Land Use Change in The Knysna River Catchment and Its Impacts on the Geomorphological Characteristics of the Estuary between 1984 and 2019

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ABBREVIATIONS AND ACRONYMS

AD	: Anno Domini – (Latin for *In the year of the lord*)
API	: Application Programming Interface
CART	: Communication Access Real Time
CBD	: Central Business District
CFMASK	: C Function of Mask
CSIR	: Centre of Scientific and Industrial Research
CTZ	: Critical Transition Zones
CZS	: Critical Zones
DEA	: Department of Environmental Affairs
DWAF	: Department of Water Affairs and Forestry
DWS	: Department of Water and Sanitation
E.coli	: *Escherichia coli*
ESRI	: Environmental System Research Institute
GEE	: Google Earth Engine
GIS	: Geographical Information Systems
IPCC	: Intergovernmental Panel on Climate Change
Km	: Kilometres
LANDSAT	: Land Remote Sensing Satellite (System)
LULC	: Land Use\ Land Cover
m^2	: Meters Square
MLC	: Maximum Likelihood Classification
N2	: National Road 2
NASA	: National Aeronautics and Space Administration
NDVI	: Normal Differential Vegetation Index
NGI	: National Geo- Spatial Information
NIR	: Near infrared
RF	: Random Forest
ROI	: Region of interest
RSA	: Republic of South Africa
SANBI	: South Africa National Biodiversity Institute
SANparks	: South Africa National Parks
SANSA	: South Africa National Space Agency
SAWS	: South Africa Weather Services

SLR	: Sea Level Rise
SR	: Surface Reflectance
SVM	: Support Vector Machines
SWIR	: Short Wave Infrared
TIR	: Thermal Infrared
TOA	: Top of the Atmosphere
UAV	: Unmanned Aerial Vehicles
USA	: United States of America
USGS	: United States Geological Survey
VAR	: Variable
VNIR	: Visible Near Infrared

SOURCES OF DATA

DIVA GIS	: Shapefiles
BGIS	: Biodiversity
SANBI	: Biodiversity
DWS	: Shapefiles
NASA	: Shapefiles and Data
GEOGLAM RAPP	: Vegetation Classes
Geospatial Ecology and Remote sensing	: Coding Data
Google Earth Engine	: Supervised Classification
Google Earth	: Aerial Photography
NGI	: Aerial Photography
SANBI	: Vegetation Classes
USGS Explorer	: LANDSAT images

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Kappa Coefficient (Cited in Harris Geospatial solutions, 2017)

$$\kappa = \frac{N\sum_{i=1}^{n} m_{i,i} - \sum_{i=1}^{n}(G_i\,C_i)}{N^2 - \sum_{i=1}^{n}(G_i\,C_i)}$$

- **i** is the class number
- **N** is the total number of classified values compared to truth values
- $\mathbf{M_{ii}}$ is the number of values belonging to the truth class I that have also been classified as class **i** (values found along the diagonal of the confusion matrix)
- $\mathbf{C_i}$ is the total number predicted values belonging to class **i**
- $\mathbf{G_i}$is the total number of truth values belonging to class **i**

Normalized Difference Vegetation Index (Cited on USGS (https://www.usgs.gov))

$$NDVI = \frac{\text{NIR} - \text{Red}}{\text{NIR} + \text{Red}}$$

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“There is no beauty better than intellect” – Prophet Muhammed (PBUH)

ABSTRACT

The Knysna catchment and estuary are recognized in South Africa for their conservation significance as a sanctuary for marine species and biodiversity alike. The economy of the area which is dependent on tourism of the Knysna Estuary and catchment. The services obtained from the ecosystem include integral biodiversity value and is of significant importance for residents and tourists. Land use and land use cover dynamics remain some of the most crucial and obvious changes that has happened in the Knysna Estuary and catchment. Such changes severely affect ecosystems health, catchment areas, estuaries and the degradation of nature reserves. A 'cloud-based platform for scientific analysis and visualization of geospatial datasets.' (Liu et al., 2020) method namely Google Earth Engine (GEE) is applied utilizing multi-temporal satellite imagery and Sentinel as interpretation to understand land use change over 35 years. A timeseries associated with land use changes and biodiversity loss were considered between the years 1984 and 2019.

Additionally, Normalized Difference Vegetation Index (NDVI) and Supervised classification were performed using GEE software and Arc Geographical information systems (GIS) to identify land cover dynamics. The images are classified into three major land use classes, waterbodies, urban areas and vegetation. Vegetation is further classified into various classes namely fynbos, thicket, plantation forestry, salt marsh and agriculture. An accuracy assessment together with ground truthing, were conducted to verify and assess the overall classification accuracy of the results. The results indicated that over the study period urban growth and cultivated land makes up the most common land use category to have impacted the Knysna Estuary. Urban areas have increased significantly in reaction to the rapid increase in population ranging from 2.5% - 2.8% during the years 1984-1992, which reached to 2.9% - 4.1% during the years 1993-2007, and finally augmented to 4.3% to 6.3% during the years 2008-2019. The major reason behind the altering in the land use and geomorphology based on the research of the Knysna Estuary is human activities that have led to key determinantal impacts on surface runoff and land degradation. Overall, the noticeable changes in surface runoff and land degradation are strongly related to land use/land cover changes brought about by human impacts.

Keywords: Land use/cover change; Arc GIS; Google Earth Engine; satellite image, Sentinel, NDVI, supervised classification, accuracy assessment

Chapter 1

1. INTRODUCTION AND RATIONALE

1.1. GENERAL BACKGROUND

For millennia people have appreciated coastal environments for their access to the ocean, their rich soils and harvestable food resources. From the stone age to the present, cities and ports have flourished at the coast and this value continues even today. Coastal cities have higher rates of population growth than other areas (Koch *et al.*, 2009). The rapidly growing population is inducing major stresses on the local and regional environment and resources base. Coastal and estuarine ecosystems are particularly vulnerable and are highly threatened by increasing land use pressures. In the time of increasing anthropogenetic disturbance that has presumably seen the dawn of a brand new geologic epoch - the Anthropocene - world environmental modification has effects that are increasing in magnitude, with estuarine and coastal ecosystems being among the foremost peril of all natural systems where the entire physical, chemical and biological processes are impacted (Adyasari *et al*., 2021).

In fact, according to Petersen *et al*., (2017), all the impacts on rivers and their catchments (including land cover changes that affects their productivity, ecological functioning and biodiversity) are ultimately received by estuarine ecosystems. Coastal ecosystems, in general, are disproportionally, economically and ecologically significant. Management strategies need to include the hinterland, recognizing the impacts on the quality of water as well as energy and material flows (Freeman *et al.*, 2019). Branch *et al.* (1985) as cited in (Van Niekerk et al., 2013) recommended that the African Austral Ecosystem, estuaries are the most endangered through human activities.

The Knysna Basin, geographically found on the southern Cape coast of Africa, is the catchment area for the Knysna river and Estuary (Marker, 2003). It has the highest ranking in

South Africa with regard to conservation importance, providing habitats and nurseries for various marine species endemic to the region while also being a significant area for migrating birds (Turpie *et al.*, 2002) and (Harvey, 2019). Conservation of both the vegetation and fauna alone would secure 42.7% of South Africa's estuarine biodiversity preservation (Marker, 2002). The Knysna Estuary provides various ecosystem services, which includes the production of food, recreation activities and the provision of jobs. Subsequently, any changes to the Estuary might result in a noteworthy effect on a wide range of environmental services (Adams *et al*., 2021). Like most estuaries located in South Africa, the Knysna Estuary is under threat from factors that include overpopulation and mushrooming development (Marker, 2002).

These threats are not merely due to human encroachment on estuaries but include their surrounding littoral and their interference with the catchment. Most impacts on estuaries are commonly very rapidly felt given that most of the South African estuarine systems are small in scale (Elliot *et al*., 2011). This leaves them extremely vulnerable to various anthropogenic threats. It also leaves them vulnerable to natural periodic physical disturbances, though estuaries and their biodiversity have some resilience to these disturbances. For example, many South African estuaries such as the Knysna Estuary have experienced long periods with little to no flow of freshwater inflow (Elliot *et al*., 2011).

Anthropogenic issues, however, seem to be more prevalent, often increasing in magnitude as human usage of the Estuary increases (Elliot *et al*., 2011). Regardless of formal security, the Estuary has been open to powerless abuse, contamination, construction, overpopulation, and freshwater influx changes (Eksteen, 2012). Some of the key impacts include declining water quality, resource use and development pressures. Moreover, the blooming of macroalga in response to eutrophication has increased significantly, supplanting fundamental seagrass environments, and influencing biota including an increase in alien species (Elliot et al., 2011).

Long-term sensitivity of the landscape becomes evident when changes reach a threshold generally related to a complex combination of climate dynamics, sea-level change and human impact. The impacts on sensitivity of the Knysna Basin landscape are clearly seen inside the Knysna Estuary, which has the biggest tidal water range along the southern coast of South Africa (Marker, 2002). The Knysna Basin, which is a southern cape catchment, has indicated that this landscape is sensitive; any changes made within the upper basin impacts the Knysna Amphitheatre and the Estuary (Marker, 2002).

The Amphitheatre found directly south of the major fault where inclines are steep, overlaying the less impenetrable Cretaceous and adolescent strata and in a few places has sensible profundities of cover sand (Marker, 2003). It incorporates a high scene affectability (Lyster et al., 2017) and (Marker, 2003). A few of the changes caused by urban development and the increment in tourism advancement has impacted the affectability of the scene. The majority of the Amphitheatre's layover keurbooms formation lithology, cover sand overlay the clay, while the disturbed slopes remain unstable.

Landscape affectability has been examined in terms of components that have acted over a period of time within the alteration of the Knysna basin (Marker, 2003). The removal of the common indigenous forest which had already been in adjust with the slopes has happened within the past 200 years; a long time which has expanded the area since 1950. There has been no time for a new balance to have been reached (Marker, 2003) Hence, the defencelessness of the Knysna Estuary and Amphitheatre to human-induced impacts are quickened by expanded development along with the requests for higher living measures.

For example, in the past 54 years, according to Marker (2002), infringement onto the supratidal range has decreased saltmarsh by 60%. Whereas salt marsh is the foundation of the estuarine nourishment chain, and future sustainability of the Estuary lies with the preservation of the environment and management of change inside the Knysna Basin. This requires a much superior understanding of the variables that result in changes in landscape sensitivity (Marker, 2002).

The large-scale and rapid changes to river catchments, floodplains and estuaries globally have been demonstrated using the application of time series using maps, aerial photography, and satellite remote sensing imagery (Marker, 2004). With increased agricultural and urban development that have resulted in substantial land-use change, there is an urgent need to reassess the vulnerability of the coastal environment 'critical zones', especially under the threat of sea-level rise and increased population pressure (Marker, 2004). Estuaries are continually being threatened by multiple and internal and external pressures and land-use changes, including urban development, by – among many factors - the continuous -increasing population, expansion of cultivation, commercial farming, and overgrazing (Marker, 2004).

Given the vulnerability of estuarine sediments to this range of human-induced impacts, individual systems must be carefully studied to responsibly manage multiple and often conflicting uses of estuarine systems such as Knysna. Estuarine and coastal wetlands are highly productive and important for the provision of a diverse range of ecosystem services (Barbier, 2019). However, the same attributes that allow them to be diverse leave them vulnerable to be exploited, degraded and subject to loss of species. This is particularly evident in estuaries that have historically been important nodes of urban development such as the Knysna Estuary.

The Knysna Estuary is also of economic importance and scientific interest to the local region and South Africa more broadly. Tourism has become one of the main growth industries within South Africa and the Knysna Estuary and its environment act as a major visitor attraction (Buckley, 2010) and (Marker, 2004). While growth in the tourism sector provides much needed employment opportunities, the Estuary itself is placed in danger by tourism-driven initiatives, urban growth and associated land use changes. Increasing population and the socio-economic need to nurture equality among people has led to efforts to broaden the provision of piped water to the whole population of the town, which impacts freshwater inflow.

This project aims to describe and account for land use change in the catchment of the Knysna River and its impacts on the geomorphology of the Knysna Estuary between 1980 and 2019. In this project, the data collected is used to reconstruct the various changes occurring within the catchment area and their impacts on the geomorphology. Furthermore, analysis of these data sets provided an understanding of the process affecting salt marsh particularly within the Estuary (Tang *et al.*, 2016). Salt marshes are indispensable to the environment of the Knysna Estuary, acting as a supplement sink during the processing of phosphate and nitrates in the system, but little is known of their dynamics (Maree, 2000). The Estuary also provides a habitat for various organisms, birds, aquatic life which includes the endangered seahorse, and lastly a diverse number of invertebrates. According to Maree(2000) saltmarsh floristics are decided by the natural gradients of salinity and immersion that happen inside the Estuary.

The Knysna Estuary has notable value for education and research and has been subject in the past to intense study as in 2018 the 'Knysna Basin project' collaborated with five South African Universities as well as researchers from America and Australia (Harvey, 2019). However, according to Marker (2004) and Smith *et al* (2021) the natural wellbeing of the Knysna Estuary is declining which suggests small victory from current preservation and management engagements. This study is much needed as rapid urbanisation and other changes in the Knysna river catchment has occurred and very few research has been conducted on the nature and impacts of land use changes particularly on the geomorphology of the Estuary.

Land use change in the Knysna catchment area and Estuary has not been well documented and there is a clear need for a detailed study, particularly for those responsible for the development and management of the Knysna basin.

1.2. AIM

- To describe and account for land use change in the catchment of the Knysna River and its impacts on the geomorphology of the Knysna Estuary between 1980 and 2019.

1.3. OBJECTIVES

- To identify the type of land use changes in the catchment between 1980 and 2019 using sentinel imagery, aerial photographs, and satellite imagery.
- Determine land use and cover changes in Knysna river catchment between 1980 and 2019 using remotely sensed data.
- To create a time series of detailed maps of the geomorphological characteristics of the Knysna Estuary and lagoon using sentinel, aerial and satellite imagery

1.4. DISSERTATION LAYOUT

This research project is divided into six chapters.

- ***Chapter 1*** presents the project together with the aims and objectives.
- ***Chapter 2*** presents the literature review to provide insight and outline the context of this study. This will be done by exploring the importance of estuaries and coastal wetlands, together with the impacts of urbanization. Furthermore, it will provide a brief introduction to estuarine morphology and geomorphology.
- ***Chapter 3*** indicates details of the study area while describing the physical attributes and various environmental processes that characterise the Knysna catchment and its Estuary.
- ***Chapter 4*** then introduces the methods used in this study which include analysis of historical satellite imagery.

- ***Chapter 5*** details the results of this chapter
- ***Chapter 6*** indicates the discussion of the results
- ***Chapter 7*** concludes by highlighting the main findings and establishing the importance of this study along with its limitations. Possible avenues for future research are also presented.

Chapter 2

2. LITERATURE REVIEW

Coastal environments and estuaries are shaped by both marine and terrestrial interactions including erosion and deposition. The range of changes in the biological, physical and chemical conditions are established by the hydrodynamic process which includes tidal flows, wave action, frequent exchange in sediment transport, steep gradients and rich diversified biota (Osland *et al*., 2013). Coastal wetlands are a result of different association and ever-changing natural forms that include human activity.

2.1.ESTUARIES

Estuaries are defined by Dyer (1997) cited in (Lavers *et al*., 2011) as 'the physical processes involved in the mixing of sea and river water together with the transport of fine sediments within the complex estuarine topographic context'. Salt marshes are defined as low-lying coastal wetlands, that border coastal lagoons and other saline water bodies (Lavers *et al*., 2011); thus it is important to recognize that these coastal environments are the link between the land and ocean. This relationship is described by a range of physical, biological and chemical processes (Freeman *et al.*, 2019). There are different types of Estuary, as Estuary types that are recognized on the premise of modern morpho-dynamics (Cooper, 2001). These are distinguished as regularly open Estuaries that maintains a semi-permanent link with the open ocean, and two types often closed Estuary, which are isolated from the ocean for a long period of time by consistent supratidal barrier as seen in (Figure 1) (Cooper, 2001).

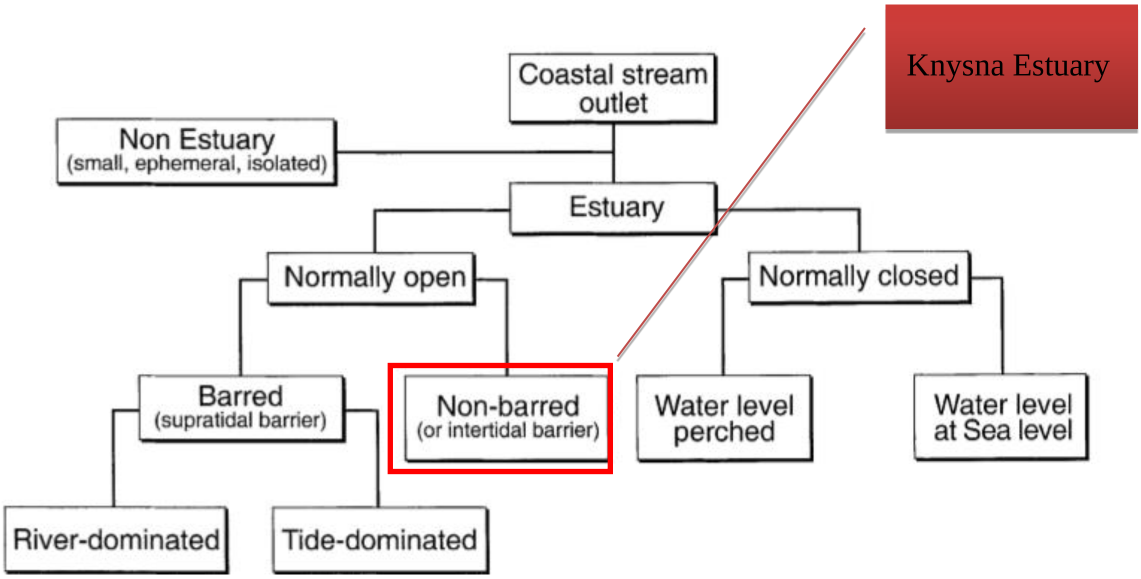


Figure 1: Microtidal estuaries. Major division are open or closed estuaries. Open estuaries are sub dived into whether a barrier is present, and the outlet is maintained by tidal or river influences. Subdivision can be done further for sediment type and physical (Cooper 2001)

Open estuaries comprise of barrier-inlet systems maintained by fluvial discharge referred to as 'river dominated estuaries' and tidal release referred to as tide dominated estuaries as (Figure 1) (Teske & Wooldridge, 2003). A third category of open Estuary has a shortage of supratidal barrier as a result of inadequate marine sediment availability. Estuaries that are closed (Figure 1) get marine impact through boundary overwatch and discontinuous breaching but are ordinarily encased behind nonstop supratidal obstructions (Teske & Wooldridge, 2003).

There are two categories of closed Estuary that are recognized as 'perched and non-perched', the perched estuaries develop behind tall berms and have a ceaseless water level which is over tall tide level within the open ocean (Teske & Wooldridge, 2003). These sorts of Estuaries are for the most part impacted by new to brackish water and breaches as well as channels occasionally. Moreover, non-perched estuaries are created behind moo height obstructions fronted by wide dissipative shoreline profiles (Teske & Wooldridge, 2003). Tall overwatch recurrence permitted marine water into such frameworks (Cooper, 2001). The breaching of Estuaries of this nature do not produce dramatic drainage, as the water level may only decrease according to the stage of the open ocean tidal cycle (Cooper, 2001). The various types of Estuaries (*Figure 2*) suggests multiple possible avenues may exist in estuarine development. Furthermore one of the most pressing issues are factors influencing these Estuarine environments and how does it affect them.

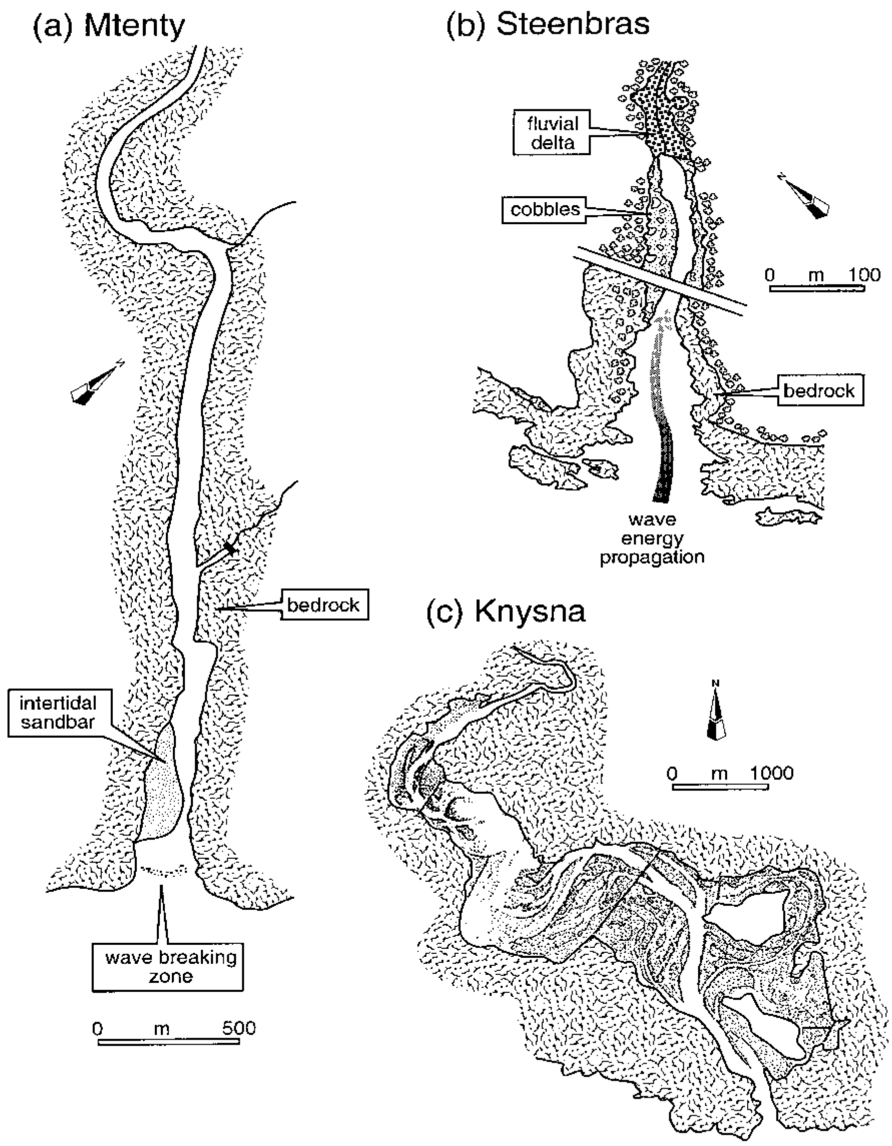


Figure 2: Non-barred estuaries (a) Mtentu (after Connel, 1974), (b) Steenbras (after Heinecken et al., 1982), (c) Knysna (after Reddering and Esterhuysen, 1987a) Whereas wave

energy attenuated on the intertidal barrier on the Mtentu, it propagates up the Steenbras to the fluvial delta. The sand within the Knysna channel relict. Cited in (Cooper, 2001)

2. **FACTORS AFFECTING ESTUARINE ENVIRONMENTS**

2.2.ENVIRONMENTAL FACTORS INFLUENCING THE SYSTEMS

2.2.1. *Climate change*

Sediment that are suspended in estuaries are regulated by multiple components that are highly sensitive to climate, which incorporates freshwater input through stream, shoreline disintegration, in situ organic generation and decay, advection, blending, resuspension of the specific matter and the rate of sedimentation (Najjar et al., 2010). Estuaries that have critical sums of freshwater or expansive flooding occasions such as the Knysna Estuary in South Africa, are anticipated to have more suspended dregs and in return, limit the essential efficiency of macrophytes and pelagic and benthic green growth. Calm estuaries that experience dry season conditions and expanded periods Temperate estuaries that encounter drought conditions and extended periods of low flows could diminish sedimentation (Gillanders *et al.*, 2011). These examples (Figure 3) show the intricacy of relationships linking climate and hypoxia in estuarine waters.

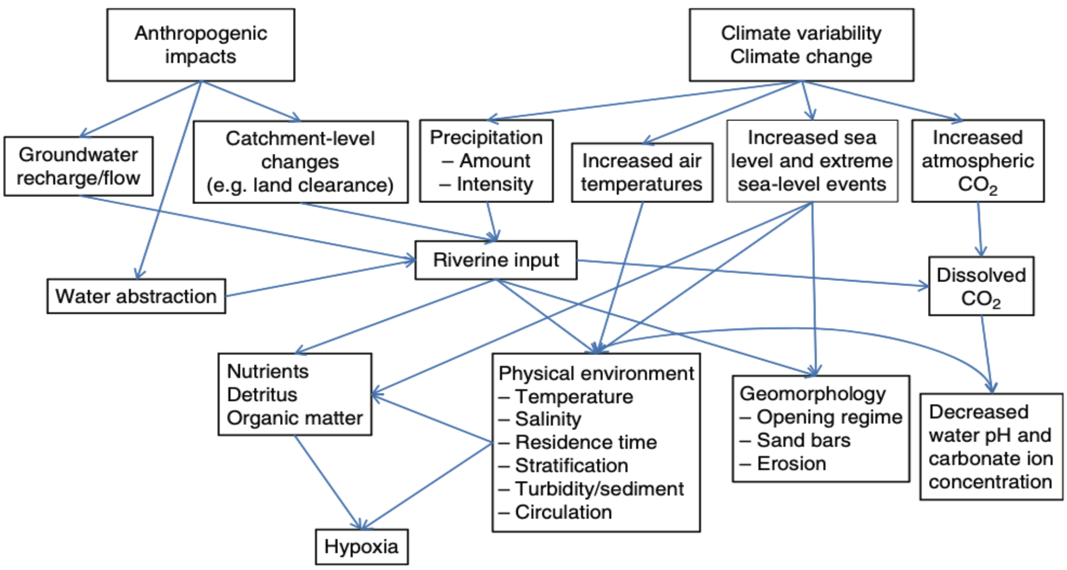


Figure 3: The possible linkages among climatic change, various anthropogenic impacts and the influence on estuarine environments, after Gillanders et al.(2011)

2.2.2. Sea level rise

During the Holocene, according to Ross *et al.*, (2015) estuaries developed because of the post-glacial rise in sea levels due to climate change . Over the last 12,000 years, sea level has slowly risen following the end of the last glaciation, but has remained largely stable during the last 6000 years. Once estuaries began to form they became traps for sediments - mud, gravel and sand carried in by rivers, streams, run-off and rain, as well as sand from the ocean floor carried in by the tides. Tidal flats also began forming along the shore as these sediments began to accumulate (Kennish, 2019). The height of the marsh platform may be a pivotal variable in that it decides and is decided by the amount of sedimentation setting a major control on the depth and common occurrence of tidal inundation and the spread of marsh vegetation (Kennish, 2019) and (French, 2019).

The working of an Estuary is dependent on an assortment of variables. These variables incorporate geomorphology, the flush of the tidal and freshwater time, inputs, climatic conditions, tidal run and the nature and degree of the intertidal zone (Adams et al., 2020). This comes about in there being numerous sorts of estuarine frameworks. Most Estuaries function as sediment traps that recycle nitrogen and phosphorous through the constant cycle of growth and decay. Estuaries are also one of the key factors in pollutants entering the land from the sea, and are among the majority nutrient- enriched ecosystems on earth (Adams *et al.*, 2020).

One of the foremost extraordinary impacts of human activities that impacts coastal zones is ocean level rise due to climate change (Fernandino *et al.*, 2018). Research by (Greiner et al., 2013), (Fernandino *et al.*, 2018) (French, 2019) and numerous others have shown that the arrangement and vertical aggregation of salt marsh to be closely related to developments within the average sea level. Firstly the rise in sea level allows new accommodation for the build-up of intertidal sediments (Greiner *et al.*, 2019). Secondly, time discrepancy in the rate and at times the course of sea level change permits for a small amount of impact over the nature of intertidal sedimentation. Most salt marshes are well known through studies to have been brought on and to have maintained their integrity through lateral and vertical growth amid long periods of a maintained rise in sea level (Greiner et al., 2019) (French, 2019). Alterations in sea level developments, the positive and negative, show evidence activating the expansions of salt marsh within the settings supportive to fine silt build-up (French *et al*., 2016).

