean water to avoid the inclusion of dust in the samples. A total of fifty (50) water samples were collected for relationship establishment and performance evaluation of generated models.

4.3. Sentinel-2A MSI pre-processing

The Sentinel-2 MSI imagery for the study area was downloaded at Level-1C (L1C) products at Top of Atmosphere (TOA) and, by implication, was received having already been radiometrically and corrected. Moreover, the Sentinel-2 imagery was received having already been spatially referenced to the World Geodetic System of the year 1984 (WGS84), Universal Transverse Mercator, Zone 35 South. The L1C products of this sensor offer the top of atmosphere reflectance (ρTOA), in a supposition of being the total of Rayleigh reflectance (ρr), aerosol reflectance (ρa) and water- leaving reflectance (ρw):

$$\rho_{TOA} = \rho_r + \rho_a + t * \rho_w \qquad (1)$$

Where:

t denotes the two-way diffuse atmospheric transmittance (Gordon *et al.* 1994). In this case, the atmospheric effects on satellite imagery is assessed using the 6S radiative transfer code for each Sentinel-2 spectral band, while the diffuse atmospheric transmittance (*t*) was also derived (Vermote *et al.* 1997). This code is primarily responsible for automatically correcting atmospheric effects of satellite data.

4.4. Derivation of spectral indices

Three (3) different spectral indices were generated to retrieve concentration levels of suspended sediments in the study area. The remote sensing-based indices were considered in the current study due to their simplicity and ease of computation (Fang, Liang, and Kuusk, 2003). The three spectral indices generated for this study were as follows:

4.4.1. Normalized Difference Turbidity Index (NDTI)

The NDTI was derived from the Sentinel-2 imagery for the retrieval of the suspended sediment patterns by subtracting the red band from the green band and then normalized by dividing with the sum of red and green bands, based on Equation (2) according to Lacaux *et al* (2007)**:**

$$NDTI = \frac{R - G}{R + G} \qquad (2)$$

Where:

Red is the radiation reflected in the red channel of electromagnetic spectrum, and

Green denotes the radiation reflected in the green channel of spectrum

This spectral index is commonly employed as a surrogate for suspended sediments (Daiman, Gupta, and Dubey, 2018). This spectral index allows detection of turbidity, which is important for understanding volume of suspended sediments (Cole *et al.* 2015).

4.4.2. The Normalized Difference Suspended Sediment Index (NDSSI)

The NDSSI was also derived using blue and near infrared bands of the Sentinel-2 imagery based on Equation (3) according to Hossain, Jia, and Chao (2010), by subtracting the blue band from the near infrared band and then normalizing the index by dividing the total with the sum of blue and near infrared bands:

$$NDSSI = \frac{B - NIR}{B + NIR} \tag{3}$$

Where:

Blue is the radiation reflected in the blue channel of electromagnetic spectrum, and
NIR denotes the radiation reflected in the near-infrared channel of spectrum

The near infrared band in the NDSSI due to its high sensitivity to suspended sediments (Pavelsky and Smith, 2009). This spectral index has a potential to estimate the spatial distribution of suspended sediment concentration.

4.4.3. The Normalized Suspended Material Index (NSMI)

The NSMI was developed on the supposition that water has peak reflectance in the blue region of the spectrum and that the occurrence of suspended material increases reflectance in the visible region of spectrum, including the green and red bands where clear water tends to absorb (Chelotti *et al.* 2019). The NSMI index was adopted from Montalvo (2010) because it showed potential to estimate and map the suspended sediment concentration. The equation for NSMI was generated by adding the red band to the green band and then subtracting from the blue band and then dividing the result by the sum of the red, green and blue bands to normalize the results by dividing the total with the sum of red, green and blue bands. NSMI was calculated using Equation (4).

$$NSMI = \frac{R + G - B}{R + G + B} \tag{4}$$

Where:

Red is the radiation reflected in the red channel of electromagnetic spectrum,
Green denotes the radiation reflected in the green channel of spectrum, and
Blue is the radiation reflected in the blue channel of spectrum

The spectral indices produce values that range from -1 to +1, whereby -1 to -0.4 signifies lower levels of suspended sediments that correspond to clear water. The range of -0.3 to 0.3 signifies medium levels of suspended sediment concentration. Any value between 0.4 and +1 signifies high levels of suspended sediment concentration.

4.5. Generation of remote sensing band ratios

Five different band ratios were explored in the current study to estimate suspended sediment concentration. The band ratios were considered due to their ability to provide distinctive information and subtle spectral-reflectance or color variations between surface materials that are commonly hard to identify in an ordinary image (Twumasi, 2019). Using the Sentinel-2 imagery, the concentration level of suspended sediments was estimated using the following band ratios (Equation 5 to Equation 9) as proposed by Pham *et al.* (2018) and Peterson *et al.* (2018).

$$\frac{B_4}{B_3 + B_8} \tag{5}$$

$$\frac{B_8}{B_3} \tag{6}$$

$$B_2 \ast \frac{B_3 + B_4}{B_2} \tag{7}$$

$$\frac{B_4 + B_8}{B_3} \tag{8}$$

$$\frac{B_3 + B_8}{B_2} \tag{9}$$

Where:

B_2 is the blue channel of electromagnetic spectrum,

B_3 is the green channel of electromagnetic spectrum,

B_4 is the red channel of electromagnetic spectrum, and

B_8 is the near-infrared channel of spectrum

The used band ratios were adopted from these two studies under possible supposition that in the near infrared and visible channels of electromagnetic spectrum, concentration level of suspended sediments increases the reflectance of the water surface (Li *et al.* 2003; Pavelsky and Smith, 2009; Vargas Cuervo, 2017; Yepez *et al.* 2018). The band ratios used in the study were adopted because several studies have indicated that the first four bands of Landsat are well correlated with total suspended matter (Li *et al.* 2003; Pavelsky and Smith, 2009; Vargas-Cuervo, 2017; Yepez *et al.* 2018).

4.6. Laboratory determination of suspended sediment concentration level

The water samples were taken to the laboratory to determine the concentration of suspended sediment. Each water sample was filtered, dried and then the filtrate was measured. The samples were filtered through 0.45-*nanometre* paper filters and pre-weighed after drying at 105ºC for the period of 1 hour and 30 minutes. After water filtration, the filtrate was dried and weighed again to determine the concentration of suspended sediment concentration. The two values were then averaged to get the value of suspended sediment concentration. The concentration of the suspended sediment was acquired by dividing the difference in weight before and after filtering by the water sample volume, expressed by Equation (10):

$$SS = \frac{(A - B)}{V} \qquad (10)$$

Where:

SS denotes suspended sediment concentration,

A denotes mass of filter and dried residue (mg),

B denotes mass of filter (tare weight) (mg), and

V denotes volume of water sample filtered (L).

4.7. Establishing the relationship between satellite and field based suspended sediment concentration

Suspended sediment concentration level estimated by the remote sensing-based band ratios and indices. Of the total surveyed points, 60% (30 samples) were used for model calibration, while 40% (20 samples) were used for model performance evaluation. The collected field-based points, containing information pertaining to suspended sediment concentration, were superimposed on the concentration level of the suspended sediment map, resulting from the models employed in the study in the ArcGIS environment. The pixel values on which the points were overlain were then extracted and used in the correlation of the concentration of suspended sediment as determined by the employed remote sensing algorithms and suspended sediment concentration as measured in the field. Linear regression was applied to establish the relationship between spectral indices values, band ratio values and field measured suspended sediment concentration values. A linear regression analysis Equation (11) was adopted from the study of (Nau, 2014) because it is simple to execute, explicate and efficient to train (Hope, 2020).

$$Y = ax + b \tag{11}$$

Where:

Y is the predicted variable (suspended sediment concentration),

a is the Y intercept,

x is the explanatory variable (spectral indices and band ratios in the case of the current study), and

b is the slope.