Sea level rise gives a moving boundary condition beneath which the dregs build-up potential, both natural and inorganic, of the salt marsh environments can be completely realized (French *et al*., 2016). Sea level rise (SLR) has driven to an aggravation of coastal disintegration and saline water interruption, which in turn influences the usual growth of estuaries in coastal areas (Smith *et al*., 2013). Multiple recent studies have shown that coastal wetlands will be relentlessly impacted by climate and the rise in sea level, depending on the rate and size of the wetland (Depledge *et al*., 2017).

Reforestation, alongside the damming of streams have significantly diminished sediment delivery around the globe (Guo *et al*., 2020). In general, the rising rates of SLR and the diminish in sediment delivery around the coast has been associated to tidal wetland loss globally (Guo *et al.*, 2020). Some of the main threats include the conversion of land for agriculture and urbanization. Furthermore natural events such as abrupt tectonic movements, cyclones and plant die back tend to upset the balance over a short period of time. Similarly, human influence may have consequences in both the shorter and longer term. Ecosystems are exposed to storm surges and SLR, which are linked to salinity intrusion, inundation and water-logging (Figure 3).

Sea level rise is commonly caused by warm extension of seawater and melted land ice (Perrette, et al., 2013). Be that as it may, other impacts such as regional land subsidence, storm surges, ocean circulation, discharge, land development as well as human activities cannot be overlooked. Ocean level rise leads to an exacerbation of coastal disintegration and saline water interruption, which, in turn, influences the usual growth of estuaries in coastal areas (Perrette, *et al.*, 2013). These changes also amplify the common occurrence and intensity of tropical cyclones.

Herbert *et al.* (2018) and Widney *et al.* (2019) have investigated the effects of supplemented saltwater on a tidal freshwater marsh in Georgia, whereas Charles *et al.* (2019) related experimentally elevated and ambient salinity effects on both the fresh water and brackish marshes in the Florida Everglades. These findings show that prolonged saltwater intrusion causes substantial changes to various biological, chemical and physical characteristics; these include the loss of elevation, which will in turn place emphasis on the impact of sea level rise in these communities. These issues will intensify in coastal wetlands, particularly in deltas which are already exposed to high levels of land subsidence (Minderhoud *et al.,* 2018).

According to (Fernandino *et al.,* 2018) the concern of vulnerability of coastal wetlands and estuaries have come about as a necessary field of investigation. In a research study on the macro-tidal mudflat-salt marsh system, by Schuerch *et al*. (2019), it was found that the rate of sedimentation on the Tillingham salt marsh in the United Kingdom's redistribution of sediment has increased on the slope between the salt marsh and the mudflat and led to the inability to be flexible to the increase in sea level rise.

The future of coastal wetlands could appear to be highly tentative at best, under the extreme of the IPCC (2013) scenarios of sea levels. While not having a complete opposing view, there are various studies that show the future conditions have been generalized. Kirwan *et al.* (2016) states that meta-analysis advocates that elevational change in coastal marshes in a variety of cases have kept pace with and possibly exceeded the rates of sea level rise. Studies have thus failed to take into consideration the acceleration of sediment accretion and the likelihood on inland migration into proper accommodation spaces. This concept was also taken into consideration by Schurech (2019), who claimed that large scale coastal wetlands loss is not inevitable, and wetland gains are possible where anthropogenic land reclamation boosts accommodation space.

According to Phillips (2018a), a model of coastal wetlands had been functional on two case studies in North Carolina. Phillips' (2018b) model defines the interaction between various environmental factors, and aids the conclusion that even though there are local disparities, the wetlands continue to be characterized by changing, unstable and non-resistance to the rise in sea level. Multiple recent studies have shown that coastal wetlands will be relentlessly impacted by climate and the rise in sea level, depending on rate and size of the wetland (Depledge *et al*., 2017).

Coastal wetlands endure mortality, if organic and mineral sediment accumulation are not able to keep up with SLR (Hopkins *et al*., 2019). This is an key factor to note when making decisions for the future of coastal wetlands. Post-modern day tidal wetlands has been created over the past thousand years when sea levels were far lower than that of today (Mallinson *et al*., 2014) and (Hopkins *et al*., 2019). As a result of the warming of the ocean, and the melting of glaciers, sea levels may increase by up to 2m by 2100 (Hall *et al.*, 2019). The decrease of sediment supply to the coastal zone continues to hinder the ability of tidal wetlands to maintain elevation relative to SLR (Kirwan, 2013). Reforestation, and the damming of rivers have also significantly decrease sediment delivery around the globe (Mallinson et al., 2014) and (Hopkins *et al*., 2019). Some of these losses can be seen in the Mississippi River Delta, Venice lagoon, northern Italy and the Blackwater Creek marshes in Chesapeake Bay. Overall, the rising rates of SLR and the decrease in sediment delivery around the coast has been connected to tidal wetland loss globally (Mallinson *et al*., 2014) and (Hopkins *et al*.,, 2019).

2.3. WETLANDS AND SEDIMENTATION SUPPLY

2.3.1. Increases – causes

The entire structure of coastal wetlands is defined by biomorphic feedbacks that encompasses the balance of material flow, derived from terrestrial and marine sources that are controlled by vegetation (Waddington & Ballinger, 2016). Various coastal zones within a wetland, such as mudflats, estuaries and fresh water marshes have unique geomorphic characteristics (Andres, 2019). For example, estuaries are impacted by short-term disturbances such as storms, floods, sea level rise and human influences.

This summary describes the importance of the duration of inundation in controlling the lower elevation limit of the salt marsh vegetation (French, 2019). The issue in the complexity of coastal and estuarine systems is examined by French *et al.* (2016), where the importance of the spatial and temporal scale, in receiving reliable predictions of coastal change is recorded. According to Bouma *et al.* (2016); Hu *et al*. (2019) and Spencer *et al.* (2016), understanding the relationship between long-term and short-term changes has made recognizable headway. As discussed by Gao (2019), sediment pathways brought together by the relationship between tidal hydrodynamics, fluvial discharge and the role of the coastal wetland vegetation remains complex, even though there has been progress in identifying them.

The elevation of salt marshes continues to increase which can also be accredited to the short-term discharge events that deliver a greater sediment load (White *et al*. 2019). The future of salt marshes according to White *et al*. (2019) remains unclear because of the unpredictable nature of storms and floods which in many cases provide crucial pulses of sediment to maintain marsh elevation. Classification schemes are defined as the fundamental framework, that a geomorphic unit can be classified based on its origin and development also known as the process (Haskins *et al.,* 1998) cited in (White *et al*. 2019).

Furthermore, the clearing of land allows for the increase in sediment delivery to coastal wetlands, as opposed to impoundments that have the inverse impact, however, both of these are likely to change sediment balances or imbalances locally (Hopkins *et al*., 2019).

2.3.2. Decreases/starvation – causes

According to Mitsch *et al.* (2013) as cited in (Hopkins *et al*., 2019), the impact of sediment starvation has been well investigated as a cause of Estuarine loss, while a similar process has also been noticed in mangroves such as in the upper Gulf of Thailand. The barriers to tidal exchange restrict the most important process in coastal ecosystems that are reliant on sediment dynamics (Adam, 2020). Barriers include different forms of sea walls, dam walls and dykes (Adam, 2020).

An example of this would be tidal marsh areas that are separated from sediment supply and high tides often undergo extreme subsidence. The damming of rivers also leads to the reduction in sediment in the lower parts of the river or Estuary. The scattering of salt marsh is set by the rate of intertidal settlement space that's protected from the sea waves and higher energy wind waves given rise over Estuarine and lagoon fetches (Adam, 2020). Stratigraphic studies show the impacts of tidal marshes as sediment sinks at different timescales (French et al.,, 2006). On the other hand, the nature of this sediment sink work changes between a framework driven fundamentally by the gathering of inside delivered natural material and those that are classified by the deposition of externally determined inorganic sediments (French, 2018). Nevertheless, the character of this sediment sink function changes between systems (French, 2018).

HUMAN IMPACTS ON CATCHMENTS

People have influenced, degraded or destroyed most coastal wetlands for the last few hundred years (Zhao *et al*., 2016). A reduction in coastal wetlands directly threatens the lives and livelihoods of those populations at the coast. South Africa has lost many of its coastal wetlands resulting in being the most threatened ecosystems of all (Kotze, 2005).

2.3.3. Natural vs Anthropogenic impacts

The main factor of anthropogenic geomorphology is that sociocultural activity that create anthropogenic landforms are generally contrasting to natural processes like deposition and erosion (French, 2018). Even though anthropogenic and natural geomorphic features may share common features in form and function, the forming processes then differ. Simple topography together with ecosystems resources and possible fertile soil alludes to humans having long exploited tidal salt marshes (Rogers *et al.*, 2015). Reclamation and drainage have resulted in more destruction and an endless area of the common salt marsh resource has been lost since medieval times (French, 2019).

With respects to common allochthonous tidal salt swamp, human impacts of the sediment budget are seen in key stages of compression and extension over the past decade (French, 2018). A less common anthropogenic affect in a time when salt marsh frameworks are debilitated with an expanded immersion since an increase within the rate of sea level rise is the lessening of tidal range as the result of building tidal floods (Figure 4).

Most of the time biophysical drivers are not the drivers of land use change directly (Verburg *et al*., 2006), but instead brought about land-cover changes such as through climate change and the influencing land use allocation decision. Major biophysical drivers for land use change are climate (Metzger *et al*., 2006) and soil conditions as all of these affect land suitability. Climate change drives land use changes as the variation in temperature and rainfall results in a transformation of water regimes. This can drive a shift in vegetation and agricultural cultivation.

The term land cover denotes the physical attributes of the earth's surface, which refers to the vegetation, soil, water and other physical land features, including attributes created by human activities such as housing and settlements (Shafiq *et al.*, 2017). The land use cover patterns according to Rawat and Kumar (2015), is the result of natural and socio-economic factors and their use in relation to space and time. The change in land use results in the change of land cover, which ultimately affects land use (Rawat & Kumar, 2015).

It is paramount to note that changes in land use do not imply that there would be a degradation of land. However, numerous changing land use patterns caused by social developments result in land cover changes. As a result, almost all salt marshes were demolished by land reclamation (Perillo et al., 2018). The impacts of human activities have been seen within the misfortune of tidal level environments with serious implications (Perillo et al., 2018). Sea level rise, the decrease in sediment inputs, and upland to tidal level obstructions, such as the building of rock dividers and urban improvement, are contributors to tidal level disintegration, persistent flooding and generally wetland loss (Perillo et al., 2018) and (Hopkinson *et al*., 2019).

The main idea of the diagram (Figure 6) is the hysteresis of the relationship between sediment supply returns to its normal level, the salt marsh may proceed in its changed state (French, 2019). A reason for this could be that salt swamp is so viable in catching silt that when it has been created it could change both the sediment budget and the hydrodynamic of an entire estuarine system (French, 2018). For example, Indonesia which hosts the world's largest mangroves had lost 40% of its mangrove by the 1980s as a result of logging transformation to agriculture and the creation of brackish water aquaculture.

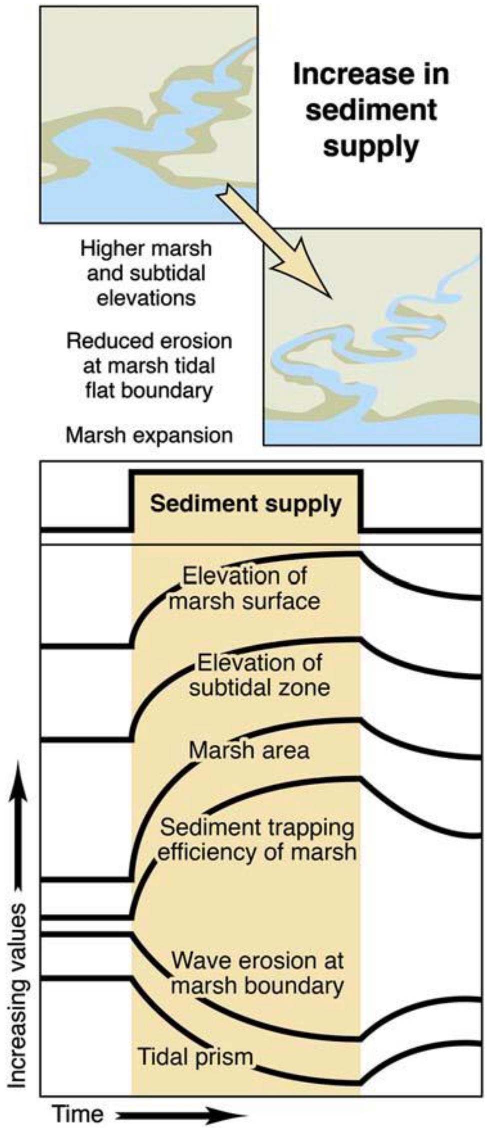


Figure 4: The sensitivity of tidal salt marsh extent and characteristics to variation in sediment supply resulting from various anthropogenic influence. [Adapted from Mudd, S.M., 2011. after French (2019)]

2.3.4. Effects caused by biotic factors (living things)

Overgrazing and deforestation in various countries have contributed to a drier climate, at the same time large unsustainable irrigation projects have diverted water from lakes and rivers (Phillips, 2018). While reduced rainfall and increased drought frequency have occurred, the continuing development of unsustainable irrigation projects can lead to the elimination of estuaries entirely. Diminished areas of coastal marsh in the present day, or a dramatic shift in their geomorphic character would have crucial consequences for coastal fisheries (Phillips, 2018). The instance of widespread impacts of human activity together with the continuous displacement of the native flora by invasive species have been well researched (Zuo *et al*., 2012).

Biotic impacts include disease and invasive species. While not all examples are listed as being caused by human activities, human impacts may have been at fault for expanding their introduction, whereas unpleasant conditions made by eutrophication may increase these impacts (Fagherazzi *et al*., 2010). The scale of organic and inorganic matter build up applies a significant pressure on marsh geomorphology and environment and this has been utilized as a starting point for certain classification plans (French, 2018). The sediment supply is an important aspect in both the formation

and perseverance of salt marshes. At decadal and centennial scales, the measure of allochthonous sediment input controls the capacity of the marsh to modify to the changing boundary conditions, especially the rise in sea level along territorial gradients in sediment supply and tidal range (French, 2006; 2018). Research in understanding geomorphological impacts on estuaries has come a long way particularly with regards to temperature, the potential collaboration impacts of changing salinity and diseases for wetlands (Adam, 2002).

The decrease in the supply of fresh water was one of the top five causes for the decline in mangroves in South East Asia between 2000 and 2012 (Goldberg *et al*., 2020). Similarly in this study the increase in salinization and turbidity in estuaries as a result of declined fresh water flow and the increase of land clearing within river basins are currently he greatest dangers to estuarine biological systems and the coastal wetlands in South Africa (Jennerjahn *et al.*, 2017). This can result in a huge concern for the Knysna Estuary.

2.3.5. Effects of localized physical change

Humanity has effected, degraded and destroyed multiple coastal wetlands by either pollution or physical degradation. Reduced coastal wetland areas will result in the increase of threat to human safety and simultaneously the development on the shoreline exposes the population to coastal disasters, such as tsunamis, flooding, erosion, surges and storm waves (Hopkinson *et al.*, 2019). Numerous salt marshes have been annihilated because of land reclamation in different temperate nations which includes Japan, Netherlands and China (Hopkinson *et al.*, 2019).

The loss of wetlands can also have economic impacts as coastal wetlands are imperative territories for numerous fishery species. The wetlands that remain behind are currently sinking and shrinking due to the non-replenishment of sediment, as rivers are being diverted or dammed for human consumption or human protection, along the coast (Hopkinson *et al.*, 2019). Human impacts now continue to threaten coastal areas; we face the possibility of a world without estuaries within this century (Hopkinson *et al.*, 2019). Some of the key threats of humans include the conversation of land for urbanization and industrialization, salt ponds rice farms and other agricultural needs.

While land clearing activities care able to extend sediment delivery to coastal wetlands; impoundments have the inverse impact with both affecting sediment balances or imbalances on a local scale (Perillo et al., 2018). The effect of sedimentation starvation has been strongly researched as the cause of tidal marsh losses (Perillo et al., 2018). Obstructions to tidal exchange affect the foremost pivotal process within the coastal biological system dependent on sediment flow such as morphodynamic processes brought about by waves and currents as well as hydrodynamic impacts.

2.3.6. Effects of chemical change

Nutrient enrichment affects estuaries in various ways (Fagherazzi *et al.*, 2010). This includes gatherings of intemperate macroalgal development, that depletes night time oxygen. It has been found by Fagherazzi *et al.* (2010) that high levels of N-enrichment led to creek bank slumping of macrotidal saltmarsh (Fagherazzi *et al.*, 2010) and (Hopkinson, 2019). In spite of the fact that not all cases have been reported to have been caused by human activities, human agents may be responsible for the increased speed and unpleasant conditions made by eutrophication which will amplify their impacts (Figure 4).

2.4. IMPACTS OF LAND USE CHANGE ON ESTUARIES

The term land cover denotes the physical attributes of the earth's surface, which refers to the vegetation, soil, water and other physical land features, including attributes created by human activities such as housing and settlements (Shafiq *et al*., 2017).

There are three characteristics of global change that have a significant effect on tidal wetland dynamics which includes (1). the fast following rise in sea level that seem to surpass the capacity of certain wetlands to keep pace, (2). a warming that could possibly stretch the range of frost intolerant species, and (3) the change in climates that may change coastal salinity and fluvial sediment delivery patterns (Dunn *et al.*, 2018). Compared to more local sort of human impacts, global changes are likely to be longer and more inconspicuous; be that as it may, this feature is set off by the huge geographic reach. Studies of past changes help us understand that coastal wetlands may be changed irreversibly if organic and mineral sediment accumulation are unable to keep up with SLR (Passerie *et al.*, 2015). This is a crucial factor to note when planning for the future of coastal wetlands (Passerie *et al.*, 2015).

An increasingly common impact on salt marsh systems is elevated frequencies and magnitude of tidal inundation as a result of sea level rise (SLR) and this is often associated with the cutting back of tidal ranges due to the development of tidal floods. Within the Netherlands, de Jong et al., (1994) as cited in (Hammond, 2001) recorded loss and degradation of salt marsh after the completion of the storm surge obstruction in 1987. Tidal run in estuaries have been diminished by more than 10%, driving to the aridity of the bordering salt marsh deposits and expanded erosion of micro scale cliff that mark the change in tidal flat (French, 2018).

In contrast with the more local sorts of human affect, worldwide changes appear to be longer and more inconspicuous. Moreover, there still lies an uncertainty in the actual amount of change. Human activities may be summarized into three categories: those that result from a global change, effects caused by biotic factors and effects from a localized chemical and physical change. Reforestation, superior land management and the damming of streams have essentially decreased sediment delivery around the globe (Shi *et al.*, 2010). In general, the rising rates of SLR and the diminish in sediment delivery due to human movement around the coast has been associated to tidal wetland loss globally (Langston *et al.*, 2020). Examples of these losses can be seen in the Mississippi River Delta, the Venice lagoon in northern Italy and the Blackwater Creek marshes in Chesapeake Bay (Wang *et al.*, 2018). Human impacts threaten coastal wetlands arising from processes that include conversion of land for agriculture and urbanization (Machiwa *et al.*, 2021).

Saltmarshes have already been degraded by land reclamation in a number of increasingly populated temperate countries such as China, Netherlands and Japan (Broome *et al.*, 2019). The few wetlands that remain are shrinking and sinking as they have not been recharged by sediment as waterways have been channelled somewhere else, intensifying floods by rivers and storm surges (Fagorite *et al*., 2019). According to Spencer *et al.* (2016) up until the year 2100, the death of global coastal wetland area will span between 0 and 30%, if no additional accommodation space in together with the current levels are taken up. Spencer *et al.* (2016) study had suggested that the durability of global wetlands is mostly due to the availability of accommodation space, which is greatly affected by the building of anthropogenic infrastructure in the coastal zone and such infrastructure is predicted to change over the twenty-first century (Spencer *et al*., 2016).

Land use changes can affect water, biodiversity, trace gas emissions, radiation and other processes that come together to impact the biosphere and climate (Rawat & Kumar, 2015). Land use change is accelerating globally mainly due to population growth, which then drives changes that in turn affect the natural ecosystem namely the Knysna ecosystem, South Africa.

Chapter 3

3. THE STUDY AREA

3.1. LOCATION

The Knysna town is situated alongside the Knysna River Estuary within the Western Cape Province of South Africa **(**Figure 5) (-34.077469° E, 23.059276° S). Located along the coastline, the so-called 'Garden Route' and Knysna Estuary are major tourist attractions. According to the classification system by the Department of Water and Sanitation (DWS), Knysna lies within the Breede- Gouritz Catchment Management Area. Before flowing into the Estuary, the Knysna river has its main source in the Outeniqua Mountain, and it exits through the gap at the Knysna heads. The major tributaries of the Knysna river are the Kruis and Gouna river **(**Figure 5).

The N2 highway runs through the study area while Leisure isle and Thesen Island are located within the Estuary itself (Figure 5). This Estuary is made up of three sections. The lower Estuary **(**Figure 5**),** referred to as the 'embayment', runs from the Knysna Heads to the railway bridge and is dominated by tidal water; the middle Estuary runs from the railway bridge all the way to the N2 road bridge, and is made up of a mix of tidal and fluvial water with salinity gradients that are strong and longitudinal (Marker, 2002). Lastly, the upper Estuary runs upstream from the N2 bridge, which according to Largier (2000) is influenced mainly the fluvial flow.

The Knysna Estuary is South Africa's single warm temperate Estuarine bay (Turpie *et al*., 2002). The surface zone secured during spring tide is 1827 ha (Allanson *et al*., 2000) as cited in (Harvey, 2019). The Estuary conceals the foot of a wide level valley, with tremendous regions subjected to tidal changes (Largier *et al*., 2000). The Estuary is also continuously open to tidal influences with the Estuary subject to substantial fluctuations in water chemistry and material content.

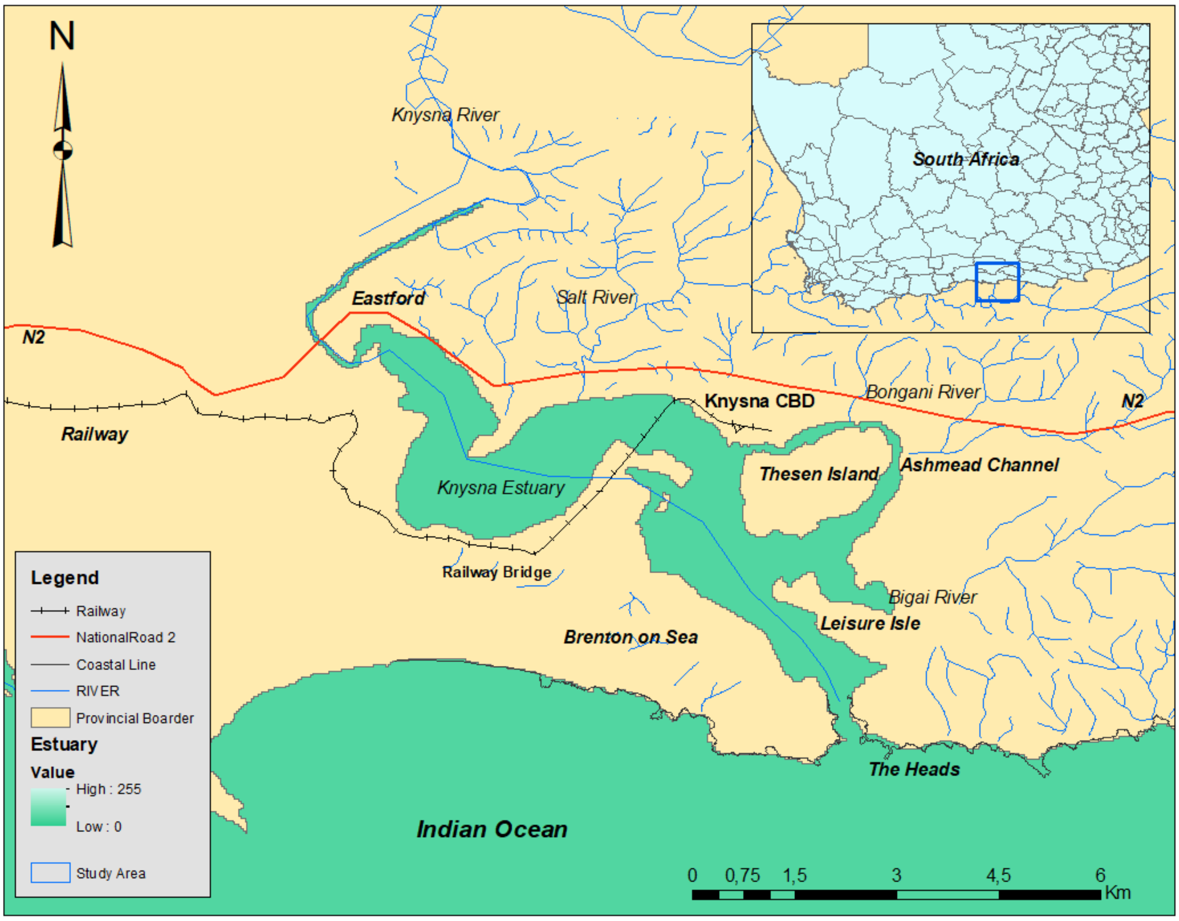


Figure 5: Geographical location of the Knysna study area along the south coast of South Africa indicating elevation as well as main areas.

3.2.1. Land use/cover

Like numerous other developing nations over the globe, land-cover changes have been observed in and around the Knysna Estuary over the last century. These changes have been said to happen by anthropogenic activities since the expanding population that has forced the clearing of certain areas for housing, agriculture or urban expansion (Mead *et al*., 2013).

The land use/cover located in the study area comprises formal, semi-formal urban development, industrial areas, golf courses, indigenous forests, fynbos and commercial forestry (Harvey, 2019). The Knysna afrotemperate forest covers roughly 25% of the entire catchment where plantation covers 23% and upland fynbos covers 13% (Mitsch *et al*., 2013).

As seen in Mitsch *et al*., (2013) the catchment areas surrounding the Knysna Estuary are dominated by alien vegetation, urban development and lowland fynbos.

The Knysna Estuary and lagoon, along with the Knysna Heads, are characterised by formal urban development which includes the Knysna CBD, Leisure Isle and various outlying suburbsFigure 5: Geographical location of the Knysna study area along the south coast of South Africa (Figure 5) (Marker, 2003). Thesen Island historically was a timber treatment plant but has been altered into an upmarket residential and commercial area attracting tourists. The plateau above the town is the watershed of the two rivers, namely the Salt and Bongani rivers, and is predominantly occupied by formal, semi-formal and informal developments. The northern part of the Salt River is less developed with land use area that is primarily commercial and forestry.

According to Mitsch *et al*., (2013) larger parts of the forest are labelled as alien/degraded; in any case, land use/cover towards the centre of the river is still considered indigenous forests (Mitsch *et al*., 2013). The Simola Golf course is arranged west of the Salt River catchment whereas the other two bigger golf courses within the Knysna zone are the Knysna Golf course found following to the Estuary and the Phezulu Golf Course situated in the origin of the Bigai River (Harvey, 2019). Within the Bongani Catchment (Figure 6) the plateau sinks into a steep sided valley that is mostly covered by the Southern Afrotemperate forest (SANparks, nd.) Land cover in the sections of the middle reaches are referred to as alien/degraded (Mitsch *et al*., 2013).