The correlation analysis between NSMI values and suspended sediment concentration field data was implemented. The calibrated models were applied to estimate the suspended sediment concentration values of the validation dataset. The coefficient of determination (R^2), Bias, and RMSE between the measured data and estimated values were calculated to assess the fitting and validation accuracy. Four models with better fitting and validation accuracies were selected for further analysis.

The subsequent chapter presents the results obtained through the applications of methods and techniques outlined in the current chapter.

CHAPTER 5

RESULTS

5.1. Introduction

This chapter provides the research findings that were obtained through applications of the methods and techniques described in chapter 4. The findings represented in the chapter are in line with the research aim and objectives of the current study. The concentration level of suspended sediments was estimated from different remote sensing band ratios and indices. The band ratios and indices are represented in the form of thematic maps and are a surrogate for the concentration level of suspended sediments in the estuary. The relationship between the field-based suspended sediment concentration level and the remote sensing based suspended sediment concentration estimates was determined with the linear regression analysis. The actual suspended sediment concentration level was modeled based on the remote sensing indices and band ratios that reflected strong relationship with field-based suspended sediment concentration level.

5.2. Retrieval of suspended sediment from imagery

The retrieval of suspended sediment features in the study area was achieved as follows:

Several spectral indices and band ratios related to suspended sediment concentration estimates were generated in this study. The remote sensing spectral indices and band ratios were explored as follows:

5.2.1. Spectral indices related to suspended sediment

The results from the use of several spectral indices, derived from Sentinel 2 imagery to detect the spatial pattern in suspended sediment concentration are presented in figure 5.1.

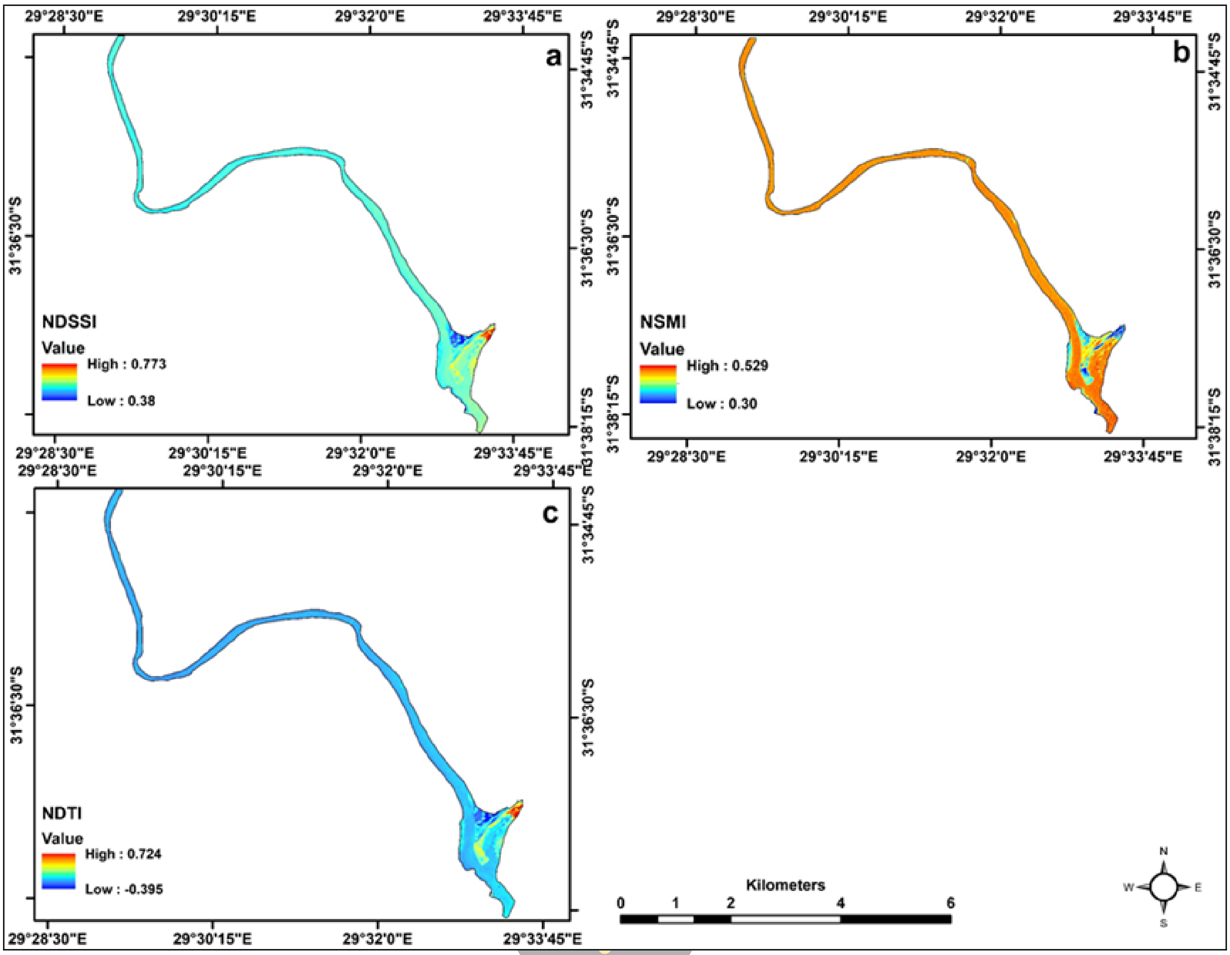

Figure 5.1: Spectral indices for suspended sediment estimated from Umzimvubu Estuary, South Africa.

The NDSSI, NSMI and NDTI images portrayed suspended sediment concentration in the study area by values that ranged from 0.38 to 0.773, 0.3 to 0.529 and -0.395 to 0.724, respectively. From Figure 5.1.a, the high values of NDSSI were noted to dominate the estuary, with moderate and higher values being observed in the lower part of the estuary. Through visual interpretation, it was also apparent that the high NSMI values were dominant in a large part of the study area, with lower NSMI values dominating some sections of the river mouth (Figure 5.1.b). On the other hand, low suspended sediments were noted to dominate the study area as predicted by NDTI (Figure 5.1.c). However, moderate and high NDTI values were noted in the river mouth.

5.2.2. Band ratios related to suspended sediment

The results from the use of several remote sensing band ratios derived from Sentinel 2 imagery to detect the spatial pattern in suspended sediment concentration are presented in figure 5.2.