The Bigai River has recently been occupied by semi formal settlements (Figure 7). Land cover within the south of the Biga River is populated by low settlements, Phezula Golf Course and marsh fynbos (ibid). The Bigai River valley which has more than 2 km of reedbeds, filter large amounts of pollution while also trapping solid waste, in turn emphasising the significance of reeds beds for the sustainability of the Estuary. The Knysna

Estuary southern catchment is less developed with only two formal urban settlements. Here the predominant land use in these catchments is marsh, forest and patches of alien vegetation (Harvey, 2019). According to the DEA (2014), parts of the catchment and the Estuary are classified as 'Special Nature Reserve' and are secured under the Protected Areas Act (RSA, 2004).The nature reserve is located north of the Knysna town.

Figure 6: Hornlee, a semi formal development in the Bongani catchment

According to Maree (2000), multiple sites of land reclamation were recognized, the supratidal wetland **(**Figure 5**)** has been filled and raised with a golf course being built on the location (Maree, 2000). The golf course still has leftovers of the wetland. The earliest rivers that bolstered the wetland proceed to exist and purge and fill with the moving of the tides (Maree, 2000). Most of the lower town locale of Knysna was built on portion of the intertidal marsh (Maree, 2000). In Ad 1997, an region of intertidal wetland, generally 0.2 km2 northwest of the Knysna Yacht Club was unearthed for commercial advancement. An zone of generally

0.3 km2 of estuarine wetland within the upper range close Westford Bridge was claimed and is right now utilized for rural activities. A region of the intertidal and supratidal marsh has been burrowed out by a private landowner in 1977 to the east of the Ashmead Channel to provide boat access from the Ashmead Resort to the Estuary (Maree, 2000). A comparative event on the western shoreline of the Estuary at 'Brenton on Sea' (Figure 7) A private landowner had uncovered a canal to guarantee direct access over marshlands on the Estuary edge. Additionally, in Ad 1992 the Zostera beds were dug to supply an region for the building of a little boat harbour north of Leisure Isle (Figure 7). A few parklands have been created for recreational purposes, found west of the Estuary and built on intertidal and supratidal marsh zone that has been recovered (Maree, 2000).

3.2.2. Topography and Hydrology

The Knysna Basin is ruled by etched valleys and a high drainage density since a well dispersed precipitation that keeps up the nonstop stream of the 6th order Knysna River and its major tributaries (Marker, 2004). The Knysna Basin moreover has an impermeable catchment area, with a steep gradient and perennial river flow with historical uplift that sheds light on the nearness of the cut. The larger part of the tributaries enter the river from the east which are longer than those within the west (Figure 7). As it were, two major rivers, the Salt River and the Bigai River, that drain directly into the Estuary (Maree, 2000).

According to Marker (2004), the Knysna catchment is known to have high landscape sensitivity prone to climatic and human impact while the Salt River is the most dynamic sub-catchment of the Knysna Basin. The river catchment measuring 330km^3 is the main source of fresh water for the Estuary (*Error! Not a valid bookmark self-reference.*). This river together with its tributaries - the Steenbras River, Swartkops river, the Kruis River and multiple others - delivers an estimated amount of 110-133 million m^3 of water into the Knysna Estuary annually that is used for ecological and social aspects alike.

Table 1: The Morphometric Parameters of the Knysna River Catchment Summarized

Parameter	**Knysna**
Catchment Area (km^3)	330
Stream Order	6
Main Stream Length (km)	64
Estuary cover (ha)	1.827

3.2.3. The Knysna River Estuary

The Knysna River originates in the Outeniqua Mountain and flows towards the Knysna Heads stretching 64 km from source to mouth, and is a defining feature of the Knysna Estuary (Figure 5). The Knysna River, measuring at 230 meters wide while also being navigable and 3.9 meters deep, is the main water source for the town of Knysna. A tidal rise and fall which is maintained far upstream measures 1.8 meters at spring tide. The reddish-brown colour of the river water is due to the Southern Cape hemic acid, which is a natural by-product of leaf decay (Cooper, 2002). Occasionally, the Knysna River carries silt into the Estuary after heavy rainfalls and flooding which tends to occur every 10-12 years.

Furthermore the Knysna Estuary is an Estuarine bay that is indelibly open to the sea (Figure 2). It has been cited by Human *et al*. (2016) as South Africa's most significant Estuary with regards to its priority to conservation. This status is due to the biodiversity importance based on plants, birds, fish, and invertebrates as stated in the National Biodiversity assessment of 2012.

The altitude of the Knysna Estuary ranges from 200- 240 meters above the average sea level while also forming part of the coastal platform (Marker, 2000). The Knysna Amphitheatre is a broken up plateau, accessible to the urban centre but still predominantly rural. While the boundary found in the north of the coastal platform runs northwest to southeast across the Knysna basin, neighbouring the mountains of the region at an elevation of 280-290m (Marker

& Holmes, 2002). This area remains easily accessible to the southern part of the Estuary, dominated by smallholdings, plantations and peri-urban expansion (Marker & Holmes, 2002).

The northern portion of the Knysna Basin, which is additionally the biggest portion of the basin, is tough, mountainous and scantily populated (Marker & Holmes, 2002). The mountain relief is overwhelmed by three discontinuous mountain edges running from the west to the east. Any changes within the upper region of the basin affect the Knysna Amphitheatre and Estuary within the south (Figure 7). The Amphitheatre lays instantly south of the major fault line where slopes are steep (Figure 9), overlies Cretaceous and more youthful strata. (Muscina & Rutherford, 2006). The Amphitheatre in many areas also carries depths of cover sand where there is high landscape sensitivity (Muscina & Rutherford, 2006).

Rivers and streams within the Knysna range have cut through the landscape according to Marker (2003). The domination of these rivers and streams are what brings the various levels of land (Figure 7). The relief of the Knysna catchment and Estuary is indicated in (Figure 7) with the colour red indicating the higher altitudes and blue indicating the lower altitudes. The topography of the Knysna Estuary has also been impacted by the various climatic conditions of the Knysna area but how has this compared to other region around South Africa .

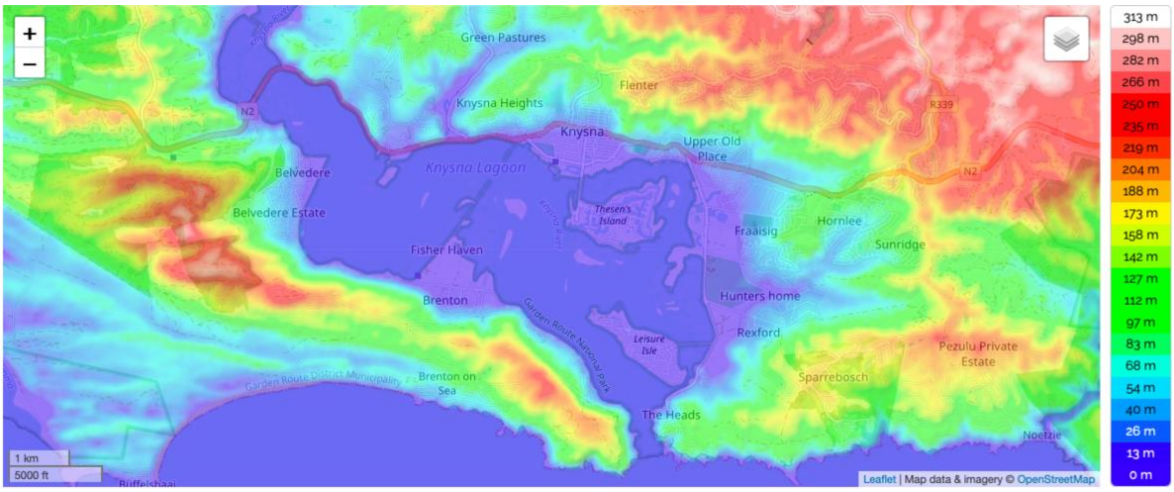


Figure 7: A Topographic relief map of the catchment surrounding the Knysna catchment area created on http//www.openstreetmap.org

3.2.4. Climate

In comparison to most of South Africa, the rainfall in the Knysna area is considered high, while being almost evenly distributed throughout the year (Figure 8**)** with winter months having the greatest rainfall. Rainfall is a variable over the Knysna catchment and Estuary, where the annual rainfall is roughly 700mm. While over the central basin it rises to roughly 1800mm, decreasing inland with ~600mm on the Outeniquaberg (Maree, 2000). Temperatures in Knysna remain equable, summer temperature averages around 25°C, while the winter seasons which occur from July, average around 7°C, the presence of frost is a rare occurrence, but possible (Maree, 2000).

Even though Knysna experiences evenly distributed rainfall and an average equable temperature, the southern Cape remains vulnerable to extreme events (Figure 9). In AD 1996 the first nine months of the year, the Knysna area suffered severe droughts where as it were 40% of the normal precipitation had fallen by the end of September and was at that point succeeded by three surge occasions amid October and November (Marker & Holmes, 2002). In this same year, the amount of rainfall had transcended the average annual total in spite of the nine-month drought. Moreover the fluctuation of rainfall influences the vegetation within the Knysna region.

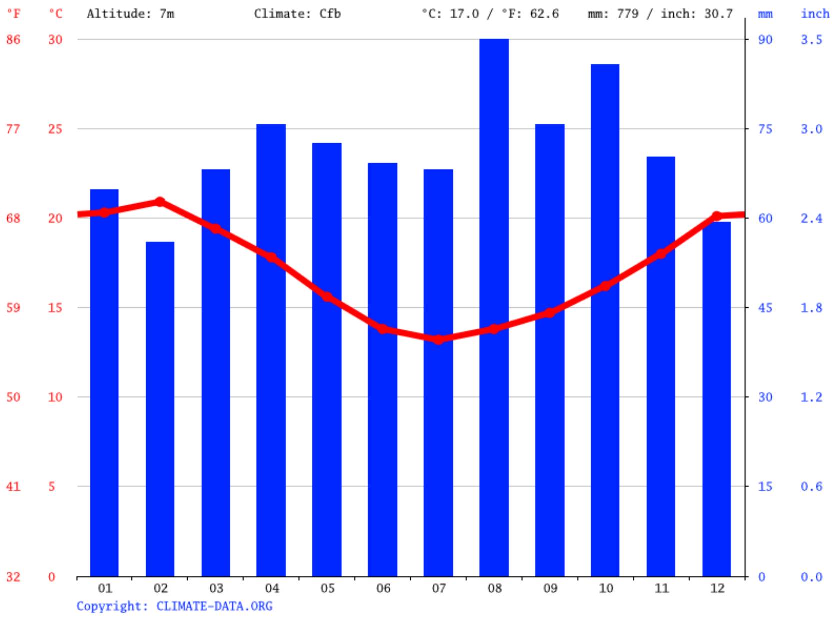


Figure 8: The average temperature and rainfall of the Knysna area in 2019 cited from https://en.climate-data.org/africa/south-africa/western-cape/knysna-57365/)

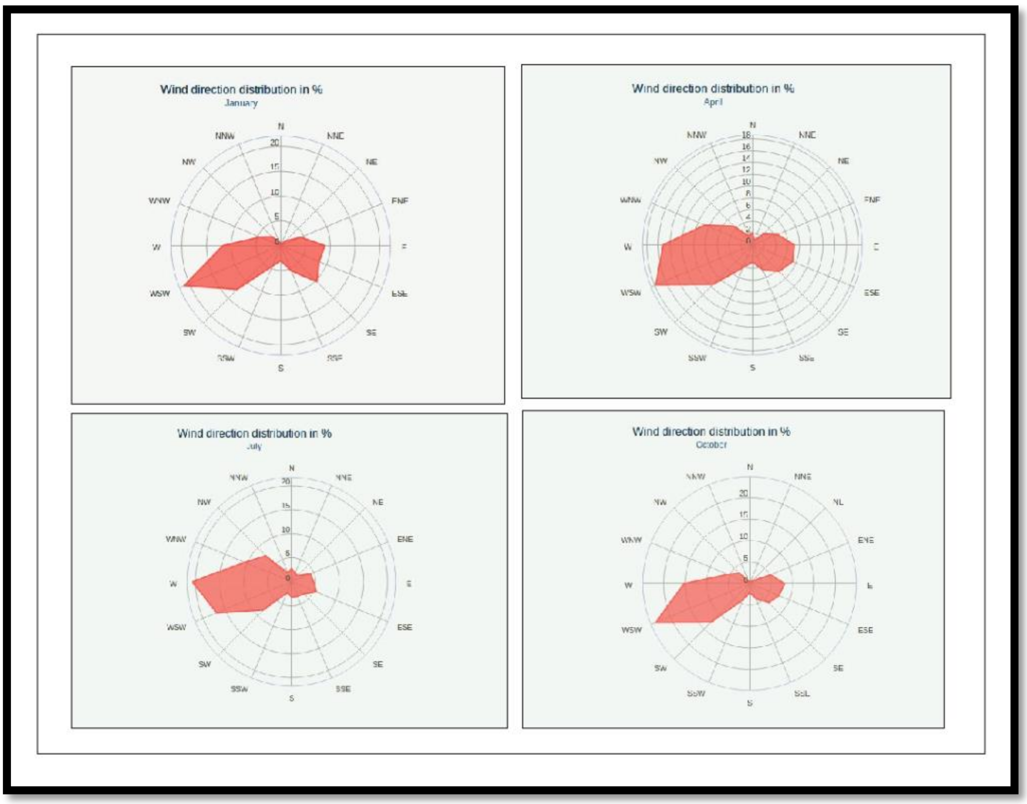


Figure 9: Wind direction distribution in the Knysna Study area, cited from (http://cip.csag.uct.ac.za April, 2018)

3.3. VEGETATION

The Knysna area holds a large variety of vegetation species spread across a varying topography. The classification system defined by Muscina and Rutherford (2006) is used as a basis for this classification. Eight vegetation types are recognized in this region, within two different biomes, namely Fynbos and Afrotemperate Forests. The Afromontane forest was the indigenous vegetation that extended from the coast inland for generally 20 km; currently the coastal forest still stay, eminently in Sparresbos Forest Reserve as well as Brenton- on – Lake (Figure 7) (Marker, 2002). As precipitation diminishes (Figure 8) fynbos also referred to as '*sclerophyll shrub'* replaces forest areas. '*Sclerophyll shrub'* also replace forest on the Eastern and Western Knysna heads because of the physiological drought as a result of wind exposure (Figure 9) (Maree, 2000). The vegetation of the specific region is combustible fynbos shrublands, combined with lesser zones of Afrotemperate woodland and shrubbery vegetation that seldom burns (Geldenhuys 1994) as cited in Muscina and Rutherford (2008).

A combination of fynbos and shrubbery grows along the coast frequently on dune sands where fire suppression over the past 50 to 70 years has led to the dominance of shrubbery vegetation (Kraaij et al. 2011). For the maintenance of fynbos, the perfect interval for fires is directly related to high-intensity fires at 10- to 20-year intervals (Kraaij *et al.,* 2013a, Kraaij and van Wilgen 2014). Plantations of invasive alien pine trees have broken up and supplanted huge tracts of fynbos inside the Knysna region (Kraaij *et al*., 2011). The in-land forest – fynbos change is categorized by fynbos on drier arched slopes with forests patches that are constrained to the north confronting profound valley (Marker, 2002). Nonstop forest is confined to a cooler south facing slopes (Marker, 2002). Small zones of fynbos occur inland, locally named 'islands' occur on levelled seats or summits where the soil has been leeched. Pre-European exploitation – Woodcutters were only seen from the 1770s - the forests had stabilized all steep slopes preventing run-off and decreasing the amount of sediment found within the Estuary. From the beginning of the nineteenth century forest exploitation increased dramatically (Frost *et al*., 2018). Eucalyptus and coniferous plantations and farms had replaced forest regions. The change in land altered run off patterns. Given that there was less forest floor there was less water mention (Marker 2002). The frequency of fire increased as seen in the year 2017 of the Knysna fire; this favoured the fire tolerant fynbos (Figure 10). Maree (2000) reported that fires that followed the extreme drought period of 1860s resulted in major erosion. However, when the fire in 1997 occurred it had impacted some cover sand slopes, resulting in no erosion as the root mat had been intact (Frost *et al* .,2018). The disruption of the natural vegetation has resulted in the invasion of alien species, namely *Acacia spp*, which occur particularly in major valleys (Maree 2000).

Figure 10:The Knysna fire of 2017 (Cited by: Rowan Abrahams)

Before the Knysna fire had taken place, the Southern and Western Cape had experienced extreme drought conditions since 2015. Vegetation greenness and conditions had declined far below the long-term normal by May 2017, resulting in vegetation being dry and combustible. The vegetation within the Elandskraal region (Figure 7) had been categorized as exceptionally dry scrub forest which comprised of a blend of shrubs, creepers and trees (Ice et al., 2018). Amid 3-6 June 2017, berg wind conditions begun to develop (Ice et al., 2018). The winds (Figure 11) proceeded to dry up and shrivel the vegetation in an zone that was already stressed due to serious dry spell.

On the 7th of June 2017, there was an increment in wind speed with north westerly winds blowing downslope off the Outeniqua Mountains, lessening the relative humidity further to only 25% (Frost *et al.*, 2018). Winds had been recorded at 50km/h and continued to rise. Vegetation in the Knysna area had been under stress attributed to the lack of rainfall; this contributed to the severity of the Knysna fire. Shrubland is categorized as an indigenous forest type which is the change between fynbos and thicket or forest (**Error! Not a valid bookmark self-reference.**). The spread of the Knysna fire altered the vegetation type and growth around the Knysna Estuary (Frost *et al* ., 2018). These alterations has affected the Estuary as well as the catchment, with many other human induced alterations fuelling various environmental changes.

Table 2: Classes description based on the USGS classification scheme cited on http://www.landsat.usgs.gov

Class Name	**Description**
Agriculture/Cultivated land	Cropland, pastures, nurseries, horticultural areas, vineyards, confined feeding operations and other agricultural land
Vegetation	Dedacious forest land, mixed forest land, evergreen forest land, natural wooded land, planted forest, alien vegetation, saltmarsh, fynbos, grassland and afrotemperate forest
Natural Wooded Land	“Forest”, spanning more than 0.5 ha; (0.005km2) with trees higher than 5 meters and a canopy cover of 5-10 percent with a combined cover of shrubs, bushes and trees above 10 percent. It

	does not include land that is predominantly under agricultural or urban land use.
Water Body	Streams and canals, reservoir, lakes, bays and sea, oceans and estuaries
Urbanized or Built-up land	Residential, services and commercial, industrial and commercial complexes, urban or mixed urban areas, built up land, industrial transportation, other urban or built-up land
Bare/ Barren Land	Bare open land
Plantation/ Alien Vegetation	A Large group of plants and especially trees under cultivation or Invasive alien species are plants that are non-native to an ecosystem.
Fynbos Shrubland	Fynbos meaning fine plants is a small belt of natural shrubland or heathland vegetation.

3.4. HUMAN IMPACTS

3.4.1. The History of Thesen Island

Thesen Island previously known as *'Paarden Eiland'* is located in the northern part of the Knysna lagoon (Figure 5). Thesen Island is a low-lying sand body, with a sawmill and manufacturing industry that has been active since the 1920s located on the island. This island has strong historical significance because of its association to the Thesen family who have been the key drivers in the development of the Knysna timber industry and history of the town. In this century Thesen Island has existed as an industrial enclave linked with the development of Knysna. The continuous development of the island is seen by a variety of industrial and associated residential structures. The first wooden jetty on the island was constructed in the late 19th century; later it serviced the new wharf and the island industry. Re-development of the island with regards to upgrades may have resulted in negative impacts on the island and in turn the Knysna Estuary.

3.4.2. The Sea Wall

According to Hart & Halkett, (1998) cited in Smith (2013) the island indicated low mud-flat which supported grasses that are semi flooded at spring tide. To ensure the island remained habitable, a sea wall was constructed to prevent inundation. The levels on various parts of the island were raised to facilitate the low water table. As of 1933, no trees or vegetation other than grasses grew on the island. The construction of the sea wall together with the raising of sea levels, created an environment on parts of the island where indigenous species including trees have since multiplied (Hart & Halkett, 1998) cited in (Smith *et al*., 2013).

3.4.3. Thesen Jetty

On the west side of Thesen Island there is a concrete jetty which lies on the state land (Figure 5). The changes in the use of the wharf will be affected by the activities held on the island. The wharf has played a significant role in activities related to Thesen industries, company and shipping lines. This feature thus has a strong historical connection with the island and town of Knysna. The wharf however considered to be a unique concrete structure poses a threat to conservation. Due to the spalling and degeneration of its fabric it is no longer deemed serviceable and is used only for light duty activities. Thesen island residential buildings are among the most striking and conservation worthy structures on the property. Building fabrics includes brick, wood and iron. Most buildings include large brick heaths and chimneys and wooden case windows. Many buildings with these structures have been demolished making these buildings increasing rare and heritage sites on Thesen Island (Quaghebeur, 2000).

3.5. DISCUSSION

These various developments in the catchment and Estuary have had major consequences. The Estuary itself has been directly affected by the removal of wetland sediment, the reduction of sediment by the damming of the upper catchment and stabilisation of dunes as well as land reclamation. This has restricted the onshore migration of sediments and overall growth (Anthony *et al.*, 2014).

The Knysna Estuary is threatened by development schemes such as urbanization and barrages and marinas (Van Niekerk *et al*., 2020). The decrease in the sediment input in Knysna has occurred because of both the damming of rivers and the reduction in soil erosion in drainage basins, as well as from coastal protection schemes that reduce both onshore and along shore sediment movements (Marker, 2002). Geomorphology has taught us that all coastal wetlands endure mortality (Marker, 2002). In case natural and mineral sediment aggregations are incapable to keep pace with critical human impacts such as overpopulation and urbanization extension at that point this gets to be an vital figure when planning for long term for coastal wetlands in this century.

The impacts of human movement can moreover be seen within the loss of tidal level environments. Human movement and declining sedimentation rates, upland tidal level obstructions similarly to the development of building rock dividers and urban development are supporting the devastation of tidal level erosion, permanent flooding and generally wetlands loss in region (Marker, 2002). The expanding rise in sea level can surpass the capacity of a few wetlands to keep pace, whereas the drying or wetting of climates too alter coastal salinity and fluvial sediment delivery patterns (Marker, 2002).

The diminishment in freshwater streams coming about from household and agribusiness extraction may increment coastal salinities and affect the presence of tidal wetlands. While activities to clear land can increment sediment delivery to coastal wetlands, impounds have the inverse impacts. Be that as it may, both might alter sediment balances or imbalances locally. Indeed in spite of the fact that not all cases have been reported to have been caused by human activities, human agents may be the cause for the increase in speed within the presentation and upsetting conditions made by eutrophication, coming about in a amplification of their impacts (Hopkinson *et al*., 2019) (Figure 11).

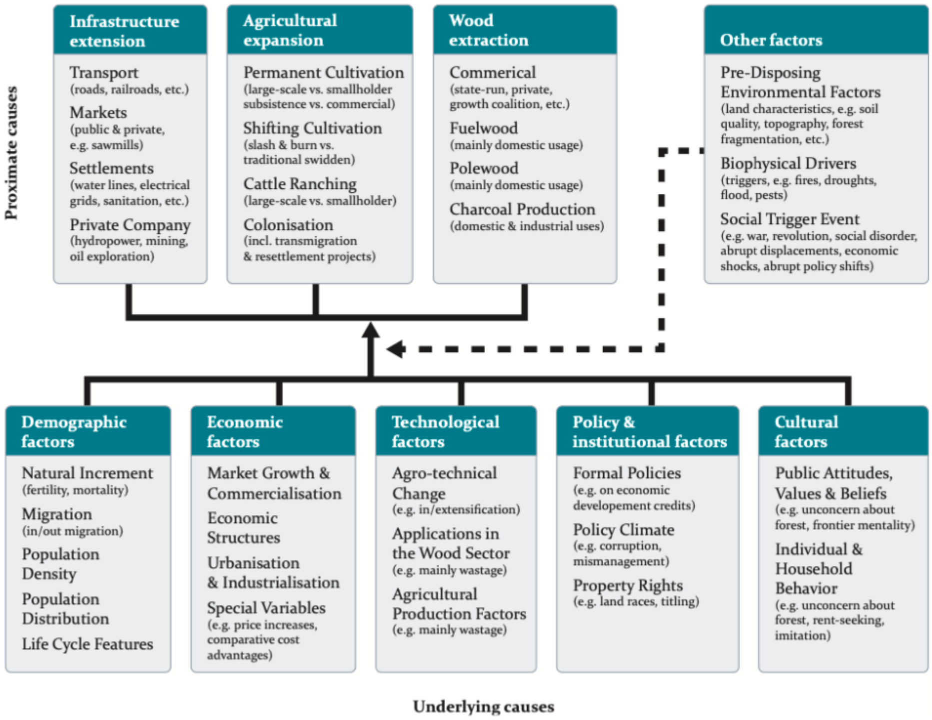


Figure 11:An approximate cause of land use changes and underlying factors effecting estuaries as a result of human impacts [after Hopkinson et al. (2019)]

As outlined above (Figure 11) the Knysna region has gone through striking environmental changes in its most recent past and continues to be affected in the present day by human activity. It is anticipated that these changes will be communicated within the land use change and geomorphology of the Knysna Estuary. In this manner, to establish the effect of land use change on the geomorphology of the catchment and Estuary, various methods are employed to ascertain the extent of these changes on catchment and Estuary over 35 years.

4. METHODOLOGY - RESEARCH AND FOCUS AREA

In combination with various data sources namely, Landsat, and Sentinel photography, the characteristics and processes contributing to the impacts of the Knysna Estuary are mapped and analysed. To achieve this, suitable methods (Figure 12) were undertaken to ascertain the land use changes and the impact thereof.

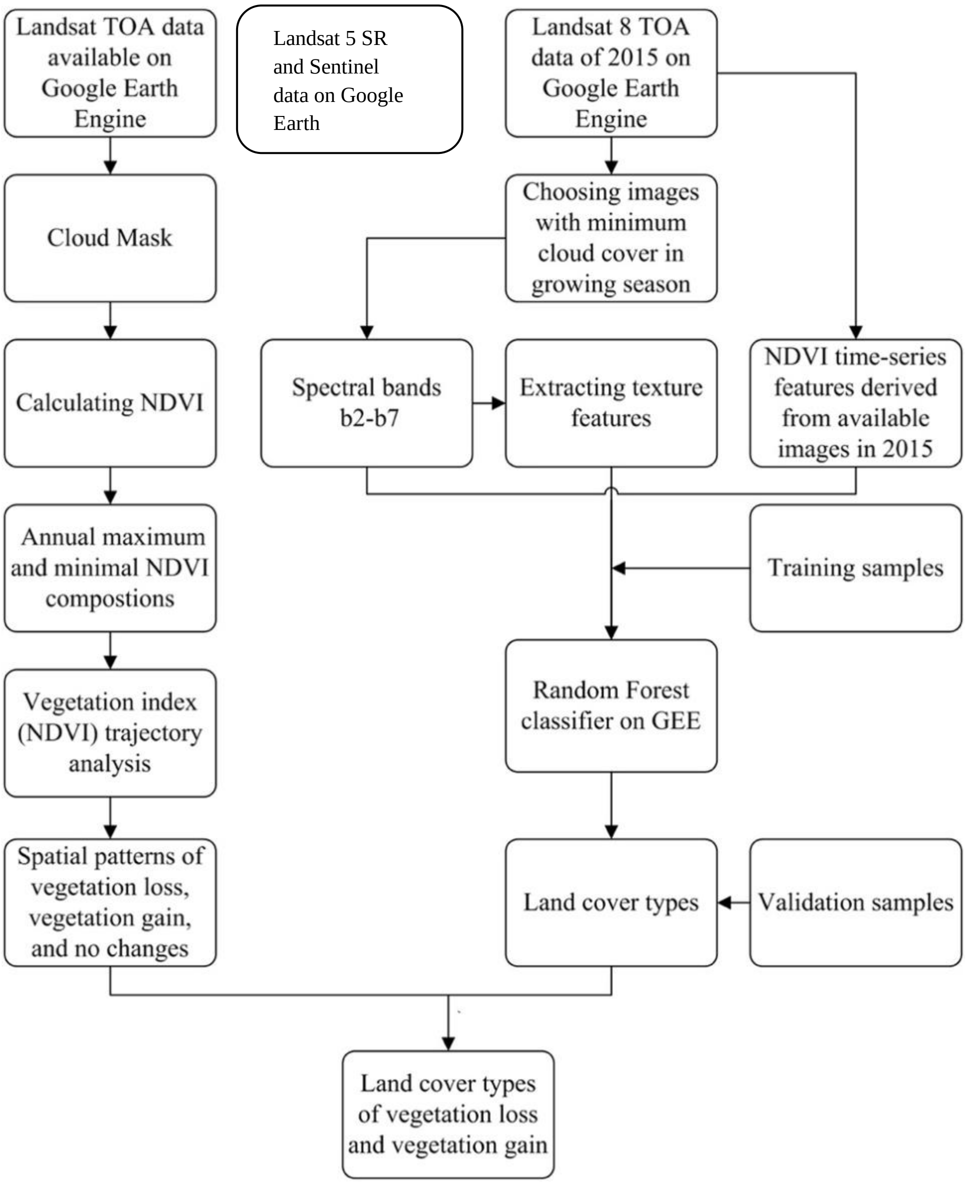


Figure 12: Methodology flow chart adapted from Zhao et al., 2016

4.1. SATELLITE IMAGERY

Distinctive spatial resolution clarifies how much detail in a photographic picture can be seen by human eye. The spatial resolution of pictures recovered by satellite sensor frameworks are commonly communicated in meters (El-Ghany *et al*., 2020). For illustration, in Table 4, Landsat is depicted as having 30 meter resolution (Table 3), this implies that two objects 30 meters long or wide sitting together can be isolated or resolved on a Landsat picture such as within the case of the Knysna study area (-34.077469º E, 23.059276º S). Other sensors may have higher or lower spatial resolutions.