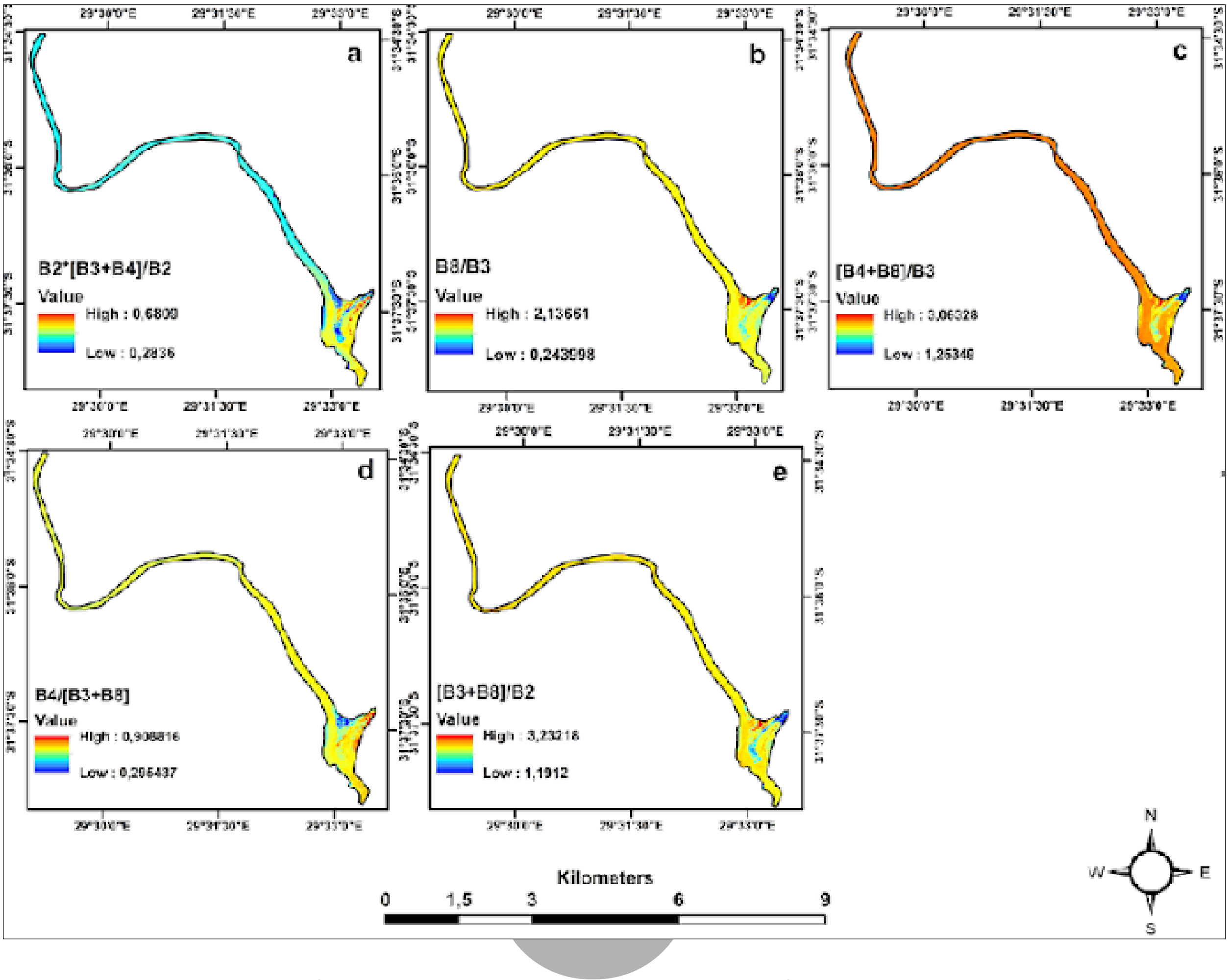

Figure 5.2: Band ratios for suspended sediment estimation of Umzimvubu Estuary in South Africa

The generated band ratio images for B_2*[B_3+B_4]/B_2 had values of suspended sediment concentration that ranged from 0.284 to 0.681, which was similar to B_8÷B_3 and B_4/[B_3+B_8] with the suspended sediment concentration values that ranged from 0.244 to 2.317 and 0.295 to 0.909, respectively. By contrast [B_4+B_8]/B_3 and [B_3+B_8]/B_2 showed higher suspended sediment concentrations that ranged from 1.254 to 3.06 and 1.19 to 3.232, respectively. Through visual interpretation of B_2*[B_3+B_4]/B_2, moderate and high values were dominant in the river mouth, with low values dominating the remaining part of the study area (Figure 5.2a). By contrast moderate values of B_8÷B_3 were noted in the larger part of the estuary (Figure 5.2b), high values were noted to be dominant as portrayed by [B_4+B_8]/B_3 (Figure 5.2c). Similarly, the moderate values of B_4/[B_3+B_8], and [B_3+B_8]/B_2 band ratio images were also noted to characterize a large part of the study area (Figure 5.2d and Figure 5.2e).

5.3. Field-based determination of suspended sediment concentration level

The distribution of field-based suspended sediment concentration was examined in the field. The null hypothesis formulated states that there is no significant variation in the spatial distribution of field-based suspended sediment concentration across the surveyed sites. Table 5.1 provides the results of Levene's homogeneity test results for field-based suspended sediment concentration.

Table 5.1: Results of Levene's k-comparison test

	Field-based SSC
F	14.219
DF1	1
DF2	48
p-value (one-tailed)	0.016
Significance alpha	0.05

The results from this study showed that the distribution of suspended sediment concentration level significantly differed across the surveyed sites [F = 14.219, P < 0.016] (Table 5.1).

Spatial modeling of suspended sediment concentration based on spectral indices

In this study, spatial modeling of suspended sediment concentration level based on the spectral indices was carried out as follows:

5.3.1. Relating spectral indices and field-based suspended sediment concentration

In this study, it was hypothesized that the spectral indices can provide invaluable information pertaining to the concentration level of suspended sediments in the study area. The hypothesis was tested by relating the Sentinel-2 based spectral indices values to the field-based suspended sediments concentration. Figure 5.3 shows the nature of the relationship between field-based suspended sediment concentration and the values of spectral indices. Using 60% of the field-based data, a linear regression analysis revealed a significant relationship between field-based suspended sediment with NDSSI (Figure 5.3a) and NSMI (Figure 5.3b), with the least square regression (r^2) values of 0.62 and 0.86 respectively. However, linear regression analysis also revealed an insignificant relationship between field-based suspended sediment concentration level and NDTI values (Figure 5.3c), with the least square regression value of 0.48.

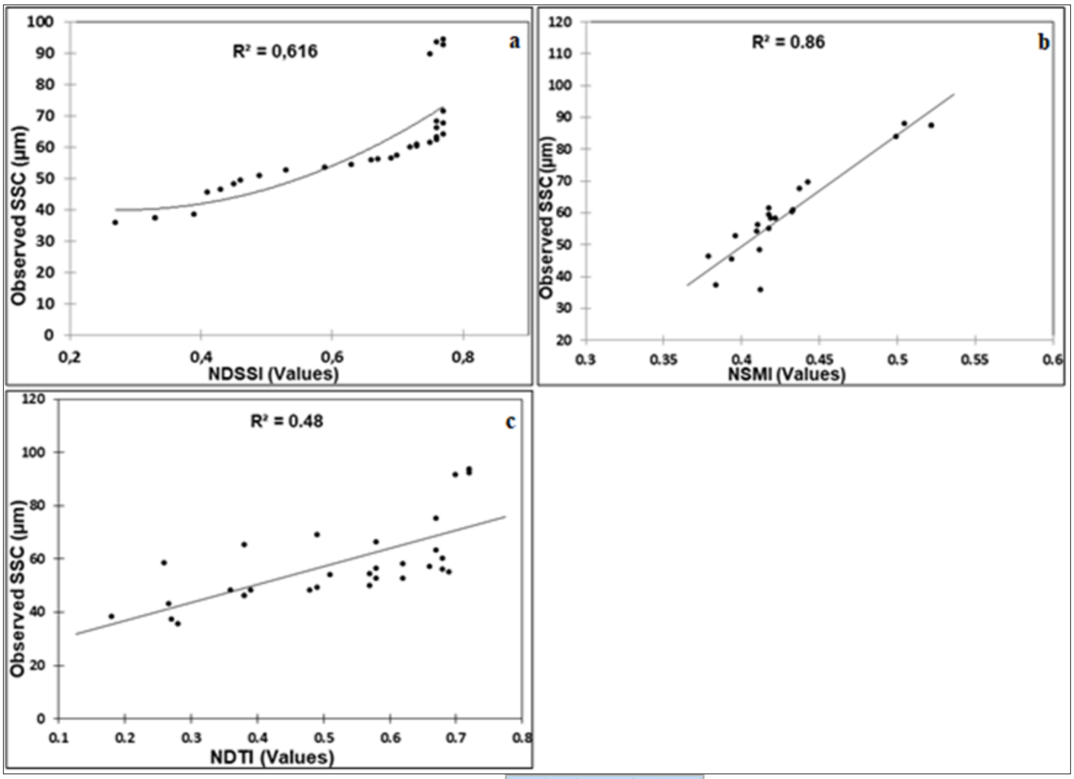

Figure 5.3: Scatterplot graphs of the relationship between spectral indices and suspended sediment in Umzimvubu Estuary of South Africa.