Table 3:Satellite imagery acquired on the Google earth engine website with the various Landsat imagery and Bands utilized for this project.[https://code.earthengine.google.com]

Satellite Images	Band name and wavelength			
USGS Landsat 8 Collection 1 Surface Tier 1 TOA reflectance	B1	0.0001	0.435-0.451 µm	Band 1 (ultra-blue) surface reflectance
	B2	0.0001	0.452-0.512 µm	Band 2 (blue) surface reflectance
	B3	0.0001	0.533-0.590 µm	Band 3 (green) surface reflectance
	B4	0.0001	0.636-0.673 µm	Band 4 (red) surface reflectance
	B5	0.0001	0.851-0.879 µm	Band 5 (near infrared) surface reflectance
	B6	0.0001	1.566-1.651 µm	Band 6 (shortwave infrared 1) surface reflectance
	B7	0.0001	2.107-2.294 µm	Band 7 (shortwave infrared 2) surface reflectance
	B10	0.1	10.60-11.19 µm	Band 10 brightness temperature. This band, while originally collected with a resolution of 100m / pixel, has been resampled using cubic convolution to 30m.
	B11	0.0001	11.50-12.51 µm	Band 11 brightness temperature. This band, while originally collected with a resolution of 100m / pixel, has been resampled using cubic convolution to 30m.
USGS Landsat 7 Collection 1 Surface Tier 1 TOA reflectance	B1	30 METERS	0.45 - 0.52 µm	Blue
	B2	30 METERS	0.52 - 0.60 µm	Green
	B3	30 METERS	0.63 - 0.69 µm	Red
	B4	30 METERS	0.77 - 0.90 µm	Near infrared
	B5	30 METERS	1.55 - 1.75 µm	Shortwave infrared 1
	B6_VCID_1	30 METERS	10.40 - 12.50 µm	Low-gain Thermal Infrared 1. This band has expanded dynamic range and lower radiometric resolution (sensitivity), with less saturation at high Digital Number (DN) values. Resampled from 60m to 30m.
	B6_VCID_2	30 METERS	10.40 - 12.50 µm	High-gain Thermal Infrared 1. This band has higher radiometric resolution (sensitivity), although it has a more restricted dynamic range. Resampled from 60m to 30m.
	B7	30 METERS	2.08 - 2.35 µm	Shortwave infrared 2
	B8	15 METERS	0.52 - 0.90 µm	Panchromatic
USGS Landsat 5 TM Collection 1	B1	30 METERS	0.45 - 0.52 µm	Blue
	B2	30 METERS	0.52 - 0.60 µm	Green

Tier 1 TOA Reflectance	B3	30 METERS	0.63 - 0.69 µm	Red
	B4	30 METERS	0.76 - 0.90 µm	Near infrared
	B5	30 METERS	1.55 - 1.75 µm	Shortwave infrared 1
	B6	30 METERS	10.40 - 12.50 µm	Thermal Infrared 1. Resampled from 60m to 30m.
	B7	30 METERS	2.08 - 2.35 µm	Shortwave infrared 2
USGS Landsat 4 TM Collection 1 Tier 1 TOA Reflectance	B1	30 METERS	0.45 - 0.52 µm	Blue
	B2	30 METERS	0.52 - 0.60 µm	Green
	B3	30 METERS	0.63 - 0.69 µm	Red
	B4	30 METERS	0.76 - 0.90 µm	Near infrared
	B5	30 METERS	1.55 - 1.75 µm	Shortwave infrared 1
	B6	30 METERS	10.40 - 12.50 µm	Thermal Infrared 1. Resampled from 60m to 30m.
	B7	30 METERS	2.08 - 2.35 µm	Shortwave infrared 2

4.2. IMAGE PREPROCESSING

Google Earth Engine (GEE) (https://earthengine.google.org/) according to (Gorelick *et al*., 2017) as cited in (Liu et al., 2020) is a 'cloud-based platform for scientific analysis and visualization of geospatial datasets.' GEE allows high speed analysis utilizing state of the art processing tools for substantial data sets and regions without having to acquire and download large remote sensing data for computational processing. With an impressive amount of servers around the world, it allows for analysis of generally trillions of pictures utilizing parallel processing as well as the utilization of calculations that put together information from different sensors and seasons, a long time or models (Zurqani *et al*., 2018). GEE combines images to determine the best cloud free pixel which results in cloud free images. Satellite images with high resolution that are available in GEE, were used as the reference layer for the validation and training of the classifications. GEE allows for a quick platform analysis using Google's computing systems (Zhao *et al.*, 2017) and (Zurqani *et al*., 2018).

Preprocessed Landsat imagery made easily accessible by GEE was utilized to assess land use/land cover all through the Knysna study region. GEE permits for access to historical Landsat information as a collection of pictures on the USGS online stage (Zhao *et al.*, 2017).

GEE dataset is atmospherically corrected surface reflectance from Landsat 8 OLI/TIRS sensors (Zhao *et al.*, 2017). These Landsat pictures have 5 obvious close infrared (VNIR) bands and 2 short wave bands (SWIR) bands that are handled to orthorectify surface reflectance, with 'Two Thermal Infrared (TIR) bands processed to orthorectified brightness temperature' (Zhao *et al.*, 2017). These data sets have been atmospherically rectified and incorporate shadow, water, snow, per-pixel saturation and cloud mask using CFMASK (Chai et al., 2019). Film lines of collected information are assembled into overlapping scenes covering roughly 170 km x 183km using a standardized reference grid (https://developers.google.com/earthengine/datasets/catalog/LANDSAT_LC08_C01_T1_SR, (Ogilvie *et al.*, 2020).

All the processing of Landsat data was done using cloud computing on GEE (https://earthengine.google.org/). Landsat images 4-8 surface reflectance (SR) were obtained for the years 1980-2019 and were chosen based on the accessibility of high-resolution satellite images for the study areas (-34.077469º E, 23.059276º S) prescribed. An algorithm referred to as 'mask function' was used to select the appropriate Landsat scene by choosing the best cloud and cloud shadow-free images (Zhu & Woodcock, 2012). Image noise and classification inconsistencies can be reduced using data normalization. When utilizing multi-sensor and multi scene pictures it is crucial to utilize this function to diminish the noise caused by the distinctive sensors (Yang *et al*., 2018)

4.2.1. Spectral response over the study area

Our planet's land surface reflects roughly 3% of all approaching solar radiation into space. The remaining radiation is reflected by the atmosphere or could be absorbed and redirected as infrared energy as cited on (*https://www.e-education.psu.edu/natureofgeoinfo/c8_p5.html*). Several objects that make up the surface of the earth absorbs and reflects varying number of energies at different wavelengths. The degree of energy that an item reflects or releases across a range of wavelengths is referred to as a ‘spectral response pattern’ (Zurqani *et al.*, 2018).

Spectral response patterns are often called ‘spectral signatures (Chai et al., 2019). This term can be deceptive because the reflectivity of an object or organism differs with the conditions, or time of year, possibly even the time of day as seen in (Figure 13, Figure 14, Figure 15, Figure 16). As opposed to thin lines, spectral responses could depict certain entities as wide swaths to explain for these variables. The graphs below indicate the spectral response patterns of water, built up area, forestry, and saltmarsh. Water absorbs most of the entering radiation across the entire range of wavelengths. Being aware of distinctive spectral response characteristics it is possible to determine what forest, soil and geological formations are in remotely sensed imagery and to determine their circumstance.

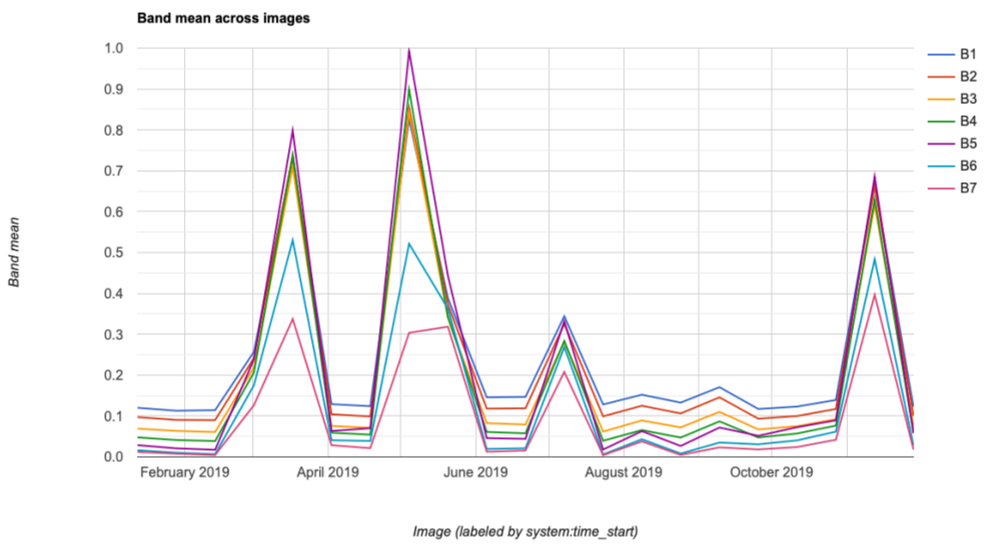


Figure 13:Spectral response of the bands for the water land class

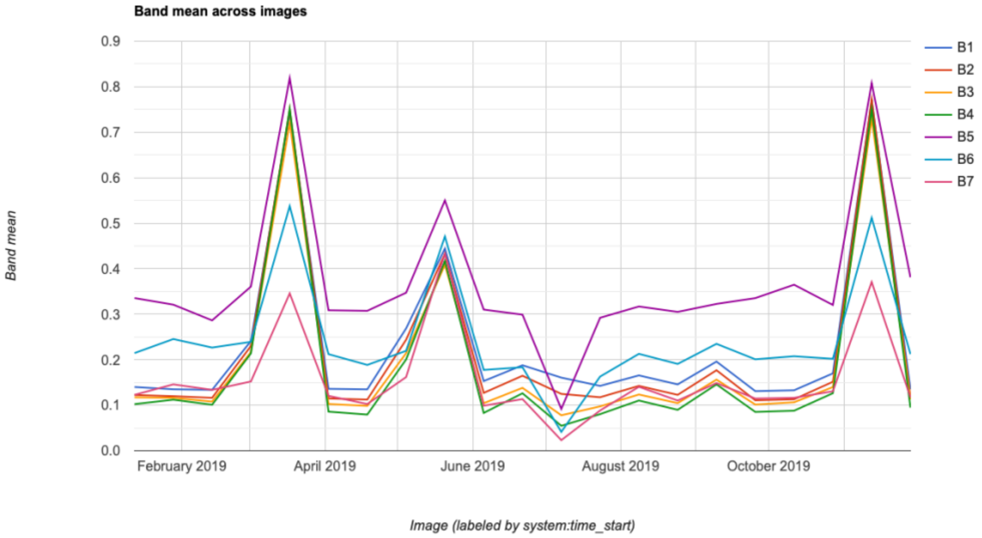


Figure 14:Spectral response of the bands for the urban/built-up land class

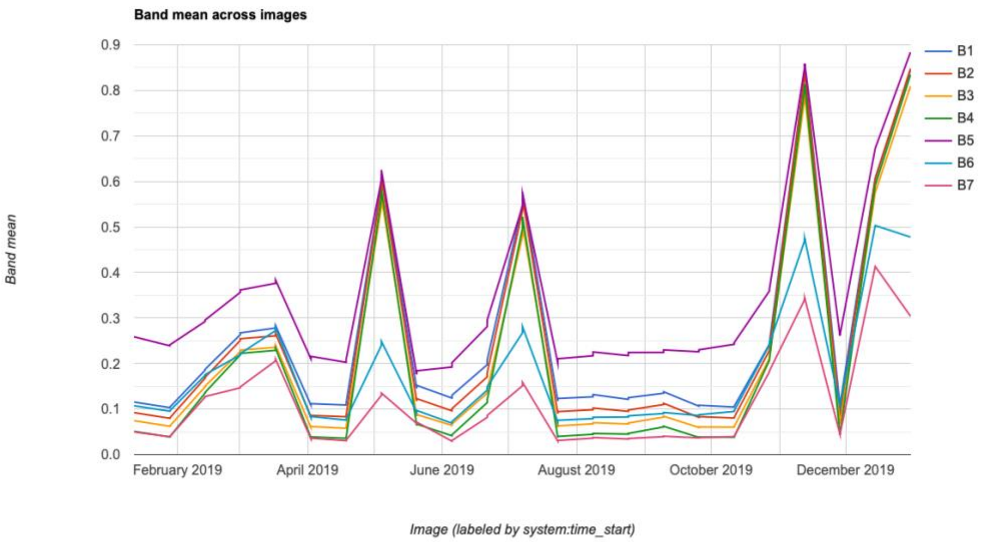


Figure 15: Spectral response of the bands for the afrotemperate/forest land class

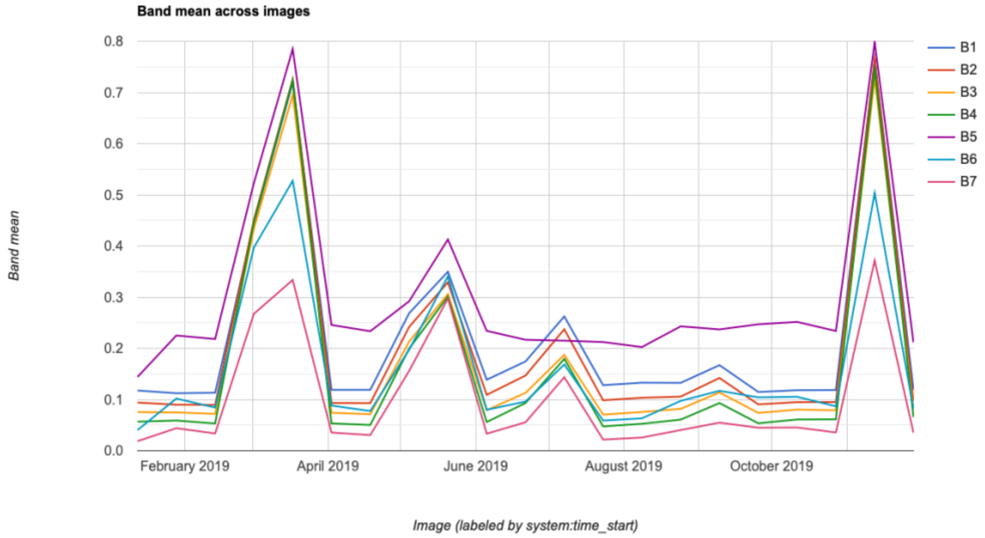


Figure 16: Spectral response of the bands for the saltmarsh land class

4.2.2. Spatial Analysis

Distinctive spatial resolution values depict how much detail in a photographic picture is obvious to the human eye, the potential to resolve or separate diminutive points of interest in what is depicted as spatial resolution (Zurqani *et al*., 2018). The spatial resolution of pictures retrieved by satellite sensor systems is commonly communicated in meters. Electromagnetic radiation sequences are recorded by sensors with separate spectral bands; thus the spectral reflectance curve, or spectral signatures of the different set of ground targets such as the four classes in the Knysna study area (-34.077469º E, 23.059276º S) proved the knowledge base to extract the information. The spectral resolution which contains specific bands (Table 4) is good with identifying specific ground features, while certain bands can create various combinations to identify particular ground features such as vegetation

Table 4: The spectral resolution which contains specific bands as cited from [https://www.usgs.gov/landsat-missions]

• Band 1 (Blue)	• Provides increased penetration of water bodies while supporting the analysis of land use, soil and vegetation characteristics
• Band 2 (Green):	• Responds to the green reflectance of healthy vegetation
• Band 3 (Red):	• Provides for one of the most important bands for vegetation discrimination.
• Band 4 (Reflectance):	• Responsible for vegetation biomass present in the scene
• Band 5 (Mid- infrared):	• Sensitive to the amount of moisture in plants
• Band 6 (Thermal infrared):	• Measures the amount of infrared radiant flux emitted from the surface
• Band 7 (Mid infrared):	• Important for the discrimination of geologic rock formation.

4.3. NDVI (Normal Differential Vegetation Index)

4.3.1. Vegetation indices

Vegetation indices calculated from satellite pictures can be utilized to screen worldly changes related to vegetation (Amutenya, 2020). The normalized difference vegetation index (NDVI) is created for approximate vegetation cover from the intelligent bands of satellite information (Sahebjalal et al., 2019). Besides, the produced NDVI pictures may well be utilized to distinguish the arrangement of changes that happened between two differentiating dates or over a long period of time (Amutenya, 2020,). (Amutenya, 2020) compared seven vegetation indices from precisely three different dates of Landsat MSS picture information for land cover change detection and distinguished that the NDVI differencing method appears the leading vegetation change detection (Sahebjalal et al., 2019). Picture differencing method is utilized in numerous applications; it can be connected not only to pictures of two diverse dates, but also to comparison of vegetation index data derived from various dates of imagery (Sahebjalal et al., 2019). It may be a straightforward condition of subtracting the two distinctive times pixel by pixel to create the differentiated picture (Al Ahbabi *et al*., 2014). When there's a land cover change between two dates, the NDVI differentiated picture ought to have a pixel value greater than or smaller than 0 (Al Ahbabi *et al*., 2014) and (Sahebjalal et al., 2019).

Remotely sensed information of vegetation growth and changes over time can give useful insights for applications that monitor the environment, biodiversity, agriculture, urban green infrastructure, conservation, and other related fields (Xue & Su, 2017). With regards to the different platforms, the advantage of satellite remote detecting information includes a spatial resolution which permits for the removal of long-time data arrangement of comparable and reliable information. There are different vegetation records just like the Ratio Vegetation List (RVI), Distinction Vegetation Record (DVI), and Normalize Difference Vegetation List. NDVI is the foremost commonly utilized vegetation file particularly in research related to regional and worldwide vegetation assessments because it includes a reactive response to green vegetation indeed in low vegetation covered areas (Xue & Su, 2017).

Employing the NDVI (Tucker, 1979; Kennedy *et al*., 2010) allows for the identification of surface vegetation based on brightness, greenness, and wetness. Changes in the Estuary can be very dynamic and even a result of tidal fluctuations. So the advantage of the NDVI approach is that it integrates changes over a longer period and therefore smooths out some of the shorter-term dynamics. Plainly put, NDVI aids to differentiate vegetation from various other types of land cover such as artificial land cover and determines its overall state. NDVI also allows for visualizing and defining vegetated areas on the map as well as showing abnormal changes in the growth process. In this research, four typical land use classes were mapped in the Knysna catchment area: water, bare land (exposed soil), vegetation and urban/ built up areas. Using GEE and GIS the following steps were implemented.

Importing Landsat data

On GEE 'Landsat 8 Surface Reflectance Tier 1' was imported and labelled 'l8sr'. A single point geometry was drawn and a region of interested (ROI) was created labelled 'roi'.

Masking and Filtering bands of interest

The Landsat 8 image was then pre-processed by filtering it to ROI with a GEE code, adding variables and masking clouds.

Plotting the NDVI time series

A chart was then made at the ROI which included a trend line for reference purposes. To decrease the time required for the classification of the high-resolution pictures, a portion of the study area (-34.077469º E, 23.059276º S) that contained the four typical land use classes was utilized to create the classification approach advance. The NDVI was calculated utilizing the close infrared (NIR) and red bands, utilizing the Stretched Renderer display. This makes use of raster cell values across a ramp of colours (Jenny *et al*., 2014). The Stretched Renderer is used to draw a band of continuous data and works well when there's a huge range of values to show in imagery and aerial photos (McDonnell, 1995) as cited in (Jenny *et al.*, 2014). The images were then downloaded and imported into Arc GIS. The formula for NDVI is as follow:

$$NDVI = \frac{\text{NIR} - \text{Red}}{\text{NIR} + \text{Red}}$$

4.4. LAND COVER CATEGORIES AND REFERENCE DATA

The Knysna catchment and Estuary can be classified into at least six classes of land cover: 1- Water bodies and wetland, 2- Plantation/ Alien Vegetation, 3- Cultivated Land 4- Natural Wooded Land / Natural/Afromontane Forest 5- Fynbos Shrubland and 6- Built

Up/Urban Area. The reference data is pivotal to the precision of remotely detected data (Congalton & Green, 2019). More than 100 focuses were defined for each year from 1980-2019, individually, based on the availability of high-resolution pictures, with the thought of more than 50 reference focuses per land cover category (Zurqani et al., 2018).

4.4.1. NDVI MAPPING AND ANALYSIS

The NDVI is a key tool to recognize changes in land use / cover change. Viable aspects of land cover can be concluded through targeted values of the NDVI. Currently, the interpretation of the NDVI index are often used in studying land use change, particularly the change in urban development. Results of the NDVI values (Table *5*) for this study have indicated fluctuations in vegetation productivity due to several factors including urbanisation and other forms of land use change as a result of population growth and economic development.

Table 5 : Vegetation classes and their NDVI value thresholds adapted from (Hashim *et al* ., 2019)

Vegetation classes	Description	NDVI value
Non- vegetation	Barren areas, built up area, road networks, etc	-1 to 0.199
Low vegetation	Shrub, saltmarsh, agriculture and grassland	0.2 to 0.5
High Vegetation	Tropical urban and temperate forests and Plantation	0.501 to 1.0

4.5. SUPERVISED IMAGE CLASSIFICATION

Modern machine learning techniques with deep learning capability have made labour intensive object detection, semantic segmentation and generic picture classification easier to make (https://www.azavea.com/blog/2019/11/05/an-introduction-to-satellite-imagery-and-machine-learning/). Through the process of supervised learning, the model has provided multiple annotated data, while training itself to mimic the handmade examples.

Referring to the land use classification process or machine learning technique in (Figure 17), '1' indicates the various land use classes namely urban, water, barren land and vegetation. '2' indicates which Landsat image is being used. This varies throughout the process as different Landsat images coincide with different years. Lastly, '3' indicates the console box where the output data is displayed such as a graph or image indicating the various changes or results. As seen in (Figure 17), different satellite images are easily identifiable by their array of bands. GEE proved instrumental in classifying the various land uses by using the java script code. This allowed for classification to take place within minutes, thus saving time on the research itself.

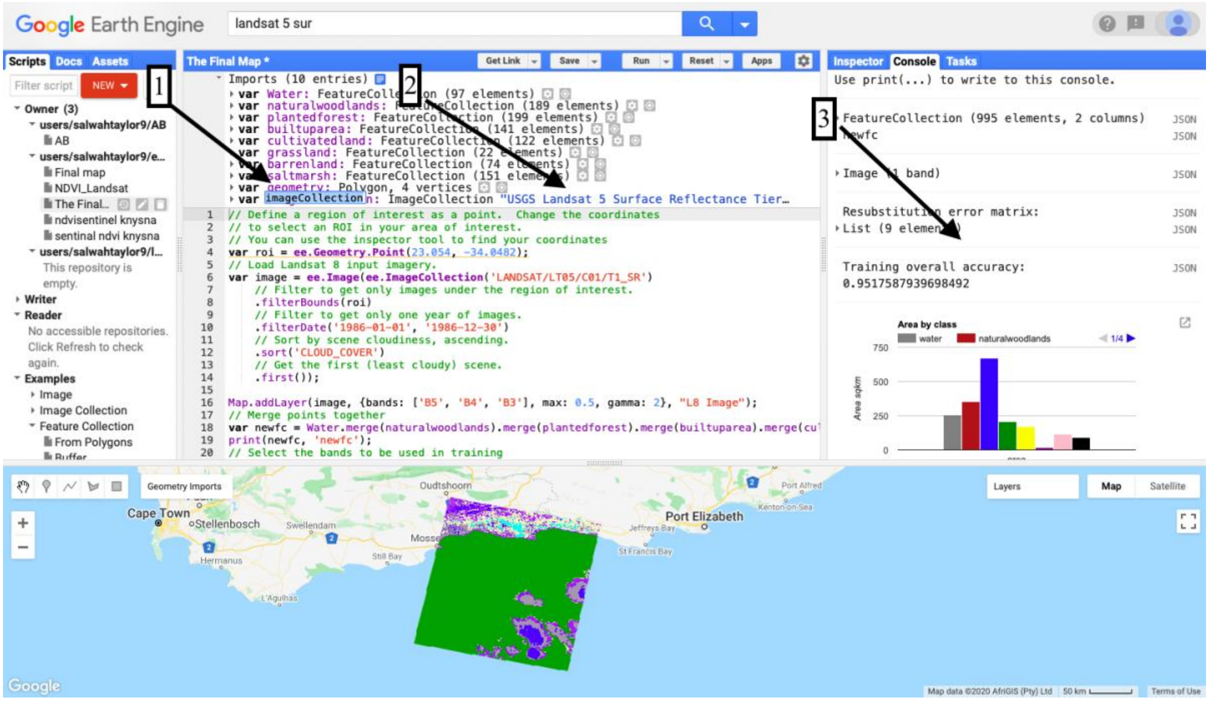


Figure 17: Land use classification process on GEE, where 1 indicates the various land use classes, 2 indicates which Landsat image is being used and 3 indicates the console box where the output data is displayed such as a graph or image indicating the various changes or results.

There are various machine learning algorithms, namely support vector machine (SVM), Decision Trees, Linear and Logistic Regression and Random Forest (RF). In this study RF has been selected. An RF algorithm is made up of decision trees, which are graphs of choices showing their course of action or the statistical probability as seen in (Figure 18). The multiple trees are mapped to one tree which is referred to as the Classification and Regression Tree (CART) Model. To name an object based on the attributes it possesses, each tree gives a classification that is said to 'vote' for that particular class. The forest method then picks the classification with the majority votes. For regression the average of the output of different trees is considered.

Supervised classification was used due to its potential to overcome the uncertainty of classes of segments and the strong transferability of rules. Several land use classes were mapped in the Knysna catchment area, namely water, vegetation, barren land and urban/ built up areas. The vegetation class was further subdivided into the following categories: plantation forestry, Fynbos, afrotemperate forest, salt marshes, and agriculture. Supervised image classification was done using the GEE Application programming interface (API) and ArcGIS. Furthermore, detailed identification of vegetation areas was identified using information acquired from SANBI, GEOSPATIAL REPP online database as well as NASA online (remote sensing data). The reclassification of the data set was completed using the reclassification tool on ArcGIS. After the reclassification of the data set, the supervised classification produces results for the respective years. The code used in this research was acquired and adapted from the Geospatial and Ecology online database.