5.3.2. Empirical model generation

Upon a successful establishment of the relationship between spectral indices and field-based suspended sediment, the empirical models generated from the linear regression analysis results were used to model spatial distribution of suspended sediment concentration based on their respective spectral indices. Table 5.2 presents parameters of the empirical models generated from the linear regression analysis of the relationship between spectral indices and field-based suspended sediment concentration.

Table 5.2: Parameters of empirical models for estimating suspended sediments from spectral indices in Umzimvubu Estuary of South Africa.

Spectral Index	r^2	Equation
NDSSI	0.62	y = 46.61x +32.62
NSMI	0.86	y = 932.75x - 329.94
NDTI	0.48	y = 68.03x + 23.18

Where x is the spectral index

5.3.3. Spatial modeling of suspended sediment concentration level based on spectral indices

The empirical models provided in Table 5.2 were subsequently applied to uncover the spatial patterns in the concentration level of suspended sediment in the study area. Figure 5.4 provides spatial patterns in suspended sediment concentration as modeled using NDSSI (a), NSMI (b) and NDTI (c).

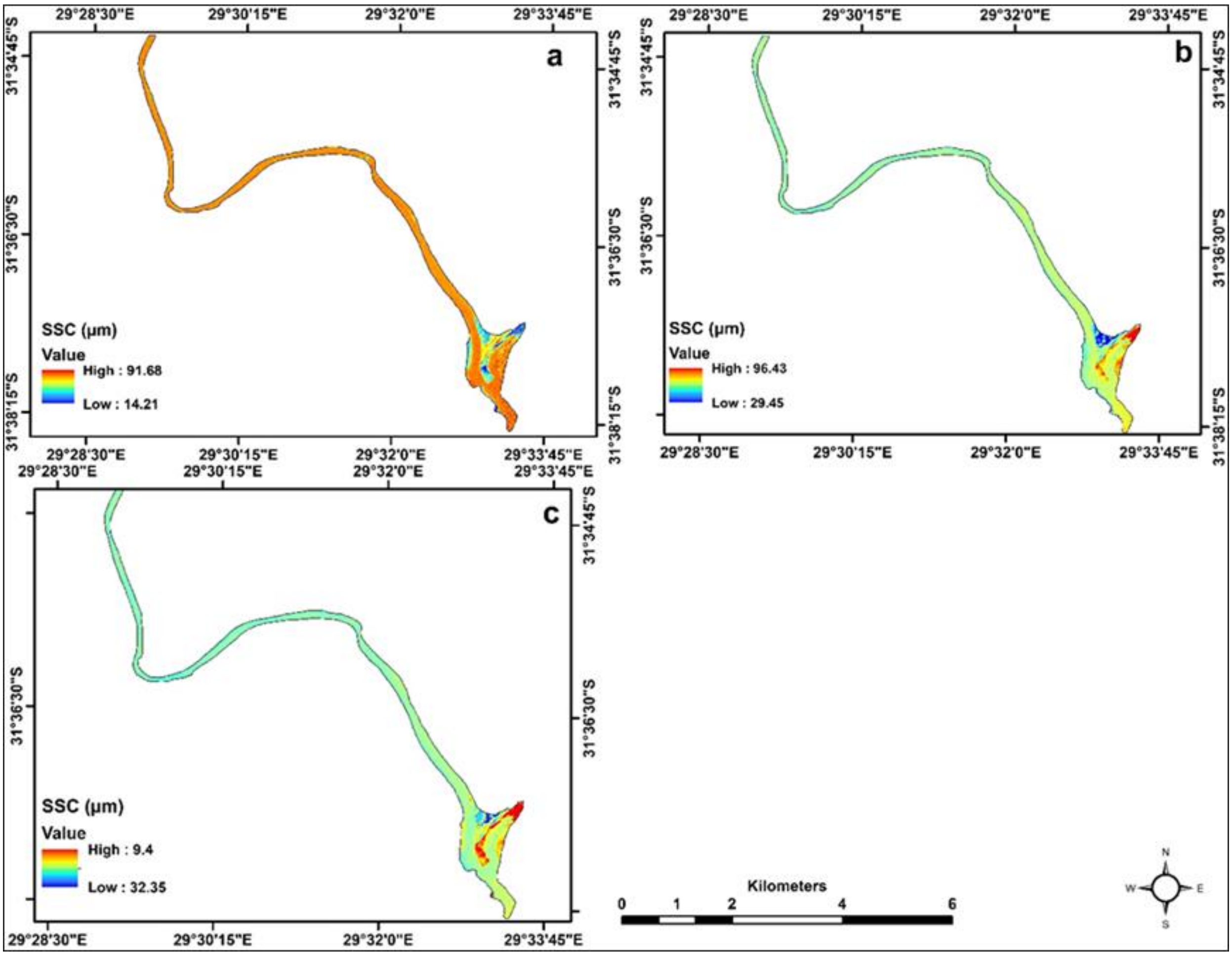

Figure 5.4: Spatial patterns in suspended sediment concentration based on spectral indices of Umzimvubu Estuary in South Africa.

5.3.4. Empirical model validation

The empirical models generated from the relationship of the field-based suspended sediment with NDSSI (Figure 5.5a), NSMI (Figure 5.5b) and NDTI (Figure 5.5c) yielded reasonably accurate estimates of suspended sediment concentration level in the study area. This was apparent from the least square regression values. The r^2 values for the NDSSI, NSMI and NDTI were observed to be 0.51, 0.71 and 0.57 respectively. Figure 5.5 provides the linear regression scatterplots for the validation of the performance of the empirical models in the current study.

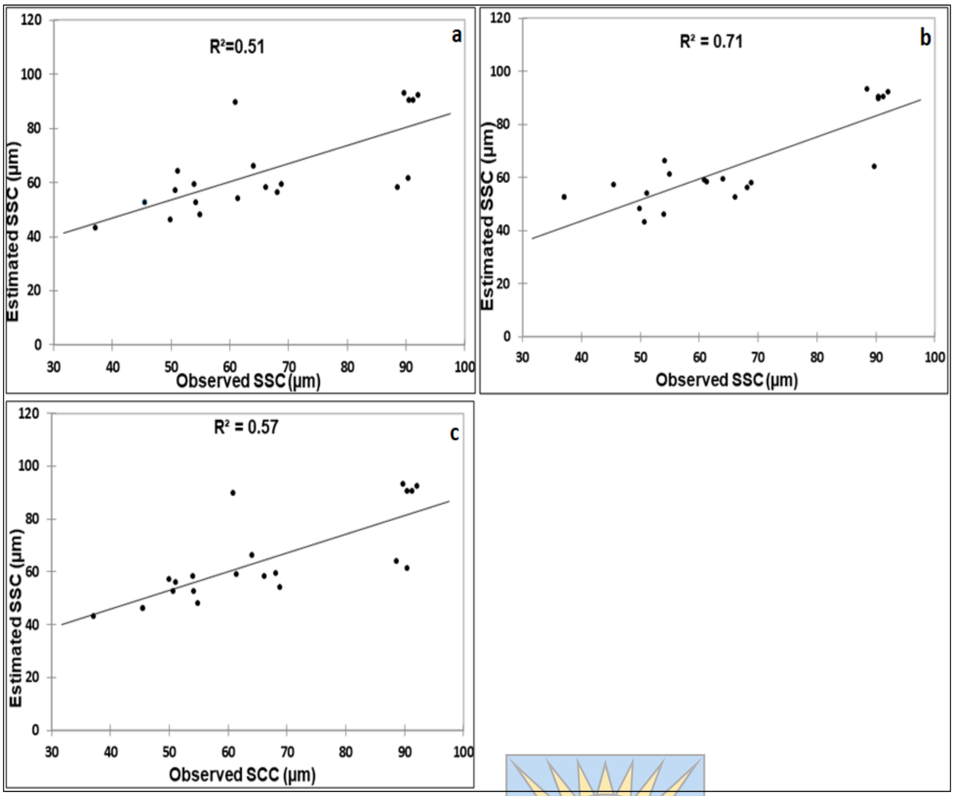

Figure 5.5: Linear regression results for empirical models' validation of Umzimvubu Estuary in South Africa.

5.4. Spatial modeling of suspended sediment concentration based on band ratios

In this study, spatial modeling of suspended sediment concentration level based on the band ratios was carried out as follows:

5.4.1. Relating band ratios and field-based suspended sediment concentration

In this study, it was also hypothesized that the bad ratios can provide invaluable information pertaining to the concentration level of suspended sediments in the study area. The hypothesis was tested by relating the Sentinel-2 based band ratio values to the field-based suspended sediments concentration. Figure 5.6 shows the nature and degree of relationship between field-based suspended sediment concentration and the values of spectral indices. Using 60% of the field-based data, a linear regression analysis revealed a significant relationship between field-based suspended sediment with $B_2*[B_3+B_4]/B_2$, $[B_4+B_8]/B_3$, $[B_3+B_8]/B_2$, with the least square regression (r^2) values of 0.86 (Figure 5.6a), 0.7 (Figure 5.6c) and 0.94 (Figure 5.6e) respectively.

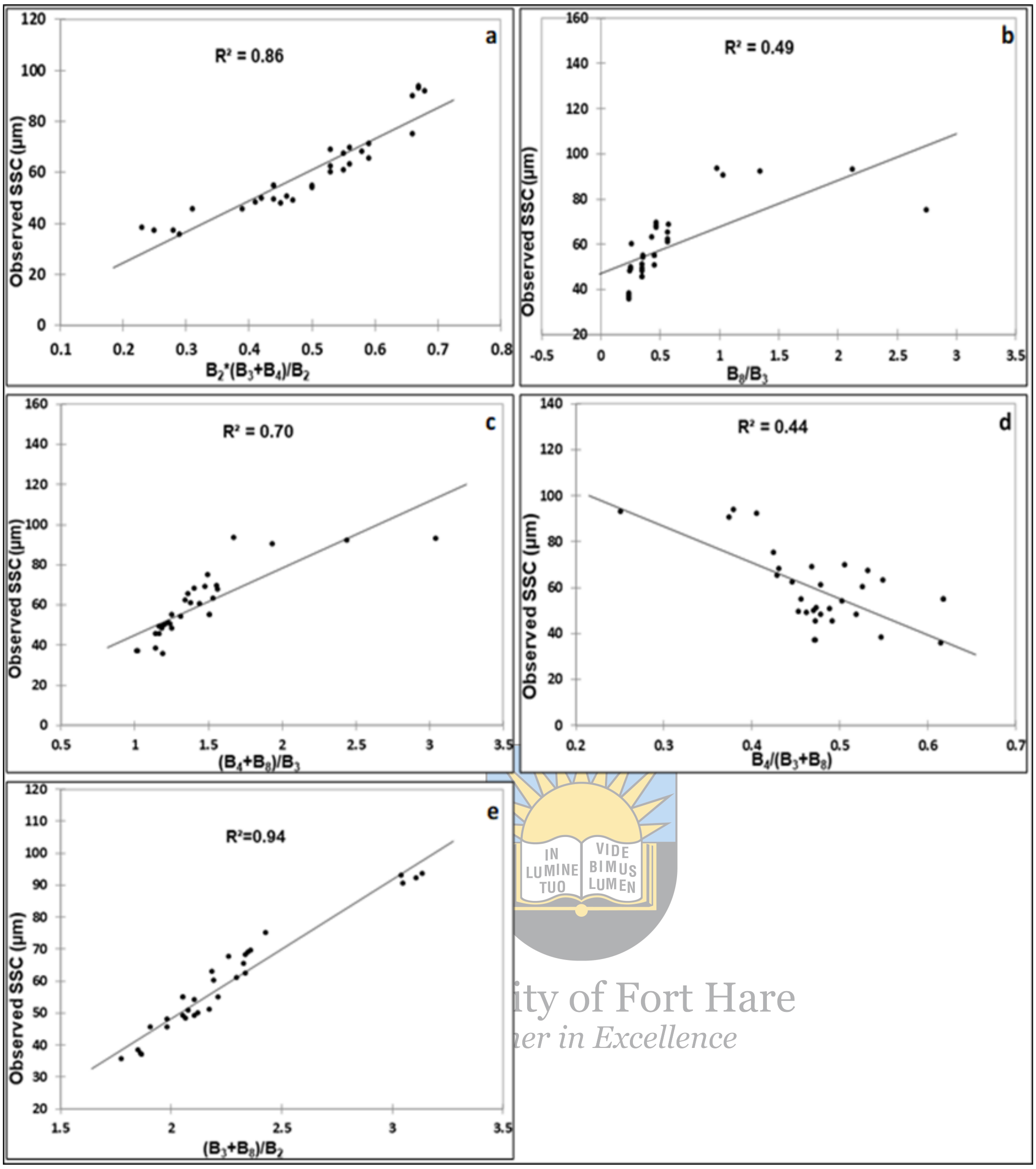

Figure 5.6: Scatterplot graphs of the relationship between band ratios and suspended sediment of Umzimvubu Estuary in South Africa.

However, linear regression analysis also revealed an insignificant relationship of field-based suspended sediment concentration level with $B_8 \div B_3$ and $B_4/[B_3+B_8]$, with r^2 values of 0.49 (Figure 5.6b) and 0.44 (Figure 5.6d) respectively.

5.4.2. Empirical model generation

Upon a successful establishment of the relationship between band ratios and field-based suspended sediment, the empirical models generated from the linear regression analysis results were used to model spatial distribution of suspended sediment concentration based on their respective band ratios. Table 5.3 provides the empirical models generated from the linear regression analysis results of the relationship between band ratios and field-based suspended sediment concentration.

Table 5.3: The established empirical models from band ratios

Band ratio	r^2	Equation
$[B_2*(B_3+B_4)]/B_2$	0.86	$y = 121.17x+0.41$
$B_8 \div B_3$	0.49	$y = 20.5x + 47.27$
$[B_4+B_8] \div B_3$	0.7	$y = 33.52x + 11.41$
$B_4 \div [B_3+B_8]$	0.44	$y = 157.09x + 133.67$
$[B_3+B_8] \div B_2$	0.94	$y = 43.55x – 38.85$

Where x is the band ratio

5.4.3. Spatial modeling of suspended sediment concentration level based on band ratios

The empirical models provided in Table 5.3 were subsequently applied to uncover the spatial patterns in the concentration level of suspended sediment in the study area. Figure 5.7 provide spatial patterns in suspended sediment concentration as modeled using $[B_2*(B_3+B_4)]/B_2$ (a), $B_8 \div B_3$ (b), $[B_4+B_8]/B_3$ (c), $B_4/[B_3+B_8]$ (d) and $[B_3+B_8]/B_2$ (e).