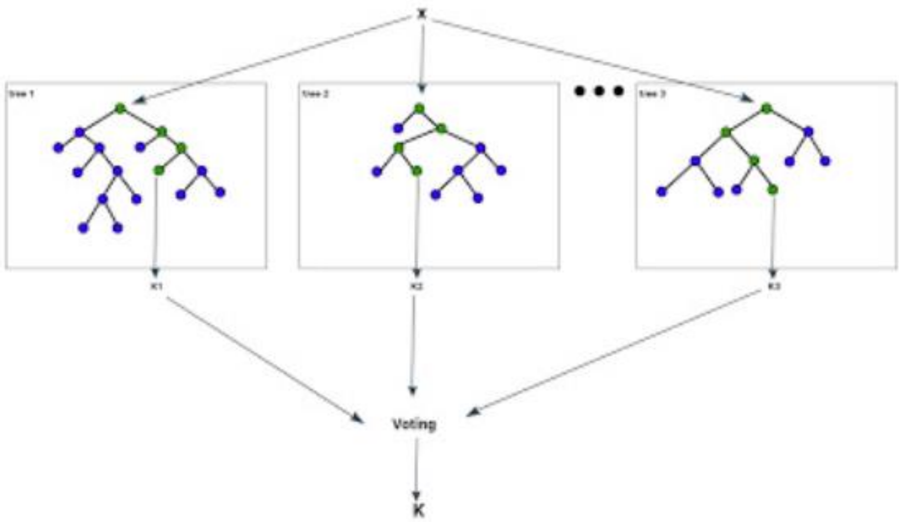


Figure 18: A visual representation of the random forest algorithm as cited in (Pachanekar, 2019)(https://blog.quantinsti.com/top-10-machine-learning-algorithms-beginners/#randomforest)

4.5.1. Classification in GEE

GEE allows users the opportunity to cover a variety of advanced analysis which includes object machine learning such as supervised classification. The idea is to produce a classified map of land cover for the study area. The study area is examined manually to identify a cluster of training points for the various classes. The training points were then used to train the classifier. The classifier was used to classify the rest of the Landsat image into various categories. The accuracy of this assessment was then tested. These steps are further discussed below.

4.5.2. Creating the region of interest (ROI) of the study area.

The study area was defined and labelled ROI, as opposed to using an imported asset, 4 coordinate was manually defined and plotted. The study area was the Knysna Estuary and thus the Estuary was the focus point of the coordinates (9)

4.5.3. Loading and filtering the image collection

The Landsat image and filter to the area and dates of interest were loaded and the *sort* filter used to filter the *ImageCollection* by cloud cover percentage (%) to generate a study area that included the Landsat image at Top of the Atmosphere (TOA) collection. The *first* or least cloudy image was arranged and selected from '*Image Collection'.*

4.5.4. Collecting the training data

The next step involved collecting the training data. Using the images as a guide, employing the '*Geometry Imports'*, each new layer indicates a single class in the training data. Thus, layer 1 was urban area, layer 2 water bodies etc. When the collection of the points was completed, configuration (Figure 11) and importing took place. The various layers were labelled 'urban' etc. and configured. These layers were then imported as a '*Feature collection*.

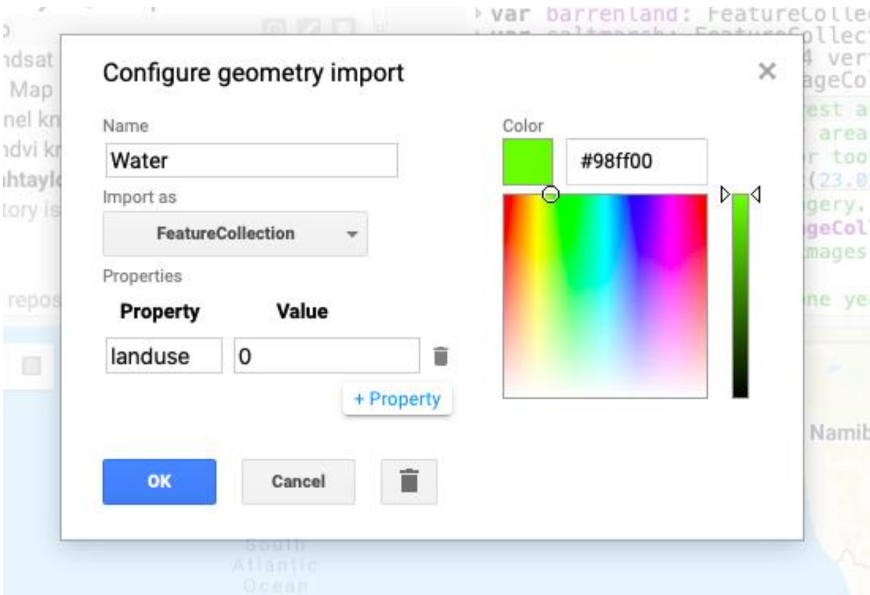


Figure 19:Configuring the image collection into a single land use feature and colour

When the *feature collection* for each land use class was completed respectively, they were then merged into one using *featureCollection.merge ().* This converted all the points into one collection where the property landcover has a value that is the class (1,2,3,4,5,6,7,8)

4.5.5. Sampling Images at Training Points to create training datasets

Once the labels and points were created, Landsat imagery sampling was conducted using *image.sampleRegions ( ).* This command allowed for the extraction of reflectance in the respective bands for each of the points created. Reflectance from the optical, NIR and SWIR bands (B2- B7) were used. The feature collection training has the reflectance value from each respective band stored for each training point together with tis class label. (APPENDIX)

4.5.6. Training the classifier

A classifier using *Classifier.randomForest ()* was used to express and *train* the data specifying the features using (training), the landcover categories as the *classProperty,* to categorise the imagery into, and the reflectance in B2-B7 of the Landsat imagery as the input properties.

4.5.7. Classifying the image and displaying the results

The new classifier was then used to classify the rest of the images using a particular code found in the (APPENDIX) section.

4.6. ACCURACY ASSESSMENTS

Before any maps could be produced, the statistics on Landsat and aerial images were calculated on ArcGIS for mosaic and Rasta datasets. This allows ArcGIS to carry out certain tasks, namely applying a different stretch, symbolizing raster data for display, the classification of data, and allowing to properly stretch and symbolize raster data for display. A classification algorithm can be defined according to Arora *et al* (2010) as a process where a single or group of pixels of remote sensing images are assigned to a land cover class, with the aim being to place each pixel into one class. Therefore, a large range of classification algorithms has been utilized to precisely outline the variations in land cover/ arrive utilize from remotely detected data (Milani *et al.*, 2018).

Accuracy assessments are an effective and valuable method to show how precisely the classification process carried out the task. (Tsutsumida and Comber, 2015). A confusion matrix, according to Tharwat (2020), could be a table that's frequently utilized to outline the performance of a classification model or 'classifier' on a sample of test information, where the true values are known. A confusion matrix of land cover maps was calculated to approve the accuracy of the results utilizing Kappa statistics (Congalton & Green, 2009). This accuracy assessment was done on GEE using an accuracy code. It was calculated utilizing the formula where the value of Kappa lies between 0 and 1, where 0 shows an agreement due to chance only, and 1 speaks to the total agreement between the two data sets (Shafri *et al.*, 2022) Negative values occur when a classification is more than random, but this is very unlikely. The result is usually expressed in a percentage (%). The accuracy assessment for this research was completed on GEE using the following code.

The accuracy of supervised classification for optical remote sensing data prescribed by Jansen et al. (2008) is deemed acceptable only if data exceeds 85% (Figure 20).

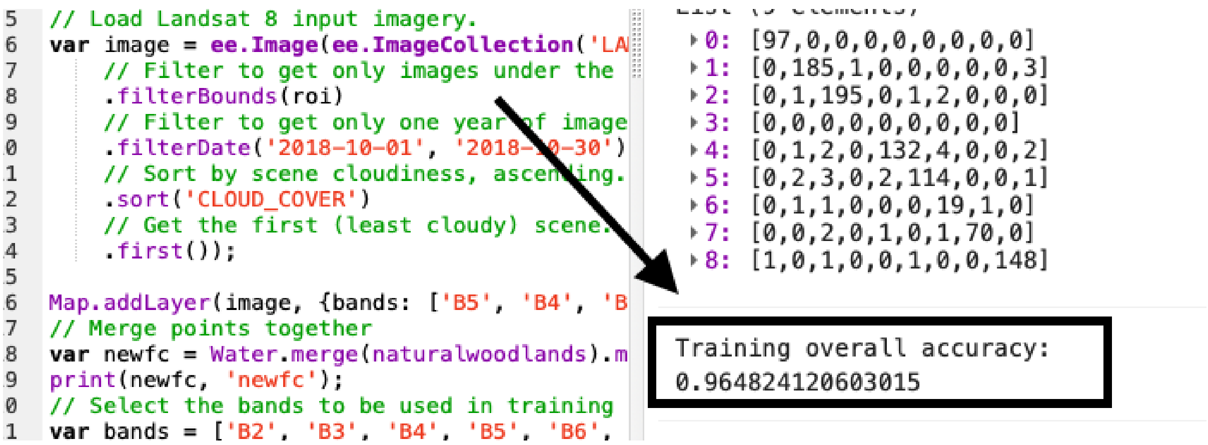


Figure 20: Accuracy assessment performed on GEE

4.6.1. Error Matrix

Overall, accuracy assessment results in an accuracy confidence percentage to estimate class error and bias, thus improving the confidence of the research. Accuracy assessments improve if classes in the classification, namely water, vegetation and urban, are not too ambiguous while the confusion matrix identifies overall errors from the user and the production of the map. A Kappa value of 0.5 to 1 reflects the agreement between data sets (Campbell & Wynne, 2011). ENVI 5 and ArcGIS-Pro runs an accuracy assessment and kappa coefficient automatically. However, in this research, the use of GEE online coding system enabled an accuracy assessment code to determine the accuracy assessment of the study area results. The Kappa coefficient is the accuracy assessment measurement used in this study imported directly from GEE using Java script coding. The Kappa method is utilized as a more present day measurement of the classifier understanding and hence comes about in superior interclass separation than in general accuracy. Exporting the image

4.6.2. Exporting the image

The image was then labelled and exported to the google drive where it was saved and exported to ArcGIS.

4.6.3. Ground truthing

Ground truthing is defined as information provided by direct empirical evidence as opposed to information provided by interference, i.e. comparing these results to the position in the field (Grabinsky et al., 2010). The importance of ground truthing is the measurement, collection as well as observation of earth surface material that has been sensed remotely, such as vegetation and land cover. This can also be used to check the accuracy of data collection and results. The ground truthing locations were verified through fieldwork in April 2019 with 15 sites inspected with 6 key sites mapped using Firefly ArcGIS online (http//:www.gisonline.com). The ground global poisoning system (GPS) points were taken with google maps cellular phone for the various land cover types that had been imported with the training dataset in GEE, while checking the predictive models' accuracy in this case random forest technique (Figure 21).

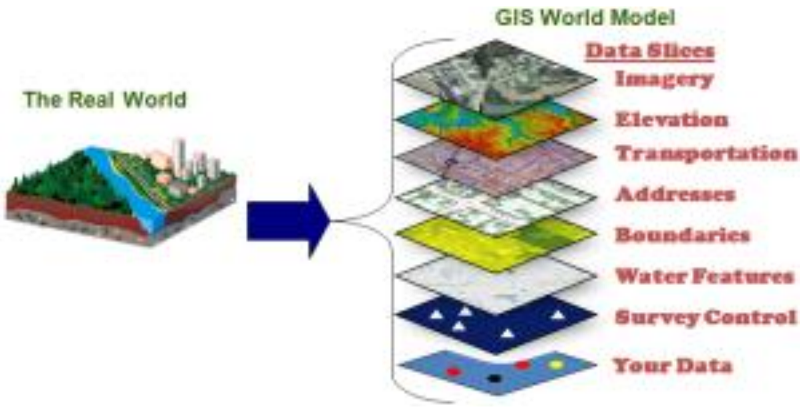


Figure 21: The visual process of ground truthing using a GIS platform cited in Gabrinsky (2010)

4.6.4. Land cover change detection

Change detection analysis distinguishes the incongruities between pictures of the same region at distinctive times (Zurqani *et al*., 2019). The land cover classification pictures of the different years were also utilized to decide the range of the different land use classes and recognize the changes that are taking place over time (Zurqani *et al*., 2019). The land cover changes are shown employing a mosaic plot strategy to permit for the visual show of measurable land use loss or gains (Tsutsumida et al., 2016). The threshold values for determining change may shift for the different sorts of land use alter (Zhu et al., 2012). The land use change module (*Error! Not a valid bookmark self-reference.*) works by reviewing various historical changes between land cover maps of various time periods combined with variables. Variables include accessibility to forest or distance to roads in order to create a layer of expression of transition potential which is possible that land use will change in the future. Future change in land use can be modelled by Markov chain analysis or through a transition probability matrix (based on an econometric model) (Mason-D'Croz *et al*., 2016).

Table 6: Studies using land use models to asses changes in ecosystem services cited from (Mason-D'Croz *et al*., 2016).

Data source	Spatial resolution	Spatial extent	Temporal resolution	Temporal extent	Thematic properties
Remote sensing/Aerial photography	Dependent on sensor (remote sensing mostly between 0.6 m and 1 km).	Dependent on sensor. Coverage is limited in case of clouds (not for radar).	Frequent. Depending on sensor/satellite.	Depending on launching and lifetime of sensor. Few remote sensing data are available before 1970s. Except for aerial photographs.	Land-cover classes. Classification is based on sensor characteristics and user preferences.
Census/ survey data	Administrative units.	Often national level.	Infrequent. Depending on census, often less than every 10 years.	Country specific depending on statistical system.	Focus on economic sectors (mostly agriculture and forestry).
Land-use maps based on field survey	Dependent on scale of mapping (often between 1:25,000 and 1:1 million).	Varying.	Often made for one year only.	-	Varying and fixed within a specific map.
Participatory maps	Dependent on scale of mapping.	Often restricted to territory of one or more communities.	For one moment only.	Participatory back casting possible.	Depending on purpose of mapping.
Cadastral information	Precise information at property level.	Dependent on cadastral system.	Continuously updated.	Often available for long time period.	Limited to tenure conditions with limited information about land use especially in urban environments.

4.7. CONCLUSION

Through the application of the GEE geospatial analysis platform, 35 years of satellite imagery could be accessed readily online, thus allowing for the analysis of real time changes on the earth's surface. The present study of the Knysna area utilized the preferences of the modern geospatial innovation of GEE along with the historical record of Landsat imagery obtained from the NGI to examine the land use changes inside the Knysna study area. There exists a assortment of land covers present within the Knysna area with a substantial region along the river engulfed by deciduous forest and wetland, whereas the larger part of the study area is secured by evergreen forest and agriculture. GEE permits for a quick investigation platform by utilizing Google's computing infrastructure (Zurqani et al., 2017). Pre-processing Landsat imagery, accessible through GEE, was utilized to assess land use and landcover change over the study area (Zurqani et al., 2017).

The analysis of the various methods incorporated and outlined above provides a framework on which changes in the natural processes can be measured. The interpretation of these methods will aid in the understanding of land use change and its effects on the geomorphology of the Knysna catchment and Estuary (Dams et al., 2007).

Chapter 5

5. RESULTS

This chapter presents the results and interpretation of the NDVI analysis and land use change data for the Knysna catchment and Estuary. NDVI brings forth a common sign of the distribution and efficiency of the vegetation and reflects its biomass and is illustrated as a series of maps accompanied by harmonic and linear average line graphs (Figure 28). This is followed by a description of the land use changes (Figure 25) recorded in the catchment and Estuary as derived from Landsat and GEE using a supervised classification technique. Six major land use categories were identified: 1.Cultivated land, 2.Natural Wooded land, 3.Fynbos Shrubland, 4.Planted forest/alien vegetation, 5.built up/Urban Area, and 6.Waterbodies.

The land use classification results then provide more detail as to what was happening in the catchment and Estuary for the period 1984-2019. It is qualitatively and quantitatively displayed and described throughout various sections of the catchment and estuarine area. This is then followed by a visual ground truthing display and analysis of population statistics. Finally, an accuracy assessment for the data is presented for the years 1984-2019. According to Machiwa (2010), an overall accuracy of 60% is acceptable while according to Im et al., (2008) accuracy is deemed acceptable only if data exceeds 85% (Figure 20).

5.1.NDVI ANALYSIS OF THE CATCHMENT

The Knysna Estuary exhibits a wide variety of vegetation types distributed according to the variable topography. The NDVI analysis in 1984 (Figure 22) indicated a shrubland mean NDVI 0.4) as a dominant land cover, covering a large proportion of both the east and west of the catchment. This is supported when looking at the land cover classification as well as ground truthing evidence presented later on in this chapter. The western side of the catchment is covered with patches of vegetation (mean NDVI 0.7) which indicates afrotemperate forest or plantation; this can be seen fluctuating up until 2016 (Figure 22). The area to the north west of the catchment remains fairly consistent in the size of the afrotemperate forest or plantation. This is confirmed through the NDVI as well as the classification and accuracy assessment.

Between 1984 and 1986 (Figure 22) an increase in the urban area can be seen on the eastern side of the catchment with an annual mean vegetation reflection of 0.0-0.1. In 1987, the northeast of the catchment indicates a high mean NDVI value of 0.7 the same as in the years 1984 and 1986. In comparison to 1987, 1989 vegetation decreases dramatically in the northeast of the catchment where the vegetation index went from 0.7 to 0.4. In 1993, the northeast of the catchment remains fairly the same with an index of 0.7. In 1995 (Figure 22) there is an average NDVI of 0.2, particularly along the eastern meander of the Estuary. NDVI in the distal part of the catchment ranges between 0.6 and 0.7.

In 1997 (Figure 22) there is a slight decrease in vegetation index on the western end of the catchment as well as in the north east of the catchment, where the average has decreased from a high vegetation index of 0.7 to 0.4. In the year 2000 there is a change in the northeast of the catchment compared to the year 1997 where the average has risen from an average NDVI of 0.3 to a high of 0.5. Furthermore, in 2001 (Figure 22), a significant change in the catchment can be seen throughout the entire western end as well as southwest of the catchment with an average of 0.7- 0.4 on the NDVI scale.

In 2002 and 2004, there was an increase in NDVI values, from an average vegetation index of 0.4 to an average of 0.6. In 2005 there was an increase in developments northeast of the Estuary which can be seen in (Figure 22). In 2007, the northeast of the catchment NDVI remains at a high of 0.4 while the west remained at an average of 0.6. In 2008 and 2010, the northeast of the catchment remains at an NDVI of 0.4 while the west of the catchment increased to an index value of 0.7.

In 2011 the northeast, as well as northwest of the catchment remain at an NDVI average high of 0.7 while southwest of the Estuary around the meander the average remains at 0.3. In 2013 and 2016, the northeast of the catchment had an NDVI average of 0.6; there also remains a patch of the area in the northeast and southwest with an NDVI average of 0.2. Lastly in 2019, both the east and the west of the catchment area remained fairly the same with an average of 0.4 while the distal border remained at an average value of 0.3.

5.1.1. NDVI Analysis of the Estuary

During 1986 there is a visible change in the amount of salt marsh in the Estuary with a mean NDVI of 0.2 with an increase in salt marsh particularly in the northwest of the Estuary. The southwest has an average value of 0.4, which remains approximately the same as previous years.

From 1989, the encroachment on the salt marsh within the Estuary is evident, salt marsh patches had increased in size, particularly within the centre. The salt marsh patch adjacent to the meander had also increased in size, while the distal end remained fairly constant. A gradual decrease can be recognized in the flood plains vegetation from the year 1984 up until 1989. From 1991 to 2010 the Estuary shape becomes irregular with the gradual enlargement of the Estuary itself presented in the Landsat data (Figure 22) However, this is due to the season in which the aerial photography was taken that led to fluctuations in the tides.

By 1993, the salt marsh patches in the centre of the Estuary had been divided into multiple sections. The proximal part of the Estuary salt marsh patches had joined together, forming larger patches while the centre salt marsh patches had also increased in size; this can be seen with a mean vegetation index reflection of 0.2. The distal part of the Estuary had salt marsh patches increase in size, indicating one new patch of salt marsh within the Estuary. In 1995, the proximal part of the Estuaries salt marsh patch had migrated slightly southward, with the centre of the Estuary merging and increasing in size.

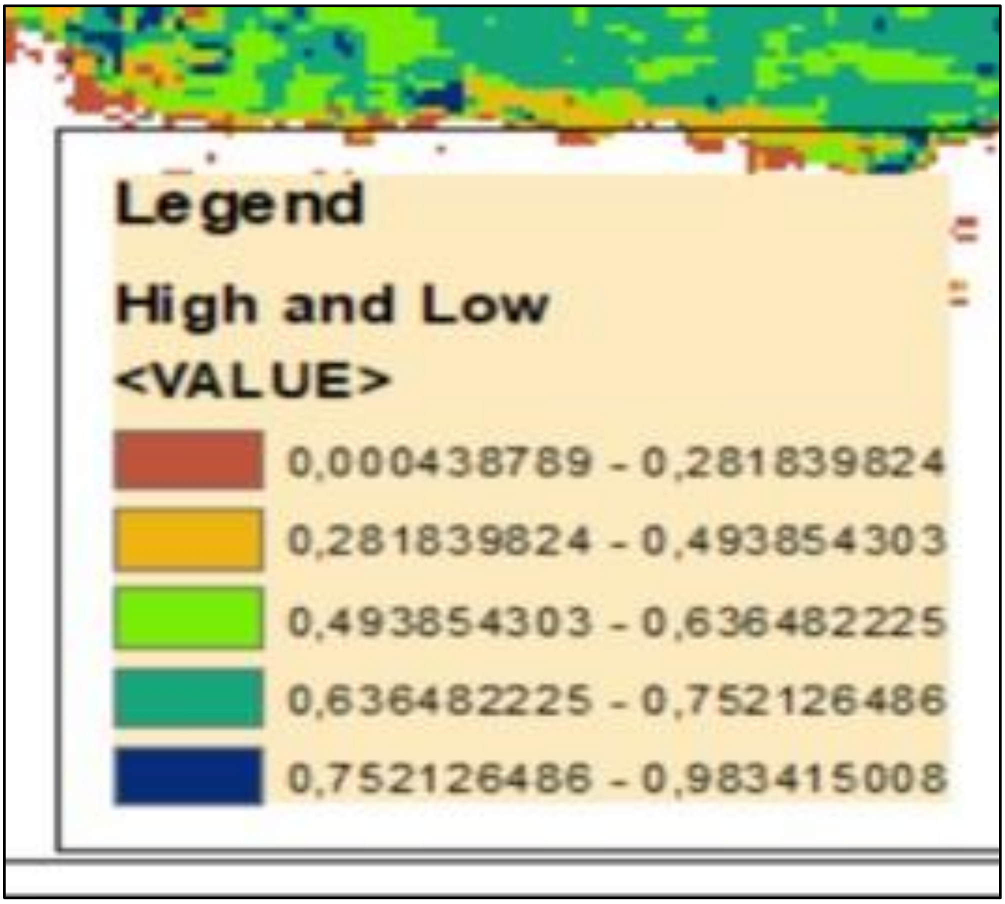
The distal part of the Estuary salt marsh patches had also merged and increased in size. Moreover, in 1997, the proximal salt marsh patch had increased in size while the centre patch of the salt marsh had slightly decreased in size. The distal salt marsh patch then continued to gradually increase in extent. In the year 2000, the salt marsh patches in the south have almost completely disappeared with the centre patches also decreasing in size. In 2002, (***Figure 5)*** the proximal patch of the salt marsh had increased significantly while the centre patch had decreased in size, with the distal patch of salt marsh staying somewhat the same in size.

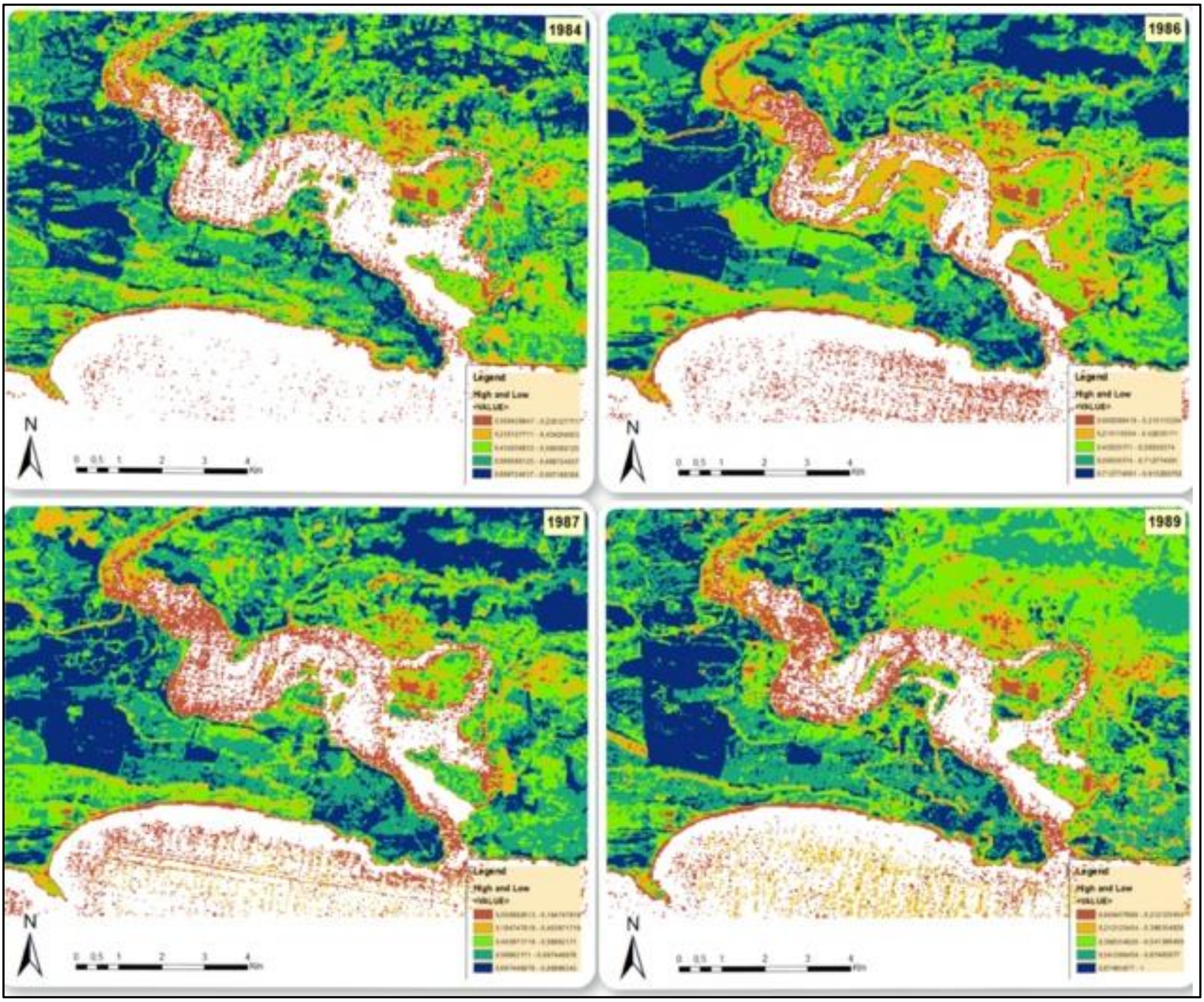
Continuing in 2004, the proximal salt marsh patches remain unchanged while both the centre patches as well as the distal patches of salt marsh increased in density but not size. In 2007, a significant amount of change can be seen throughout the entire Estuary; in the proximal part, salt marsh patches had increased vastly. The centre of the Estuary salt marsh patches increased in size and quantity as well as in the distal part of the Estuary. By 2010, salt marsh throughout the entire Estuary had decreased in percentage and continued to decrease overall in 2011.