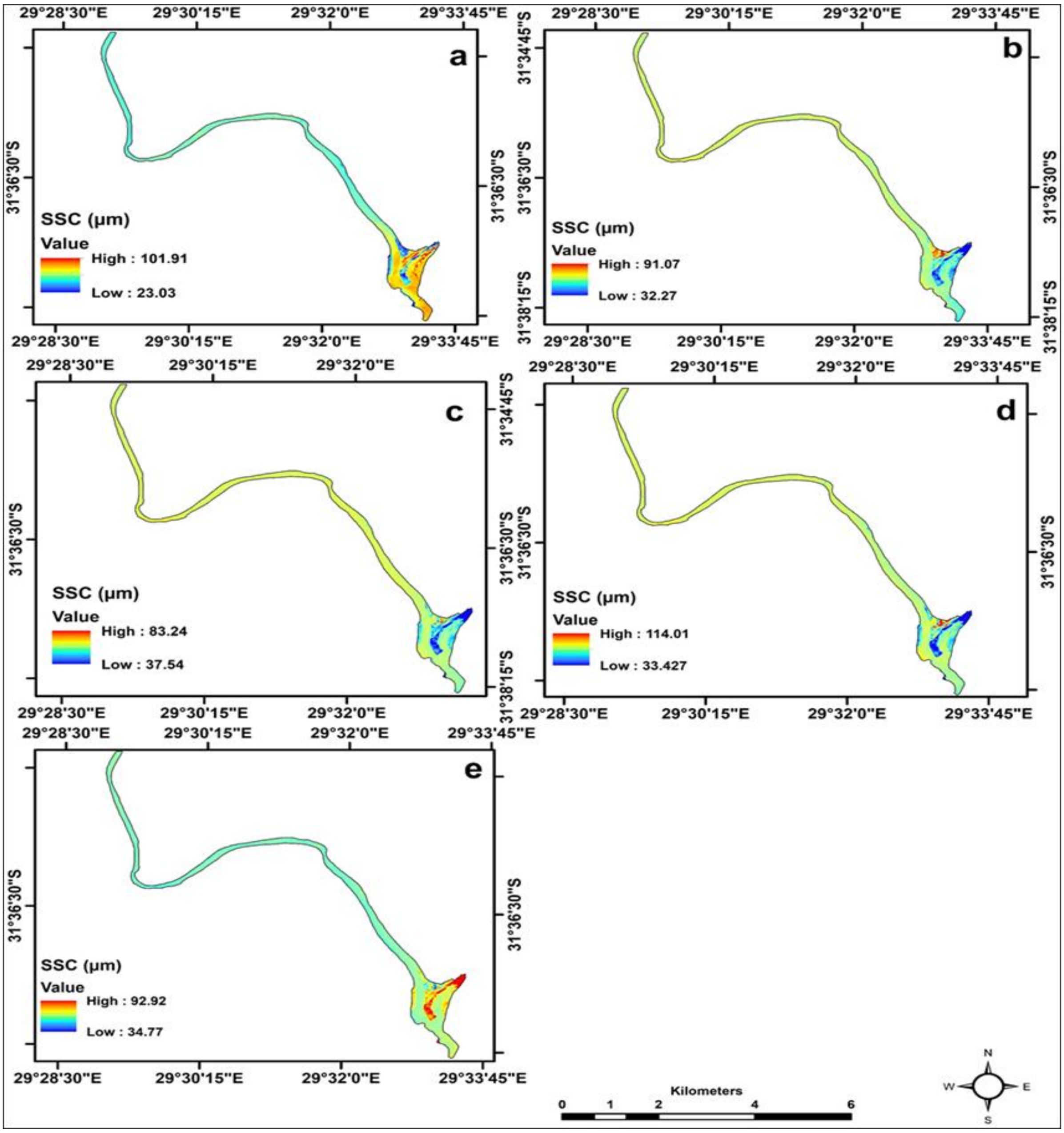

Figure 5.7: Spatial patterns in suspended sediment concentration based on band ratios of Umzimvubu Estuary in South Africa.

5.4.4. Empirical model validation

The empirical models generated from the relationship of field-based suspended sediment with $[B_2*(B_3+B_4)]/B_2$(Figure 5.8a), $[B_4+B_8]/B_3$ (Figure 5.8c) and $[B_3+B_8]/B_2$ (Figure 5.8e) yielded reasonably accurate estimates of suspended sediment concentration level in the study area. This was clear from the least square regression values. 2 r^2 values for the $[B_2*(B_3+B_4)]/B_2$ $[B_4+B_8]/B_3$ and$[B_3+B_8]/B_2$ were observed to be 0.64, 0.52 and 0.71 respectively. Figure 5.8 provides the linear regression scatterplots for the validation of the performance of the empirical models.

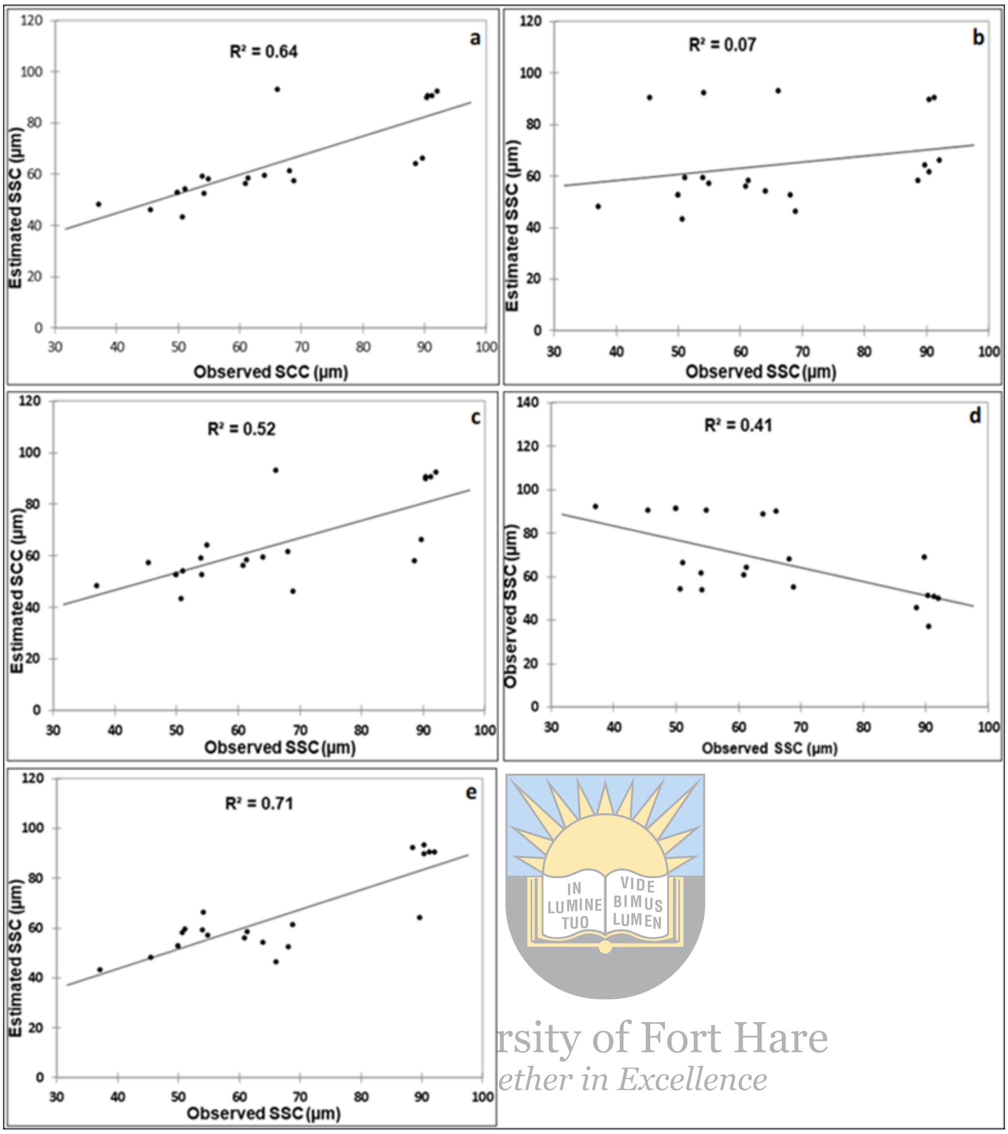

Figure 5.8: Linear regression results for empirical models' validation of Umzimvubu Estuary in South Africa.

However, the empirical models generated from the relationship of field-based suspended sediment with $B_8 \div B_3$ and $[B_3+B_8]/B_2$ yielded less accurate results, with r2 values of 0.07 and 0.41 respectively.

The subsequent chapter (Chapter 6) provides discussion of the results presented in this chapter.