By 2014, salt marsh patches began to increase once again, predominantly in the proximal and centre part of the estuary. In 2016, the proximal part of the Estuary had almost been entirely cleared of salt marsh patches, while in the centre small patches of salt marsh began to disappear. Within the distal end of the Estuary, elongated patches of the salt marsh had remained. In 2018, the entire catchment area had an average NDVI value of 0.4. By 2012, the salt marsh across the Estuary began to reduce in size and by 2018 the amount of salt marsh present in the Estuary had significantly decreased.

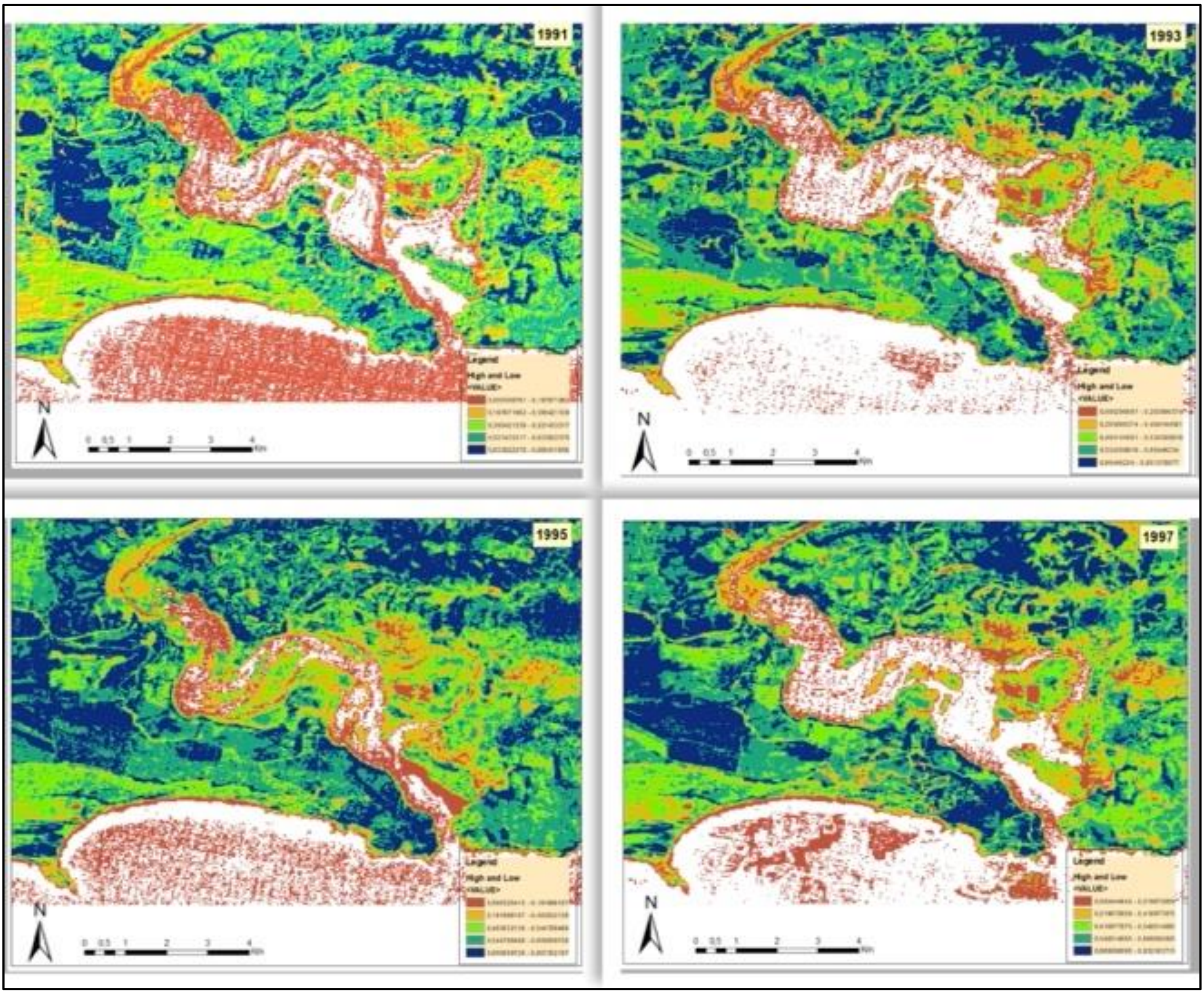
In 2018, both the proximal and distal patches of the salt marsh had decreased in size while centre salt marsh patches remained relatively the same. There is a visible increase of urban area on Thesen Island in the estuary since 2016 with a presented vegetation index of 0.1. There are various changes in vegetation cover within the Knysna study area as shown in (Figure 22). The results of the land cover analysis had confirmed the increase of non-vegetative classes as a result of the increase in urban areas.

a)

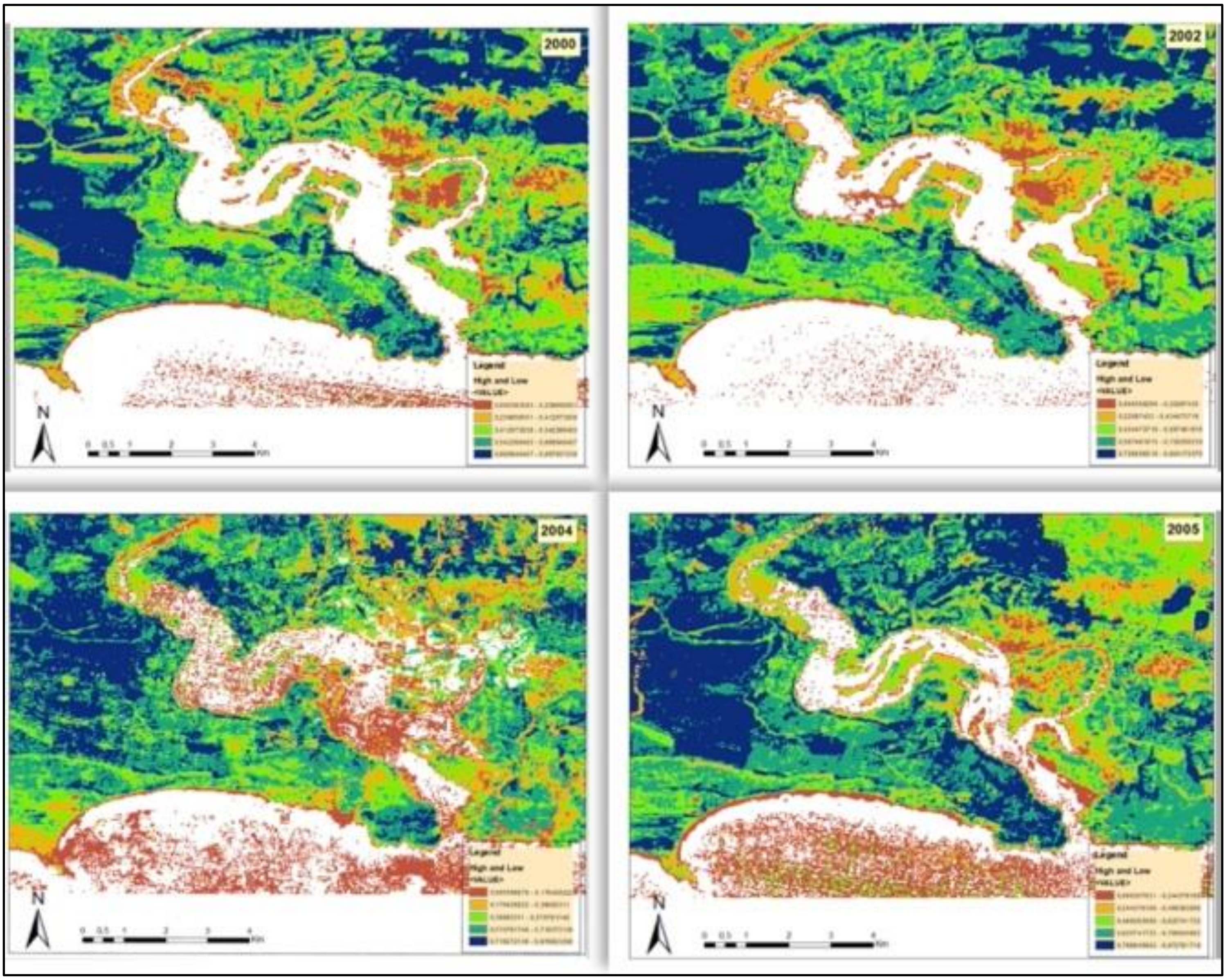



1984
1986
1987
1989
Legend
High and Low
<VALUE>
N
0 0.5 1 2 3 4
Km

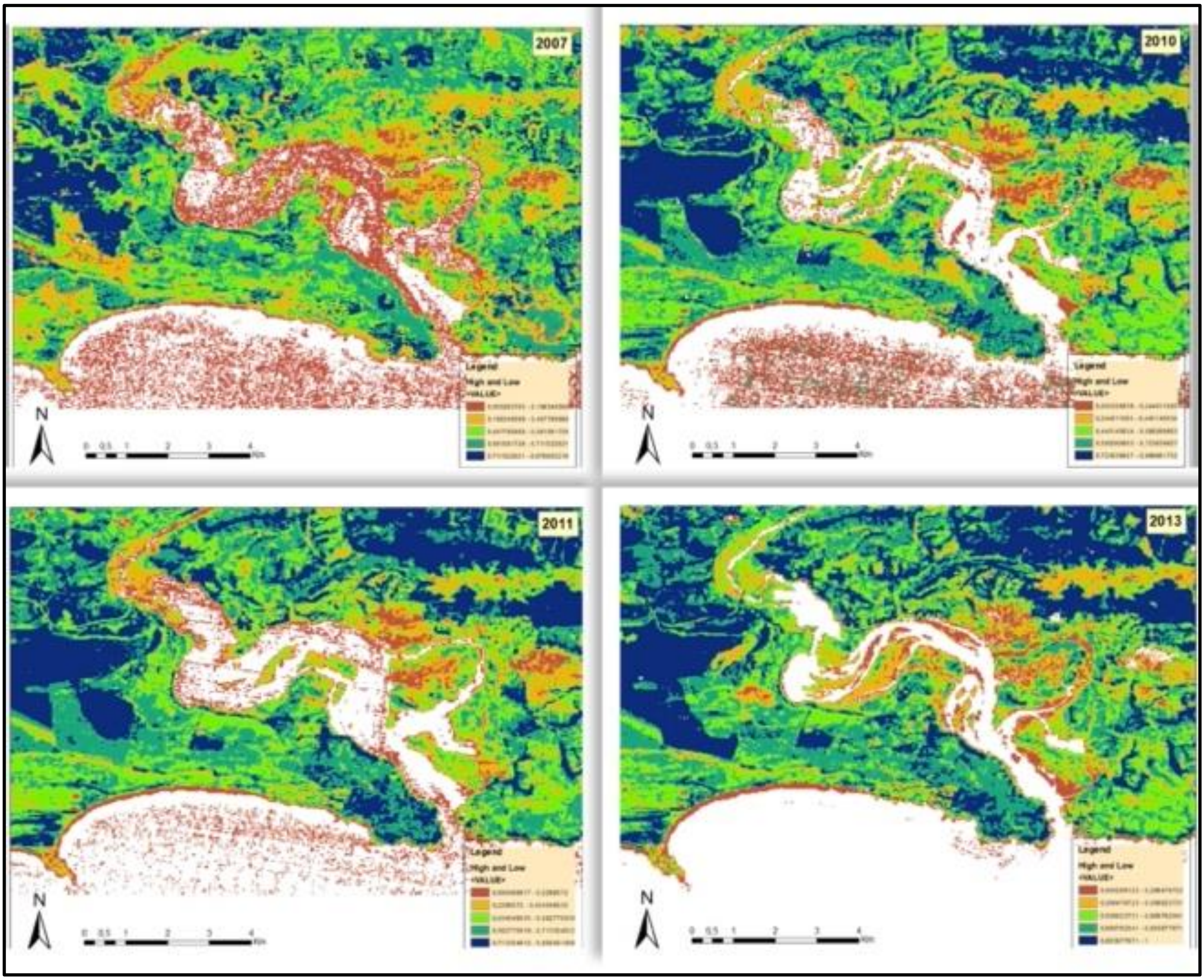
b)



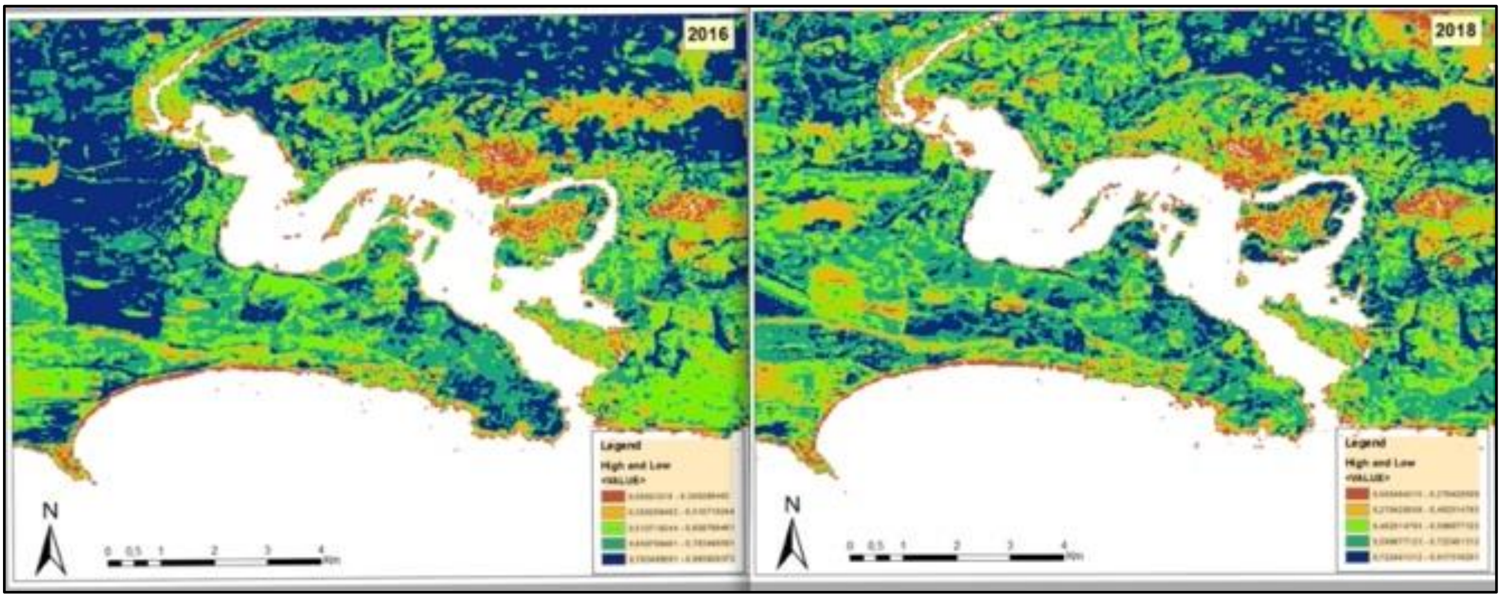
c)


2000
Legend
High and Low
<VALUE>
N
2002
Legend
High and Low
<VALUE>
N
2004
Legend
High and Low
<VALUE>
N
2005
Legend
High and Low
<VALUE>
N

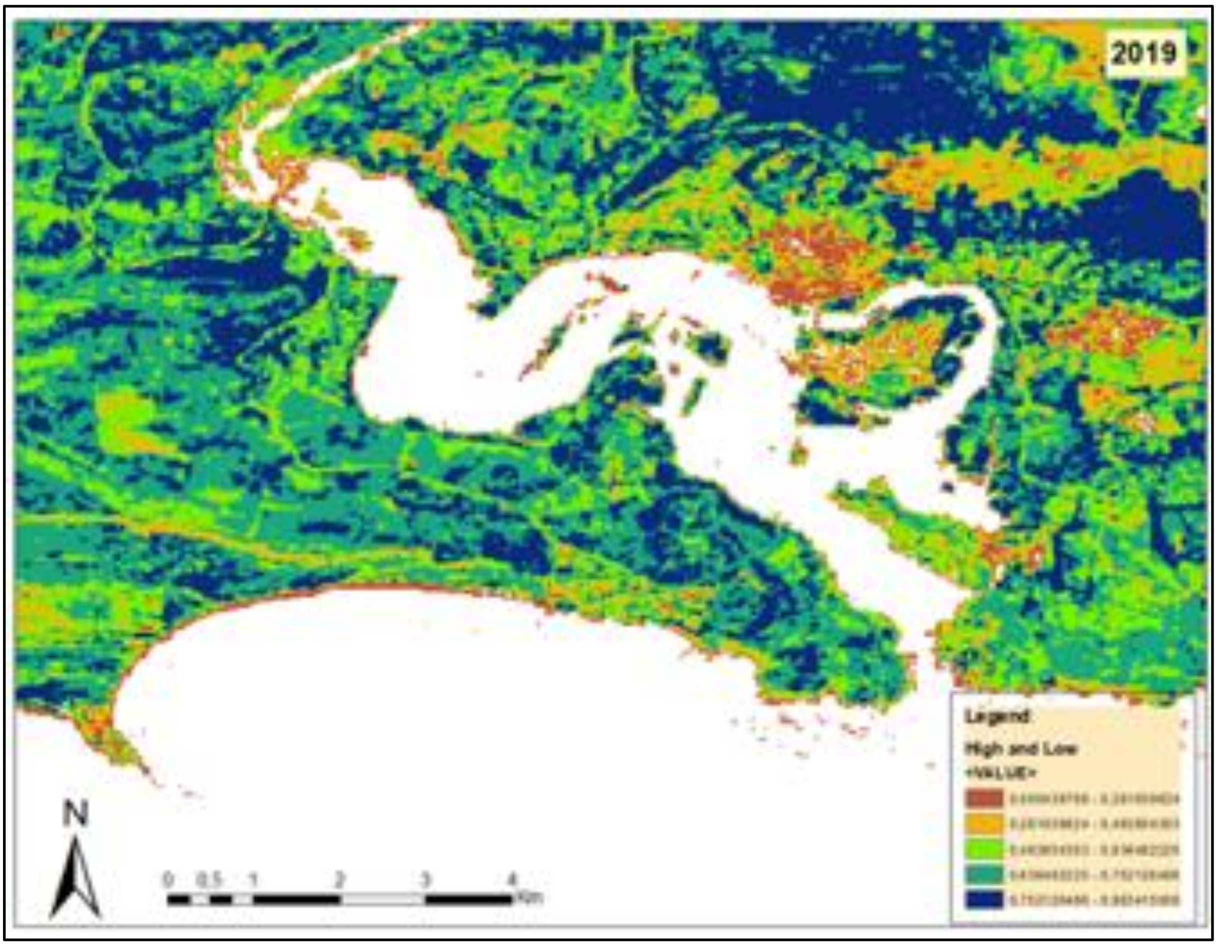
d)



e)


2016
2018
Legend
High and Low
<VALUE>
N
0 0.5 1 2 3 4
Km

f)


2019
Legend
High and Low
<VALUE>
N
0 0.5 1 2 3 4
Km

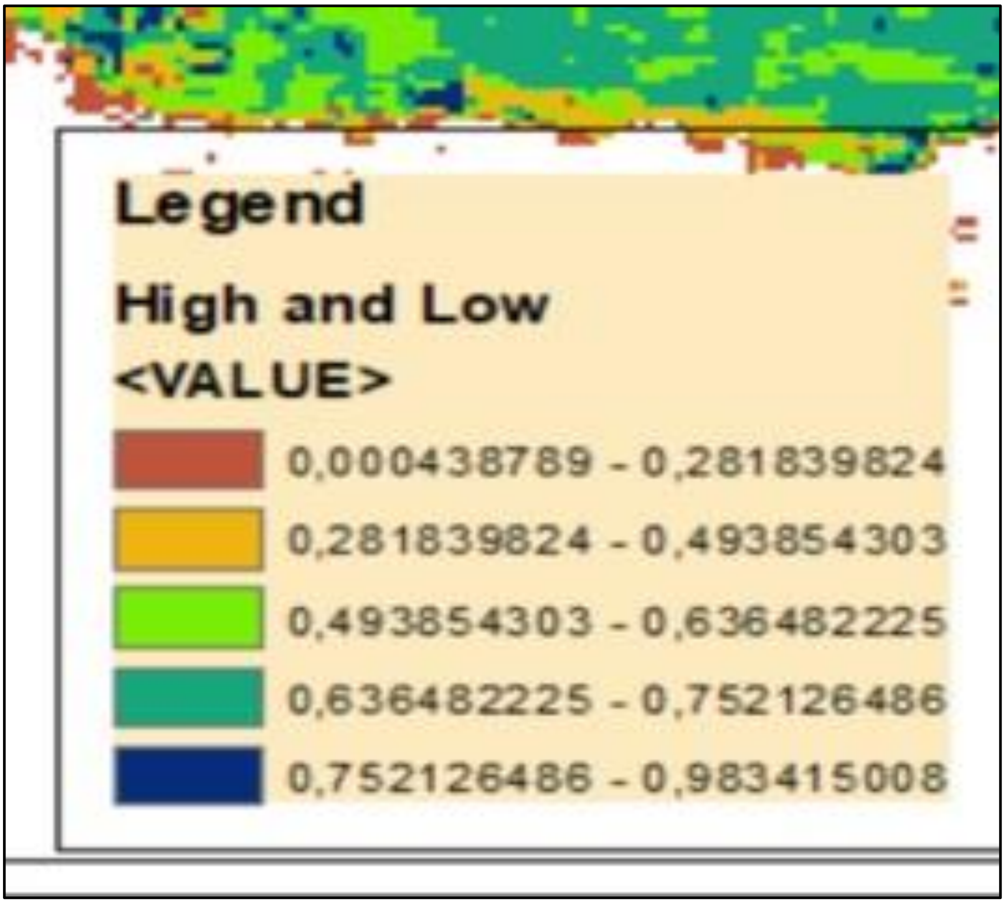


Figure 22: Five Maps showing annual spatial distribution of vegetation cover using NDVI with the corresponding NDVI graph (below) for the respective years 1984-1989 (a),1991-1997 (b),2000-2005(c),2007-2013 (d), 2016-2018 land 2019 with an expanded legend (f)

5.2. SUPERVISED CLASSIFICATION OF LAND USE

Analysis and discussion of both quantitative and qualitative elements of land use forms the basis of this section. The classification (Table 7) was conducted and validated by utilizing the created training methods on the various images portrayed in the previous chapter. Different classification maps for each year together with their charts were obtained.

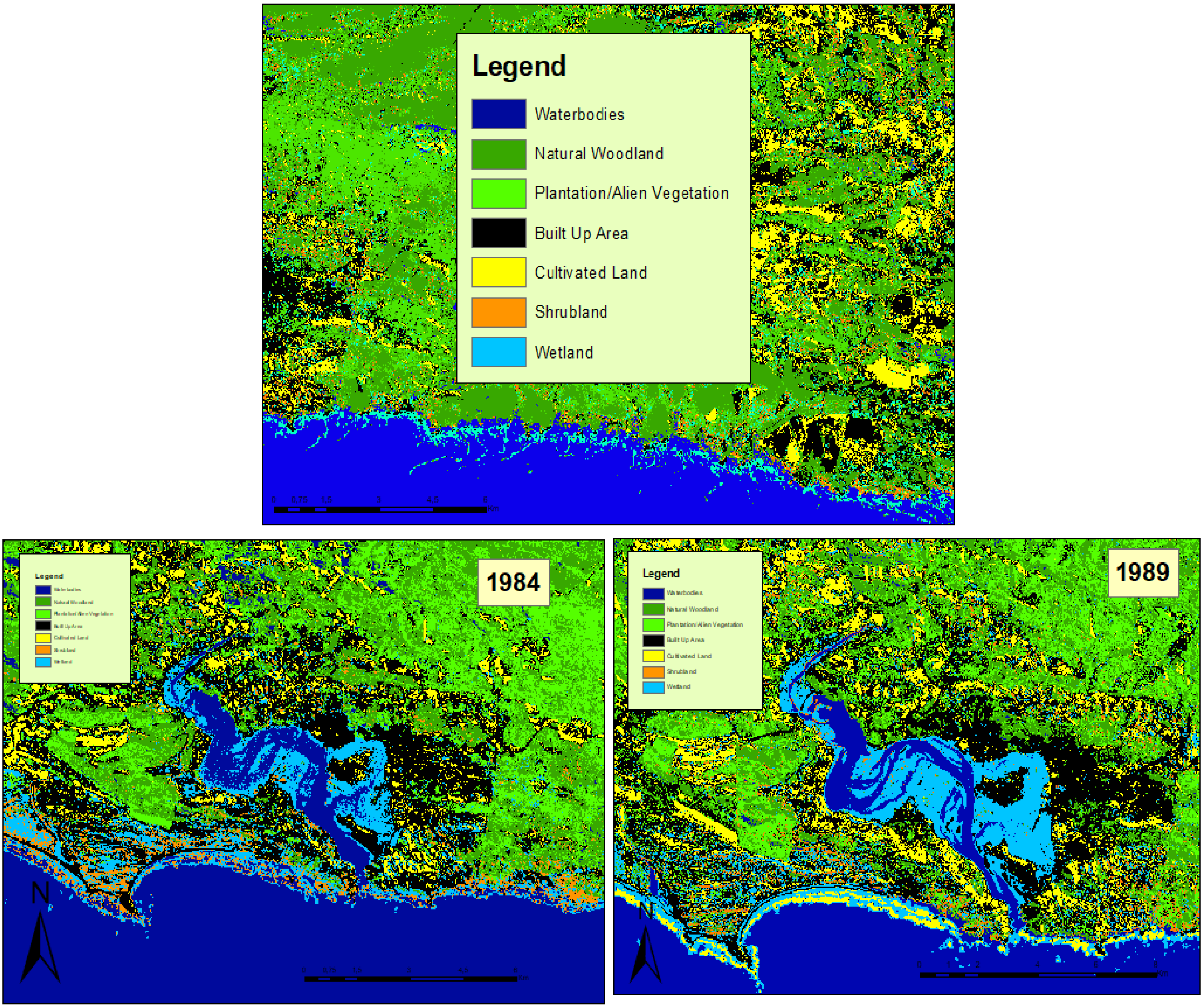
Table 7: Classes description based on the USGS classification scheme [https://www.usgs.gov/landsat-missions]

Class Name	Description
Agriculture/Cultivated land	Cropland, pastures, nurseries, horticultural areas, vineyards, confined feeding operations and other agricultural lands
Vegetation	Dedacious forest land, mixed forest land, evergreen forest land, natural wooded land, planted forest, alien vegetation, saltmarsh, fynbos, grassland and afrotemperate forest
Natural Wooded Land	"Forest", spanning more than 0.5 ha; (0.005km2) with trees higher than 5 meters and a canopy cover of 5-1 % with a combined cover of shrubs, bushes and trees above 10%. It does not include land that is predominantly under agricultural or urban land use.
Water Body	Streams and canals, reservoir, lakes, bays and sea, oceans and estuaries
Urbanized or Built up land	Residential, services and commercial, industrial and commercial complexes, urban or mixed urban areas, built up land, industrial transportation, other urban or built up land
Bare/ Barren Land	Bare open land
Fynbos Shrubland	Fynbos meaning fine plants is a small belt of natural shrubland or heathland vegetation.