CHAPTER 6

DISCUSSION AND CONCLUSION

6.1. Introduction

This chapter discusses the results that were presented in Chapter 5 using the methods and techniques described in Chapter 4. The results obtained in the current study are discussed against the findings by other studies. The current study was primarily aimed at Estimating estuarine suspended sediment concentration through spectral indices and band ratios derived from Sentinel-2 data. Therefore, the main aim was specifically achieved through:

- Quantification of the inherent optical properties of suspended sediment in estuarine waters through spectral indices and band ratios
- Development of empirical models to determine suspended sediment from Sentinel-2 data using the optical properties obtained from the first objective
- Validation of empirical models' performance using suspended sediment concentration data measured on field

The importance and reliability of remote sensing methods and techniques in estimating suspended sediment concentration level are discussed in this chapter. Recommendations emerging from the findings of this study regarding spatial assessment of suspended sediment concentration in the Umzimvubu Estuary are also made in this chapter. Limitations and challenges encountered during the course of this study are also presented in this chapter. Lastly, directions for future research are proposed and conclusions are drawn based on the results attained in this study.

6.2. Discussion

Several spectral indices and band ratios were generated and applied in the current study to estimate the suspended sediment concentration level. The current study demonstrated the reliability and efficacy of spectral indices and band ratios in estimating suspended sediment concentration level in the Umzimvubu Estuary. The remote sensing techniques facilitated a successful derivation of various spectral indices and band ratios for estimating suspended sediments. Baban (1993) also noted that the monitoring of water quality variables, such as suspended sediment, through remote sensing technology is time-efficient and provides an overall view of a water body condition. Moreover, field-based techniques also enabled the provision of data for evaluating the reliability of the spectral indices and band ratios. However, field-based techniques for retrieving suspended sediment concentration are not suitable for comprehensively understanding spatial patterns in suspended sediments (Sa'ad *et al.* 2021), especially in large water bodies. Therefore, when integrated into remote sensing spectral indices and band ratios, they have proven to be capable of estimating the concentration of suspended sediments in the study area. The derived values from the band ratios and spectral indices were just a proxy for suspended sediments in the estuary, instead of the actual concentration of suspended sediments (Montalvo, 2010). Kapalanga *et al.* (2021) noted that regression algorithms are the most suitable modeling techniques for predicting water quality indicators from remote sensing data. The study subsequently employed the generated empirical models to map spatial patterns in water quality variables in the dam. The study found a significant relationship between field-based suspended sediment, spectral indices and band ratios generated from the Sentinel-2 imagery.

6.2.1. Evaluation of spectral indices for estimating suspended sediment

Furthermore, the NDSSI, NDTI and NSMI were explored in the study in order to evaluate their efficacy and reliability in estimating the concentration of suspended sediments. The relationship established between the NSMI and the field-based suspended sediment using linear regression showed a significant relationship. These findings are in agreement with Arisanty and Saputra (2017), who noted a strong relationship between NSMI and field-based suspended sediment, with the r^2 value of 0.7. Although Bid and Siddique (2019) noted a strong relationship between the NDTI values and total suspended sediments concentration, with an r2 value of 0.9, the current study noted an insignificant relationship. The linear regression analysis results between field data and the NDSSI also revealed a strong relationship in the study area. These findings agreed with Shahzad *et al* (2018) who noted the strong relationship between the NDSSI and suspended sediment concentration, explained by r^2 value of 0.88. By implication, the NDSSI and the NSMI are capable of estimating spatial patterns in suspended sediment concentration in the study area. However, the NDTI was observed to be less efficient in estimating the suspended sediment concentration level in the study area. The NMSI and NDSSI performed well because the equation has two principles, stating that the peak reflectance in the blues range of the visible spectrum is contained in water, and reflectance through the visible spectrum can be increased by the presence of suspended sediments.

6.2.2. Evaluation of band ratios for estimating suspended sediment

Furthermore, the $[B_2*(B_3+B_4)]/B_2$, $[B_4+B_8]/B_3$, $[B_3+B_8]/B_2$, $B_8 \div B_3$ and $B_4/[B_3+B_4]$ were also explored in the study in order to evaluate their efficacy and reliability in estimating the concentration of suspended sediments. The results of the current study revealed a significant relationship between field-measured suspended sediment concentration with $[B_4+B_8]/B_3$. These results are in keeping with the study by Pham *et al.* (2018) who noted the r^2 value of 0.76 from the relationship between field measured suspended sediment concentration and this band ratio. Although Pham *et al.* (2018) noted the insignificant relationship of $[B_3+B_8]/B_2$ with field-based suspended sediment data, the current study found a significant relationship, with r^2 value of 0.94. This finding is in line with the study by Doxaran *et al* (2002) who noted strong correlation between the near-infrared and green band ratio of ($r^2 = 0.91$). The results also revealed insignificant relationships for field data with $B_4/[B_3+B_8]$ and B_8/B_3 band ratios. These results are also in keeping with the study by Pham *et al.* (2018) who also noted the weak and moderate relationship between these band ratios and field based suspended sediment concentration. By implications, $[B_2*(B_3+B_4)]/B_2$, $[B_4+B_8]/B_3$ and $[B_3+B_8]/B_2$ band ratios also proved to be capable of estimating suspended sediment concentration level, compared to $B_8 \div B_3$ and $B_4/[B_3+B_4]$ that were noted to be less efficient in estimating suspended sediment concentration level.

6.3. Conclusion

The current study has demonstrated the importance of employing Sentinel-2 sensor in estimating suspended sediment concentration in the study area. This was achieved through the evaluation of in-situ data relationships with the remote sensing spectral indices and band ratios. The reliability of the remotely sensed spectral indices and band ratios to estimate suspended sediments in a South African estuary was evaluated using least square regression. The relationship between the in-situ data and reflectance behavior of Sentinel-2 spectral channels revealed significant relationships. The linear regression analysis results between the in-situ data and spectral indices and band ratios revealed the response of the suspended sediment concentration to NDSSI and the NSMI spectral indices, and $[B_2*(B_3+B_4)]/B_2$, $[B_4+B_8]/B_3$ and $[B_3+B_8]/B_2$ band ratios. By implication, these spectral indices and band ratios are recommended for estimating spatial patterns in the suspended sediment concentration in the study area.

6.4. Limitations of the study

The following limitations were identified during the process of carrying out this study:

- The accuracy of the results could have improved if a high spatial resolution imagery was employed. However, the study resorted to the medium resolution Sentinel-2 data due to its availability at no cost.
- The acquired estuarine boundary shapefile of the study area might have slightly extended beyond the area covered with water. This might have played a role in the inclusion of pixels containing exposed soils in the riverbank as sediment.

6.5. Recommendations

Based on the results, the current study demonstrated the ability of remote sensing techniques in estimating and monitoring the suspended sediment concentration level in the Umzimvubu Estuary. However, the following recommendations are brought forward with regard to the applications of remote sensing techniques in the estimation of the suspended sediment concentration level in the study area:

- It is recommended that the estuarine managers and environmental specialists consider the inclusion of remote sensing techniques in a regular monitoring of suspended sediment concentration and the implications for biodiversity.
- It is also recommended that future research on sediment monitoring must include remote sensing indices and band ratios because they present a feasible way of understanding patterns in suspended sediment concentration.
- The government should consider implementation of a database to archive in situ data on the patterns in suspended sediments in the study area to ensure availability of historical data that could serve to predict future trends.

6.6. Direction for future research

The following directions for future studies arose from the findings of the current study:

- The application of the high spatial resolution data such as WorldView-2 or UAV imagery to account for small variations in suspended sediment concentration. This is because a variation in sediment concentration occurring within 30 meters distance may not be visible using the sensor used in this study.
- Seasonal assessment of suspended sediment be carried out in order to understand the implications thereof. This will help to understand these patterns influence seasonal estuarine ecosystem function.

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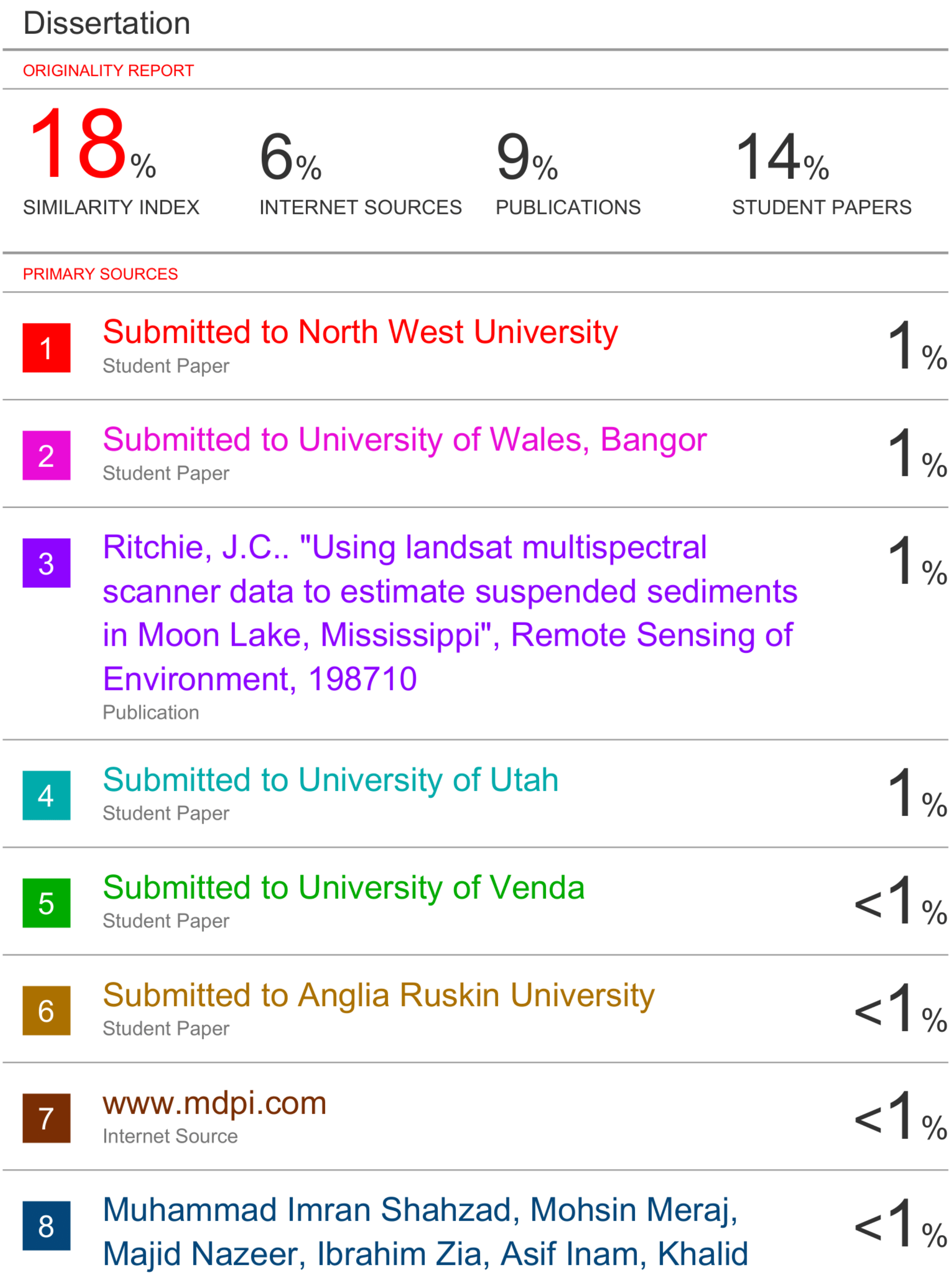
Appendix A: Turnitin Report



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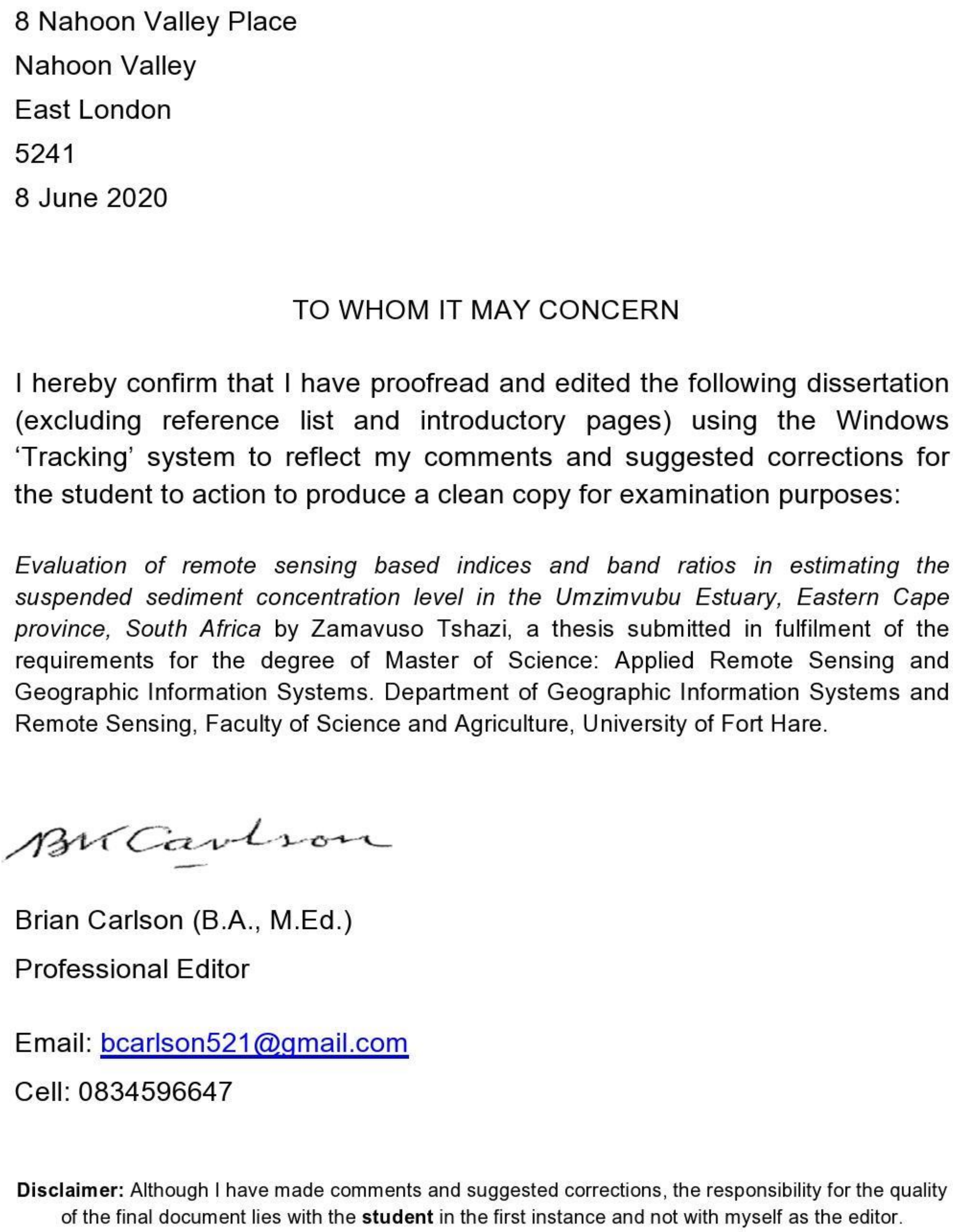
Appendix B: Confirmation letter of language editing



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I hereby confirm that I have proofread and edited the following dissertation (excluding reference list and introductory pages) using the Windows 'Tracking' system to reflect my comments and suggested corrections for the student to action to produce a clean copy for examination purposes:

Evaluation of remote sensing based indices and band ratios in estimating the suspended sediment concentration level in the Umzimvubu Estuary, Eastern Cape province, South Africa by Zamavuso Tshazi, a thesis submitted in fulfilment of the requirements for the degree of Master of Science: Applied Remote Sensing and Geographic Information Systems. Department of Geographic Information Systems and Remote Sensing, Faculty of Science and Agriculture, University of Fort Hare.

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