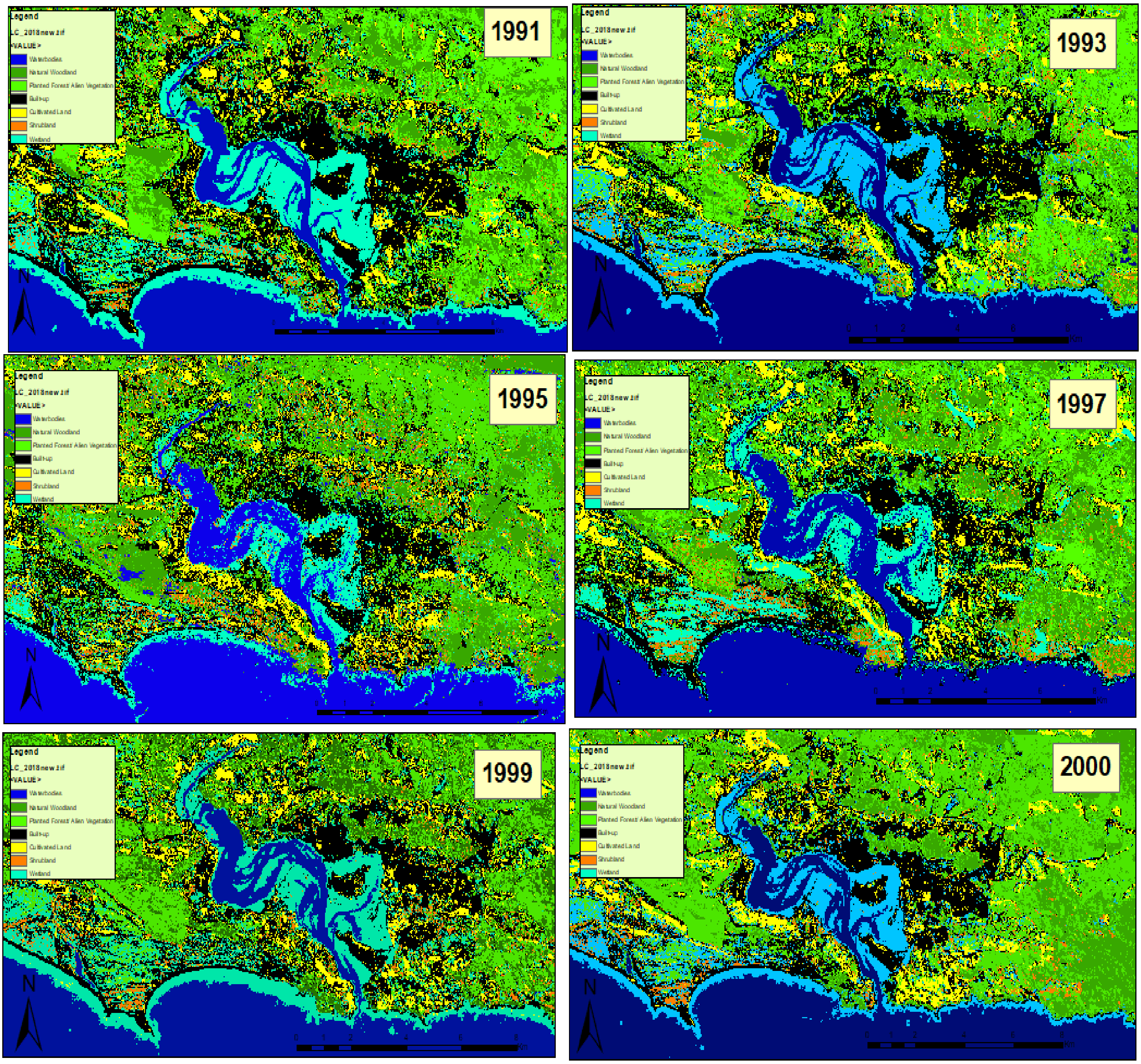
5.3. CLASSIFICATION RESULTS AND OUTPUT

Random forest (RF) were chosen for pixel based supervised classification on all images from 1984-2019 (Figure 25).

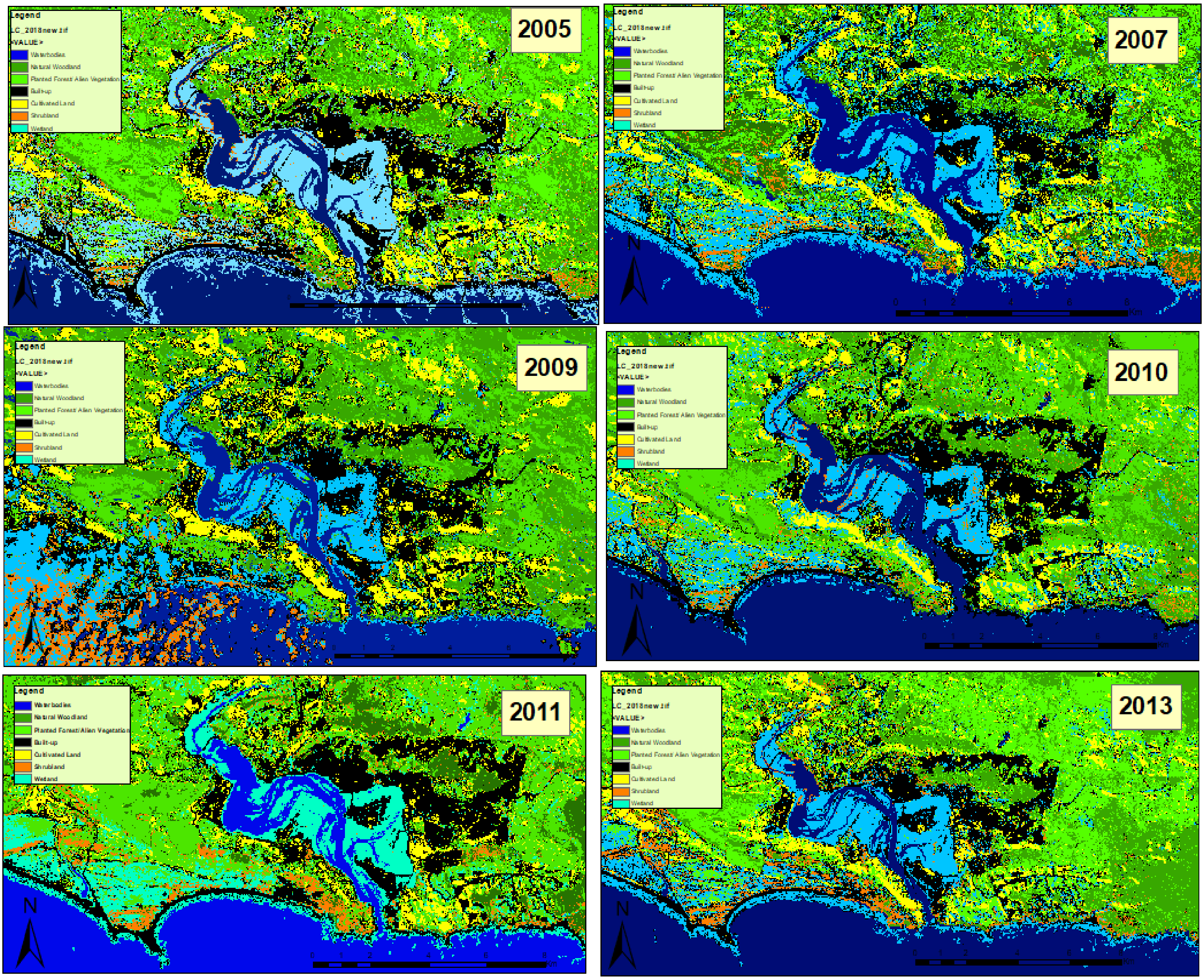
a)


Legend
Waterbodies
Natural Woodland
Plantation/Alien Vegetation
Built Up Area
Cultivated Land
Shrubland
Wetland
1984
1989

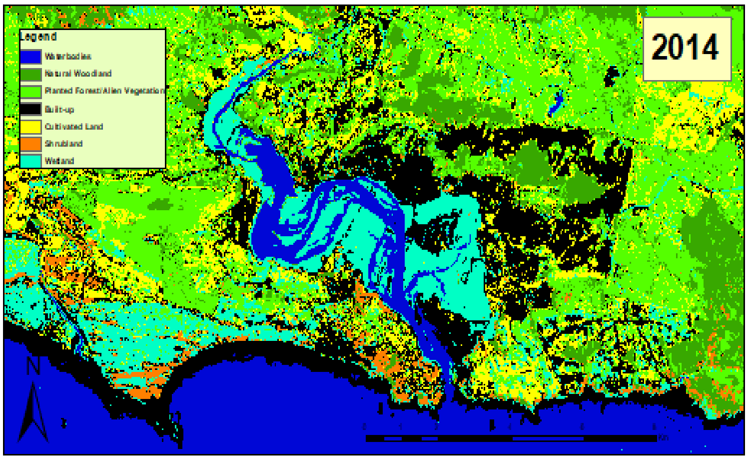
b)

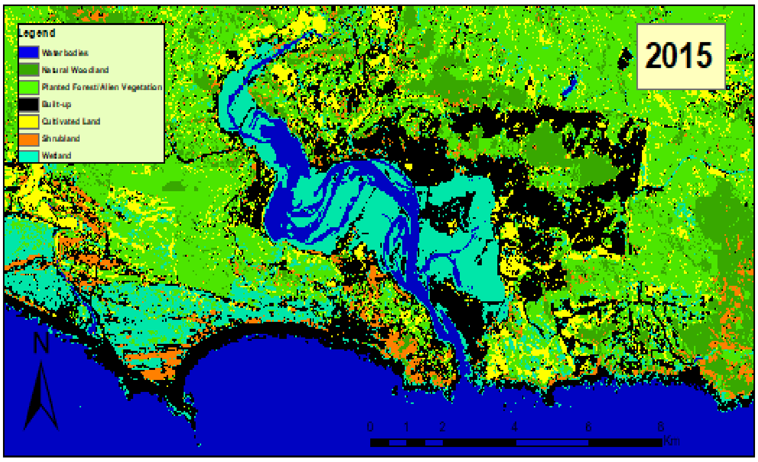

1991
1993
1995
1997
1999
2000
Legend
Waterbodies
Natural Woodland
Planted Forest Alien Vegetation
Built-up
Cultivated Land
Shrubland
Wetland
N

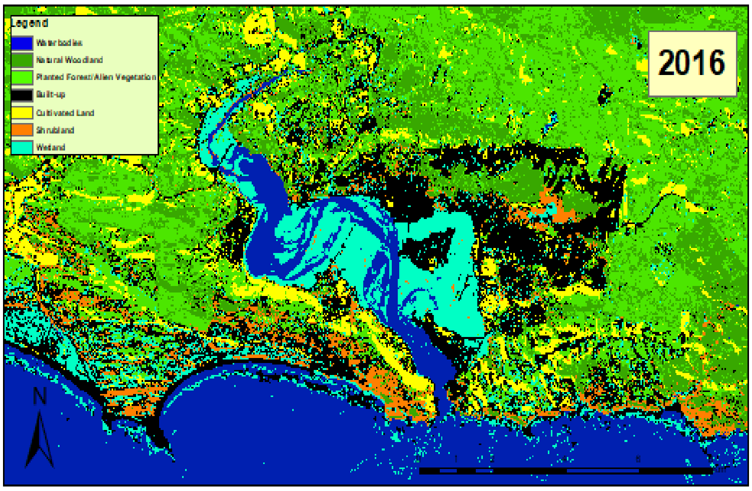
c)

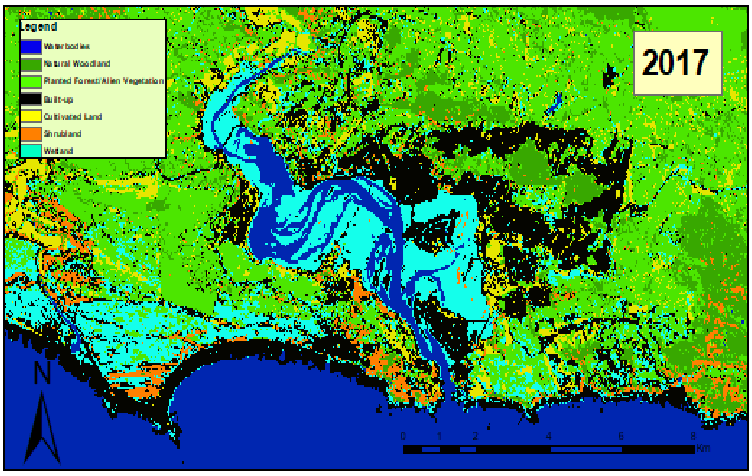

2005
2007
2009
2010
2011
2013
Legend
LC_2018new.tif
<VALUE>
Waterbodies
Natural Woodland
Planted Forest/Alien Vegetation
Built-up
Cultivated Land
Shrubland
Wetland
N

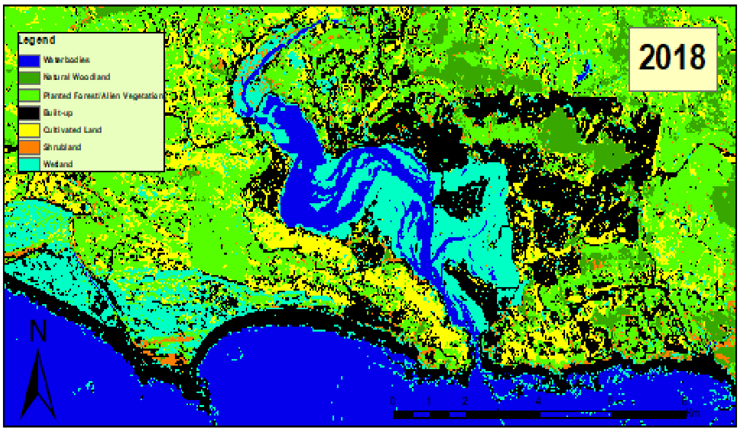
d)

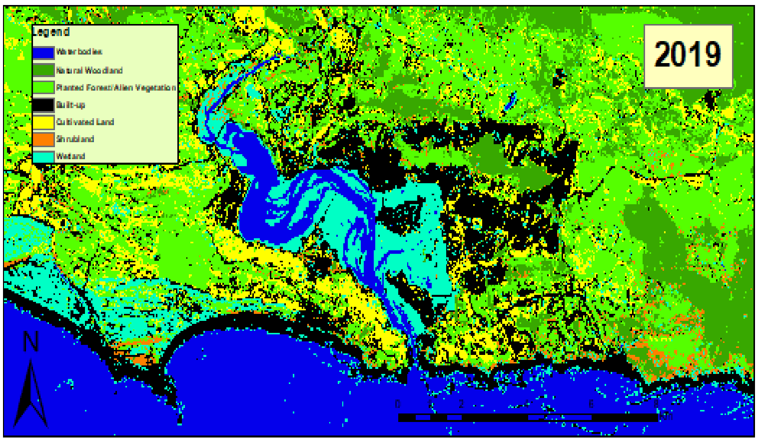

Legend
Waterbodies
Natural Woodland
Planted Forest/Alien Vegetation
Built-up
Cultivated Land
Shrubland
Wetland
2014
N


Legend
Waterbodies
Natural Woodland
Planted Forest/Alien Vegetation
Built-up
Cultivated Land
Shrubland
Wetland
2015
N


Legend
Waterbodies
Natural Woodland
Planted Forest/Alien Vegetation
Built-up
Cultivated Land
Shrubland
Wetland
2016
N


Legend
Waterbodies
Natural Woodland
Planted Forest/Alien Vegetation
Built-up
Cultivated Land
Shrubland
Wetland
2017
N


Legend
Waterbodies
Natural Woodland
Planted Forest/Alien Vegetation
Built-up
Cultivated Land
Shrubland
Wetland
2018
N


Legend
Waterbodies
Natural Woodland
Planted Forest/Alien Vegetation
Built-up
Cultivated Land
Shrubland
Wetland
2019
N

e)

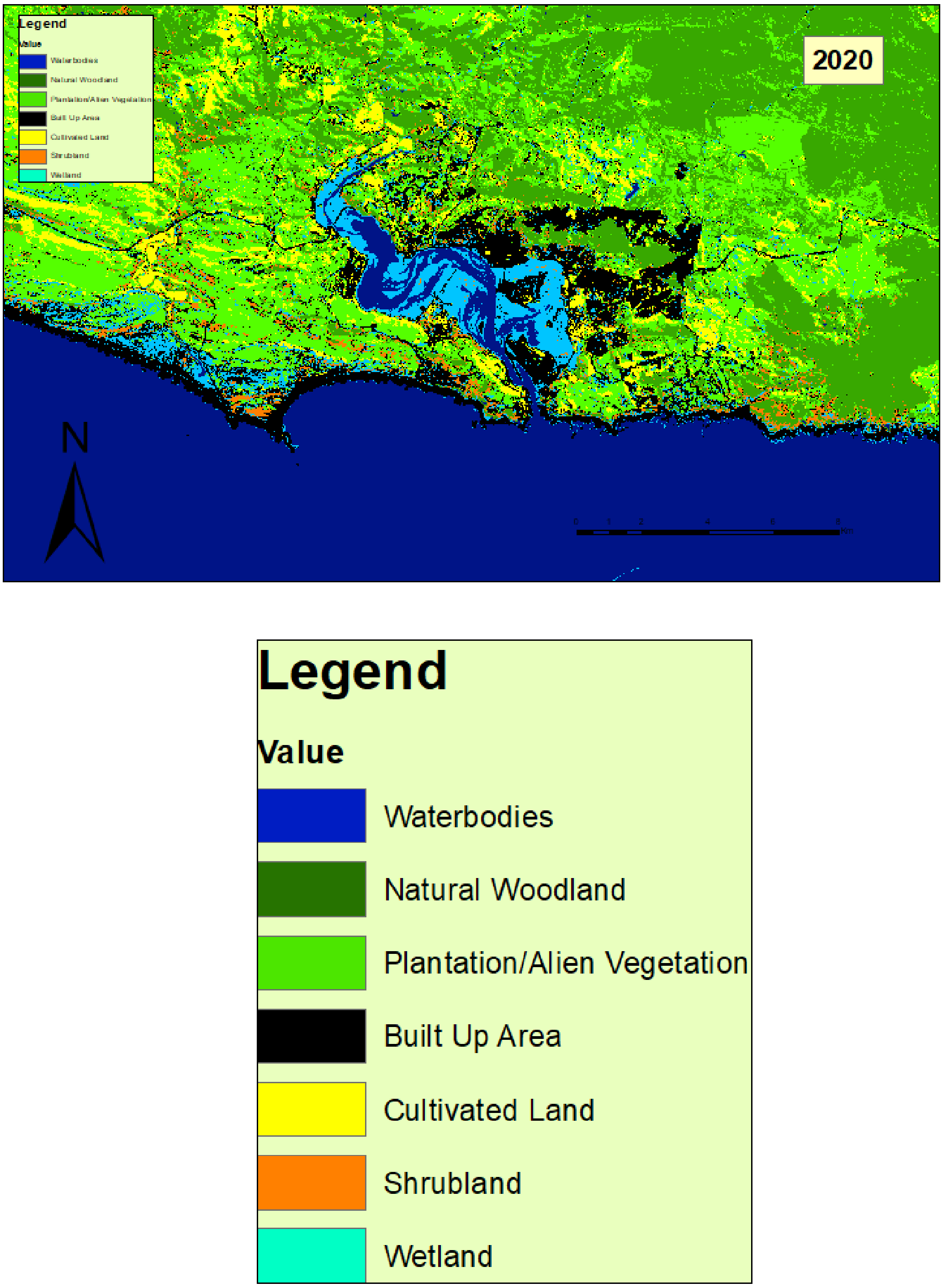
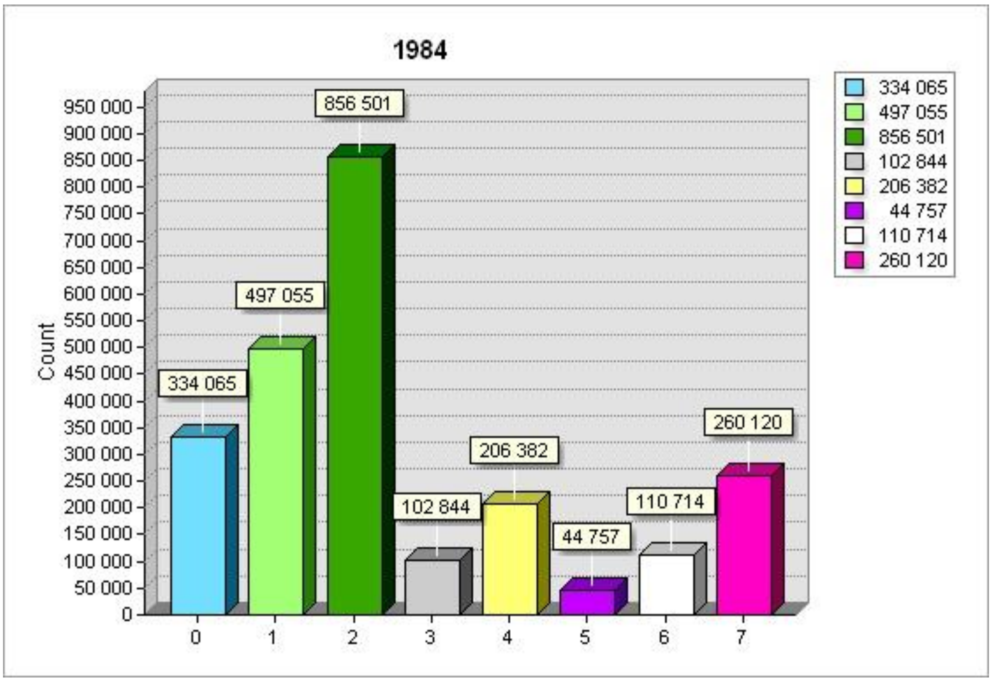
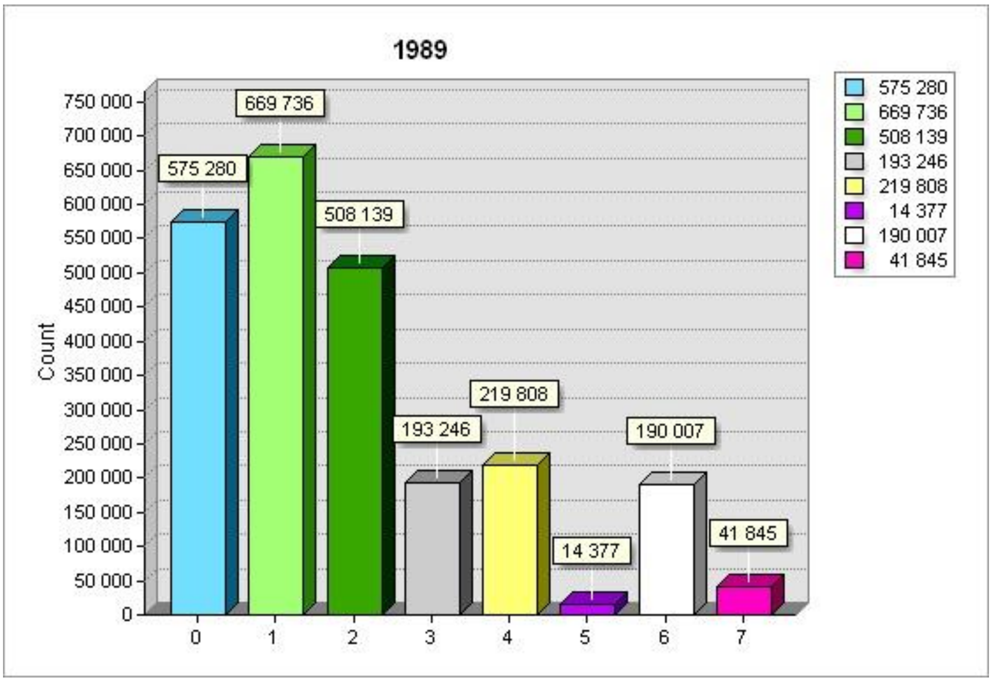
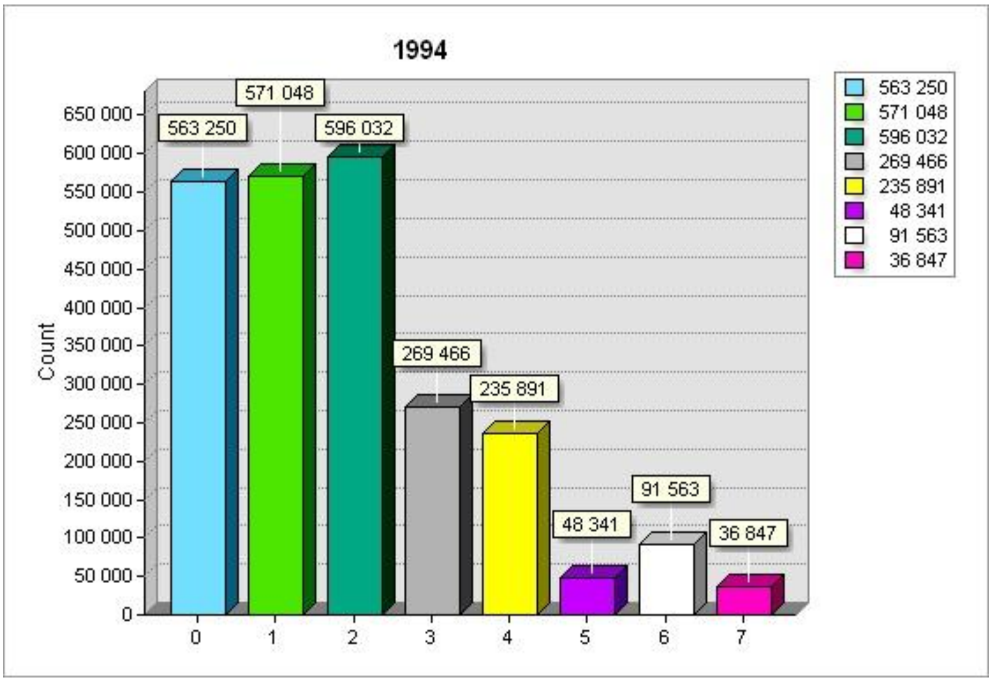


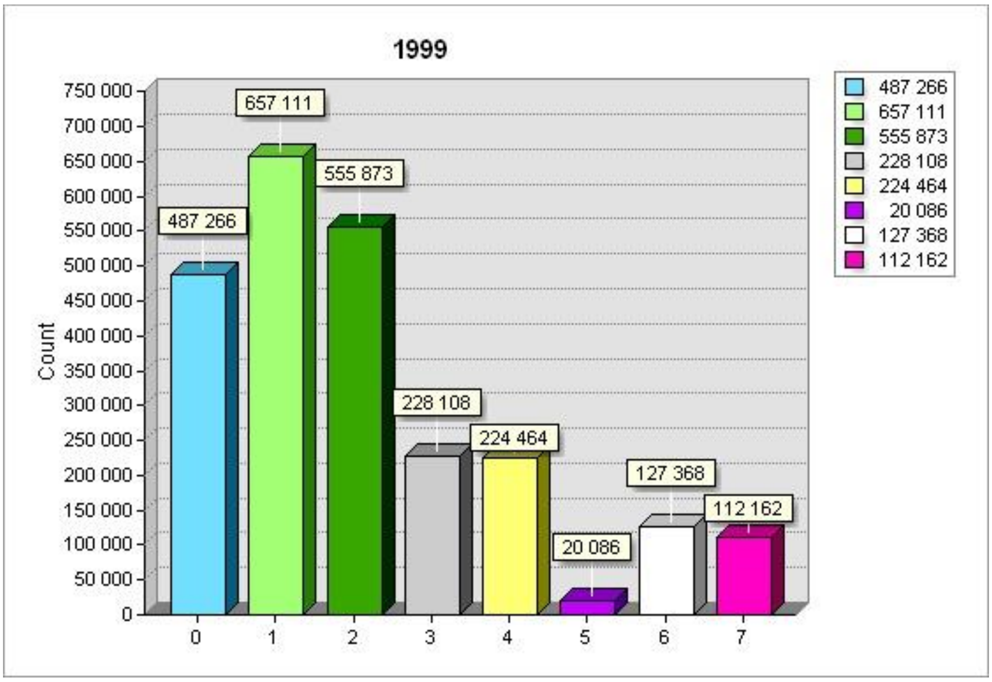
Figure 23: Maps showing supervised classification with the corresponding graph (below) for the respective years 1984-1989 (a),1991-2000 (b),2005-2011(c),2014-2019 (d),2020 and expanded Legend (e)

a)


1984
Count
950 000
900 000
850 000
800 000
750 000
700 000
650 000
600 000
550 000
500 000
450 000
400 000
350 000
300 000
250 000
200 000
150 000
100 000
50 000
0
0
1
2
3
4
5
6
7
334 065
497 055
856 501
102 844
206 382
44 757
110 714
260 120


1989
Count
750 000
700 000
650 000
600 000
550 000
500 000
450 000
400 000
350 000
300 000
250 000
200 000
150 000
100 000
50 000
0
0
1
2
3
4
5
6
7
575 280
669 736
508 139
193 246
219 808
14 377
190 007
41 845


1994
Count
563 250
571 048
596 032
269 466
235 891
48 341
91 563
36 847
0
50 000
100 000
150 000
200 000
250 000
300 000
350 000
400 000
450 000
500 000
550 000
600 000
650 000
0
1
2
3
4
5
6
7


1999
Count
487 266
657 111
555 873
228 108
224 464
20 086
127 368
112 162
0
50 000
100 000
150 000
200 000
250 000
300 000
350 000
400 000
450 000
500 000
550 000
600 000
650 000
700 000
750 000
0
1
2
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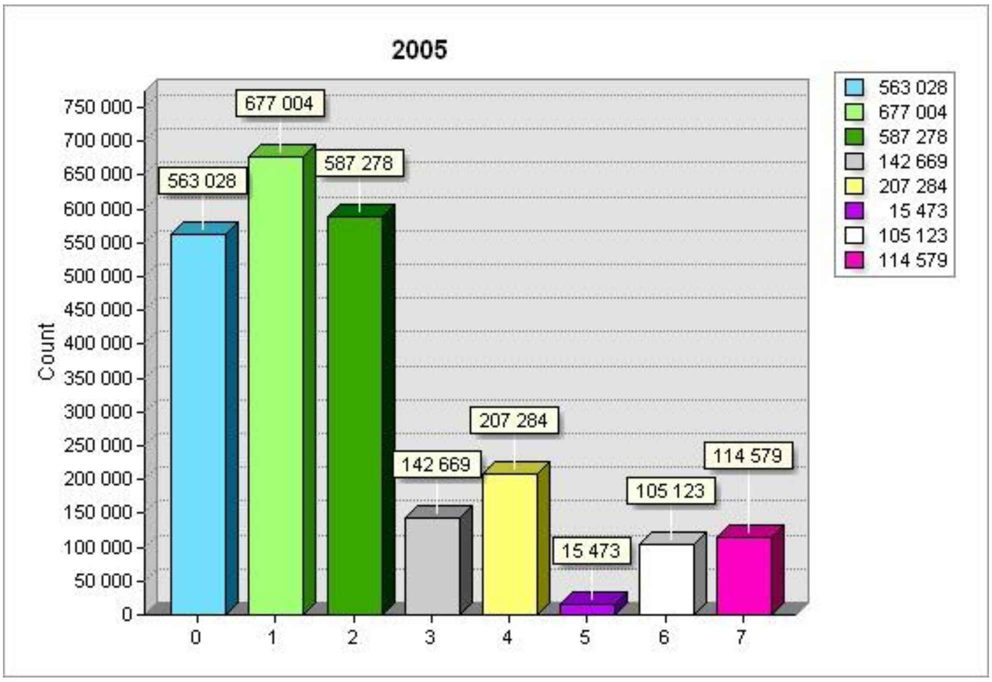
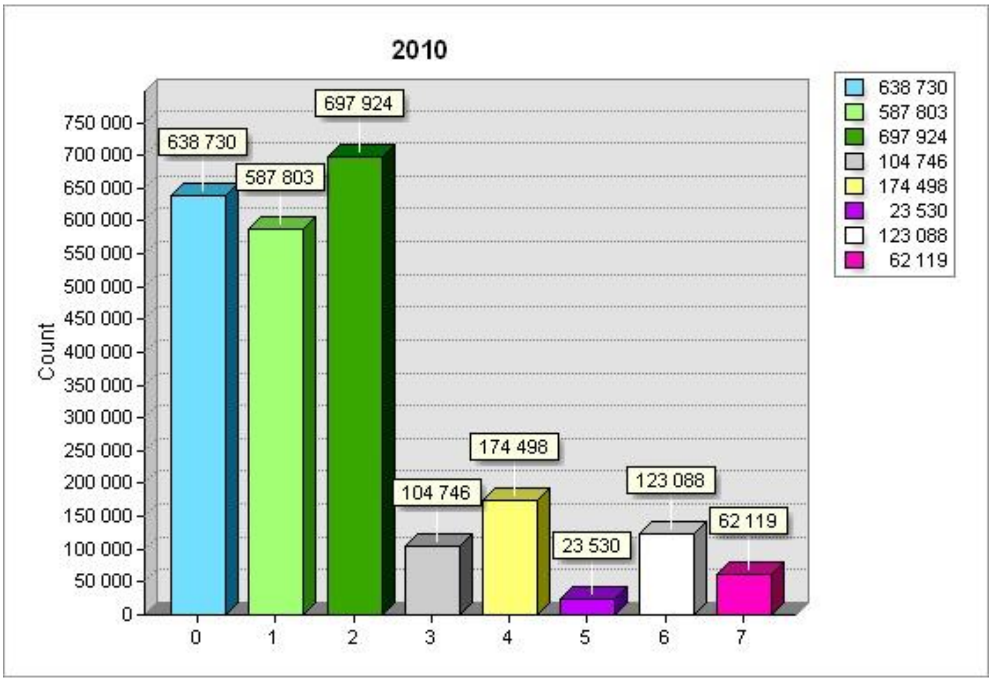
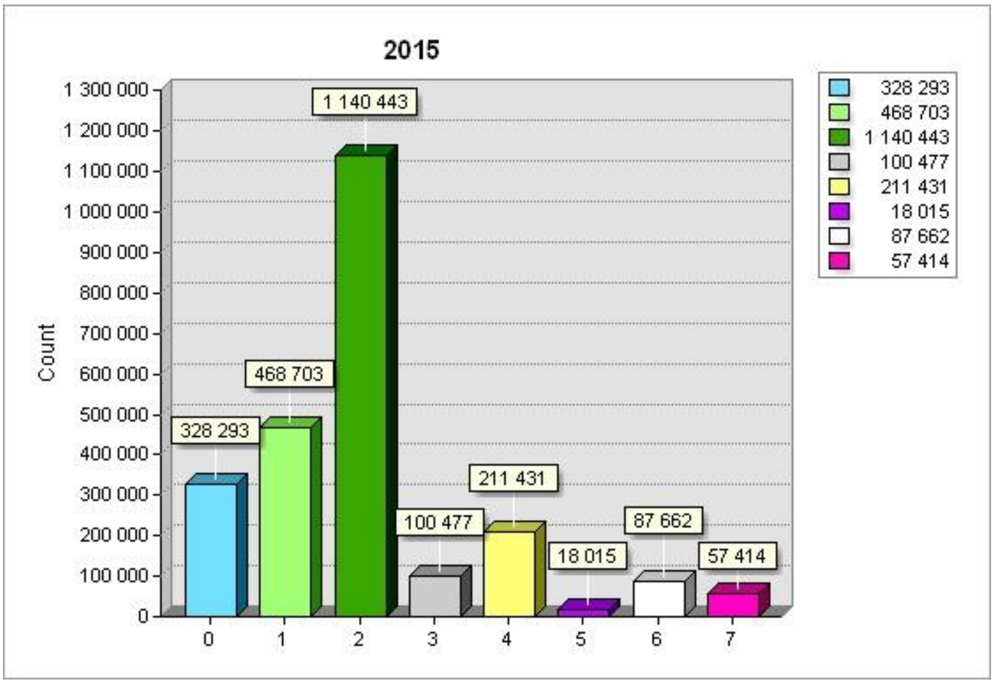
6
7


2005
Count
0
50 000
100 000
150 000
200 000
250 000
300 000
350 000
400 000
450 000
500 000
550 000
600 000
650 000
700 000
750 000
0
1
2
3
4
5
6
7
563 028
677 004
587 278
142 669
207 284
15 473
105 123
114 579


2010
Count
0
50 000
100 000
150 000
200 000
250 000
300 000
350 000
400 000
450 000
500 000
550 000
600 000
650 000
700 000
750 000
0
1
2
3
4
5
6
7
638 730
587 803
697 924
104 746
174 498
23 530
123 088
62 119



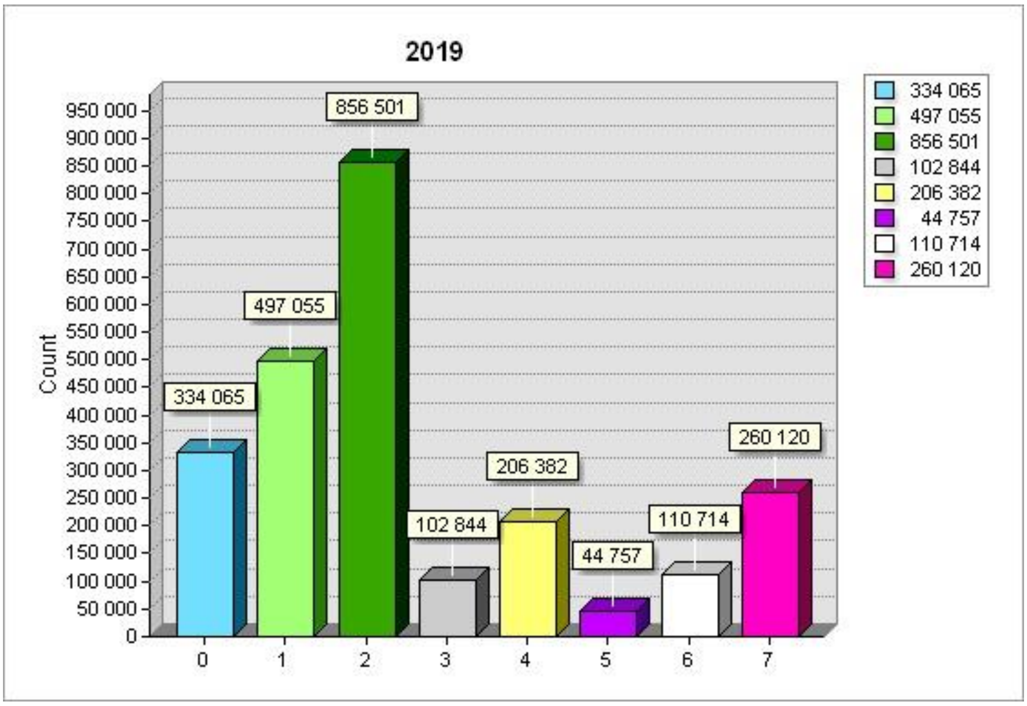


Figure 24: A Map showing spatial distribution of various land use classes as derived from supervised land use classification for the year 1984-2019 with this being the respective graphs indicating area in km2 and expanded legend.

5.4. ANALYSIS OF LAND USE CHANGE

5.4.1. Land use change in the catchment

Between the years 1984 and 1989, there is an extensive decrease (14%) in planted forest and alien vegetation, particularly evident in the year 1989 towards the north of the catchment. Cultivated land had also decreased from the year 1984-1989, and increased (0.6%) in the year 1989 (Figure 25) In 1990, planted forest and alien vegetation particularly to the west of the catchment can be seen increasing as well as shrubland towards the southwest of the catchment. Urbanisation increased (3.8%) significantly towards the east of the catchment, as opposed to natural woodland (7.1%), cultivated land (0.6%), and barren land (3.2%) that had all decreased since 1989. This can be seen towards the northeast of the catchment (Figure 25).

In 1991 a significant decrease in natural wooded land (0.5%) can be seen towards the north-east of the catchment as well as a decrease (1.6%) in the amount of barren land. Between 1993 and 1994, there was an increase (3%) in plantation and alien vegetation towards the east of the catchment as well as (2%) shrubland towards the west of the catchment. Furthermore, there was a significant increase (8.3%) in the built-up area on the east and west of the catchment between the years 1993-1994, whereas there had been a decrease in cultivated land southwest of the catchment. Natural wooded land towards the northeast together with barren land had both decreased between 1993 and 1994. However, between the years 1992 and 1993 there was a notable increase in the barren land (Figure 25).

Between the years 1995 and 1997 shrubland continued to decrease (0.1%). After 1997, it continued to decrease up until the year 2000, particularly towards the southwest of the catchment where it increased by 1.8%. Furthermore, from the year 1995, built up area increased (4.6%) towards the west of the Estuary up until the year 2000 (Figure 25). Planted forest and alien vegetation had increased significantly (7.6%) towards the southwest of the catchment; together with built up area (4.6%), cultivation (4%) and shrubland (0.8%) increasing towards the west.

In the year 2000, there had been an increase (4.8%) in built up area west of the catchment around the meander, as well as east of the catchment. In the year 1997, some of the most dramatic changes in the Knysna catchment occurred, where agriculture continues to flourish (7%) on the north-eastern side of the catchment (Figure 25) Between the years 1995 and 1996, natural wooded land had increased significantly towards the north-east of the Estuary, then continued to decrease in 1997, and then further increased in 1998.

In 1996, plantation and alien vegetation increased significantly (9.8%) towards the southwest of the catchment then continued to increase every alternate year up until the year 2000. Whereas barren land continued to fluctuate every alternate year from 1995 to 2000, particularly along the southwest meander of the Estuary, with 1997 being the highest yield (3.5%) of barren land. From the year 1995 to 1997, cultivated land had increased (3.2%) north of the catchment whereas, in 1999, it began to decrease by 1%, and then slightly increased in the year 2000 by 0.4%.

In 2003, a clear increase (4.1%) can be seen in built up areas towards the northwest of the catchment as well as the southeast of the catchment. The proximal part of the catchment indicates more (1.3%) cultivated land than previously seen in the year 2000. In the year 2004, an increase (0.2%) in natural wooded land particularly, along the northwest of the catchment while most of the catchment appears to be dominated by plantation or alien vegetation (Figure 25). The year 2003 and 2004 appear similar, where in both years the north-eastern side of the catchment is dominated by natural woodland and planted forestry or alien vegetation. Cultivated land and built up areas appeared to be dominating in the north-western part of the catchment. In 2005, natural woodlands begin to prevail within the northeast again, together with planted forestry or alien vegetation and a few areas of agriculture towards the south of the catchment.

The years 2005 and 2006 seem almost identical, except for the increase (4.8%) in planted forestry and alien vegetation west of the catchment as well as the natural woodlands (8.5%) east of the meander of the catchment in 2006. Compared to 2006, in 2007 the natural woodland in the north increased (11%), while plantation or alien vegetation decreased significantly (9%) within the northeast region of the catchment. In 2009, natural woodland, barren land, and alien vegetation and plantation had a minimal increase (0.1%) in the catchment (Figure 25).

In contrast, cultivated land (8%) along the north of the catchment, built up area (0.6%) at the west meander of the catchment and shrubland (2%) particularly towards the southwest of the catchment had all increased in comparison to 2007. In 2013 and 2014, natural woodland decreased (8.4%) particularly in the northeast of the catchment while cultivated land increased by (3.3%) towards the southwest of the catchment. Plantation and alien vegetation have increased (3.2%) as well as barren land increased (0.7%) particularly in 2014 (Figure 25). Between the years 2010 and 2011, natural woodland had decreased significantly (4.9%) while plantation or alien vegetation increased (5.6%) in 2011 towards the west of the catchment. Built up area had increased (0.2%) with cultivated land (0.9%) and shrubland (0.2%) decreasing in the southwest of the catchment, whereas the amount of barren land had increased (0.4%) in 2011 (Figure 25) .

In 2015, natural wooded land had increased (2%) particularly in the western side of the catchment as well as a plantation (5.2%) in the northeast of the catchment. Alien vegetation had also increased whereas cultivated land (0.2%), shrubland, (0.3%) and barren land (1.2%) have all decreased in comparison to 2014 (Figure 5.1). Between the years 2016 and 2017, there was an increase (8.4%) in natural woodlands particularly towards the west of the catchment area. There had also been an increase in plantation and alien vegetation towards the east of the catchment (12%). Followed by a further increase in cultivated land (2.7%) along the west of the catchment, barren land and shrubland towards the south-eastern end of the catchment. In 2017 the Knysna Estuary experienced a severe fire on the western end of the Estuary that resulted in an increase in erosion as well as sedimentation (Figure 25). Evidence of this can be seen when comparing the years 2017 and 2018.

In 2018, natural woodlands started to increase (4.3%) as well as plantation (0.6%) and alien vegetation, particularly in the northeast of the catchment. Shrubland also increased (0.4%) on the eastern side of the catchment. However, built up area decreased (2%) slightly as well as barren land (0.4%). In 2019, natural woodlands decreased (11%) in comparison to 2018, particularly in the northeast of the catchment as well as cultivated land (0.2%) towards the south of the Estuary (Figure 25). Moreover, there was an increase (0.9%) in plantation and alien vegetation particularly towards the west of the catchment. Built up area (0.1%) along the western end of the Estuary, shrubland (0.8%) on the south of the Estuary, barren land (0.7%) on the western end of the catchment had all increased in 2019 in comparison to 2018.

5.4.2. Changes in the Estuary

Between 1984 and 1986 salt marsh can be seen increasing within the Estuary (Figure 25). Saltmarsh within the Estuary increased significantly towards the east of the Estuary. Furthermore, in the year 1991, a significant decrease in salt marsh present in and around the Estuary can be seen. Between 1993 and 1994, the amount of salt marsh present within the Estuary had also decreased. During the year 1995 salt marsh within the Estuary began to fade particularly towards the middle of the Estuary, while the meander and proximal region of the Estuary continued to be covered in a salt marsh (Figure 25).

In the year 1997, some of the most dramatic changes in the Knysna Estuary occurred, where salt marsh continued to increase within the Estuary between 1997 and 1998. Subsequently, the salt marsh started decreasing up until 2000, particularly towards the northeast of the Estuary. The amount of salt marsh in the Estuary continued to fluctuate in the years 1995 to 2000, with 1999 being the year of the highest amount of salt marsh present within the Estuary. Moreover, in the year 1999, the majority of the Estuary appears to have less salt marsh present (Figure 25).

In 2003 the Salt River was discoloured after rainfall, according to Marker (2004).The terrace banks were not eroded; however the banks were vegetated. Salt marsh within the Estuary appears more prevalent in the year 2005 as opposed to that of 2003 and 2004. Overall the years 2005 and 2006 seem almost identical; however, there was an increase in salt marsh within the Estuary particularly. Compared to 2006, in 2007 the salt marsh within the Estuary decreased and became more concentrated compared to the previous year (Figure 25). In 2009 salt marsh had a minimal increase within the Estuary while in 2013 and 2014, salt marsh within the Estuary had also increased. Between the years 2016 and 2017, there had been an extreme decrease in salt marsh within the Estuary. In 2018, the amount of salt marsh present within the Estuary had then also decreased. Lastly, there had been a significant increase in salt marsh in the Estuary during 2019 in comparison to 2018 (Figure 25)

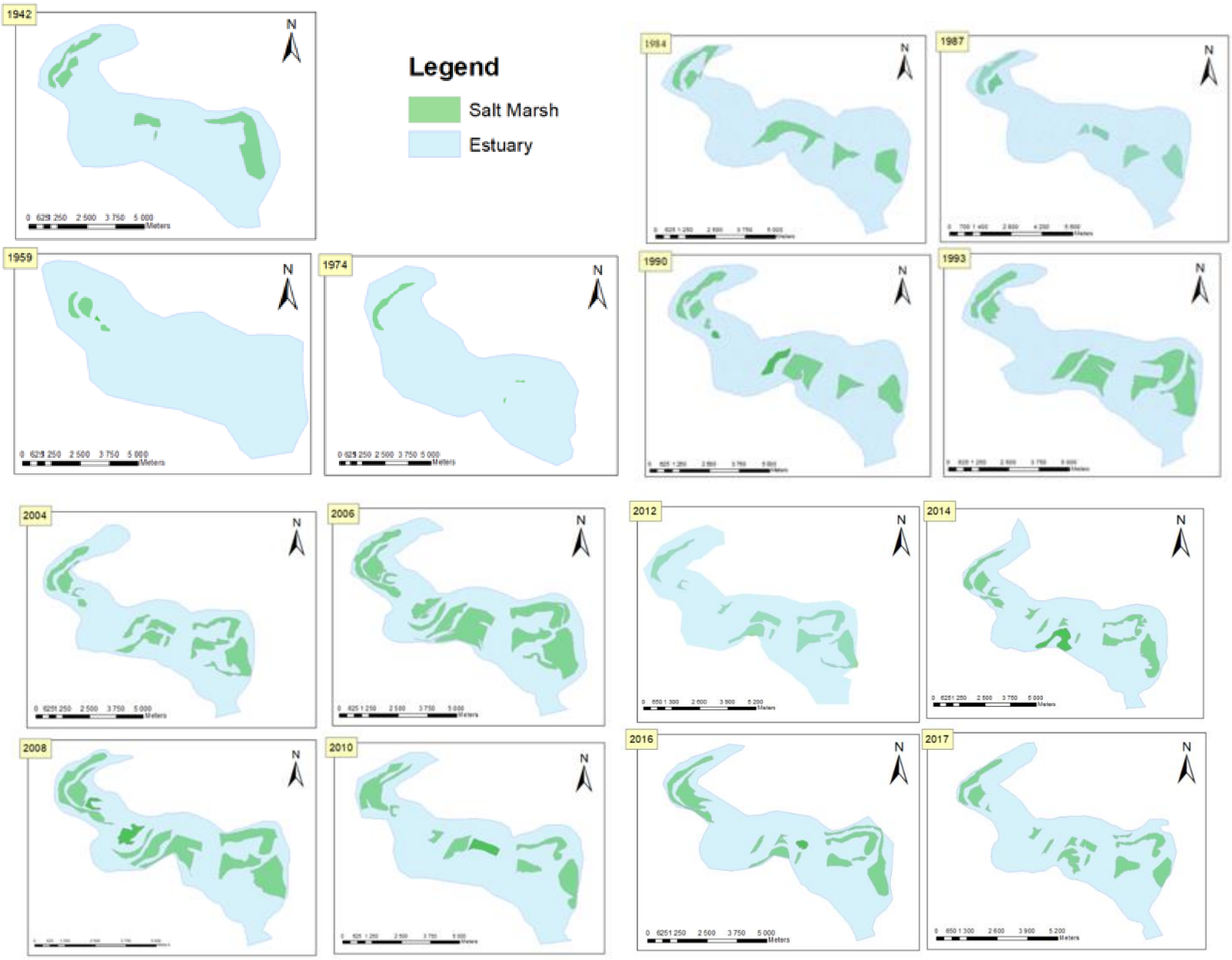


Figure 25: Estuarine Changes of the Knysna Estuary from 1942-2017 using Arc GIS

5.5. GROUND TRUTHING

Data were collected in the field from the period June 2018 – July 2019. The results are displayed below indicating the various areas around the Knysna catchment and Estuary where ground truthing was performed. This is then followed by harmonic modelling of NDVI indicating seasonality with original, as well as fitted values for the ground truthing location points. The ground truthing data accompanied by a linear mean NDVI band graph has shown a decreasing trend for the various ground truthing sites (Figure 26).

Different land use /land cover types produce various phases and amplitude values as seen in (Figure 28). The results have indicated that values of amplitude generated for a single year in the time series can be used to identify land use cover types. Hobbs (1990) discussed several types of vegetation change which include seasonal variability, climatic variability anthropogenic influence or a change in global climatic patterns. These changes can be seen in the harmonic model analysis when examining the changes in fluctuation in the graphs (Figure 26).

The changes in amplitude indicate a change in the landscape. In this instance the ground truthing sites such as fire destruction, plantation and crop land have all indicated a change in 'greenness'. Major changes include results from postfire destruction, the change in land management or the change in the climate in the region (Figure 28). This becomes clear when looking at the fire destruction ground truthing site in collaboration with the fire destruction harmonic model (Figure 28).

The harmonic model acts as a noise filter. The noise produced by clouds and processing are infrequent and the harmonic module thus serves as a filter by using a small number of lower harmonic terms to recreate the NDVI profile (Jakubauskas *et al.*, 2001). The use of the harmonic module eradicates the need for the smoothing of data that have been applied in other temporal NDVI studies (Koch *et al.*, 2009) by concentrating the first three heavy harmonic terms while the higher frequency noise is redirected into the higher harmonic terms (Figure 28).

Plantation

Salt Marsh

Crop land/ Agriculture

Fire Destruction

Built up Area (Hornlee)

Figure 26 Ground truthing the various land use areas around the Knysna Catchment study area

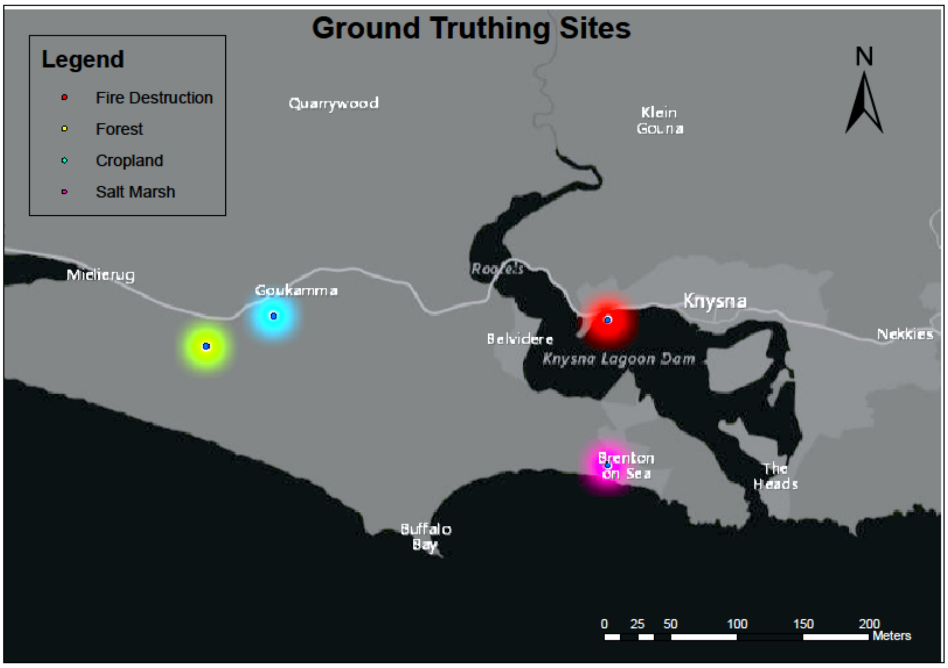
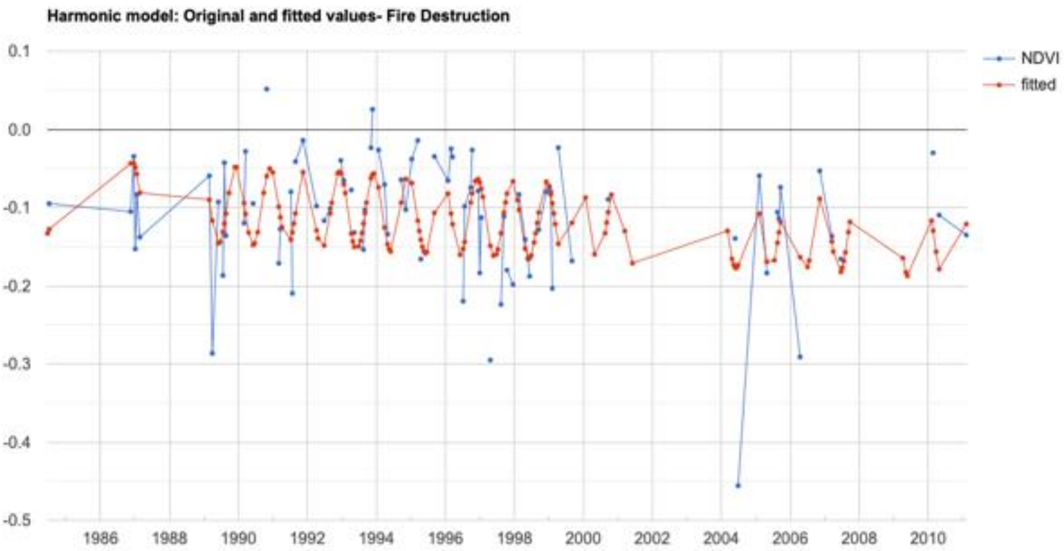
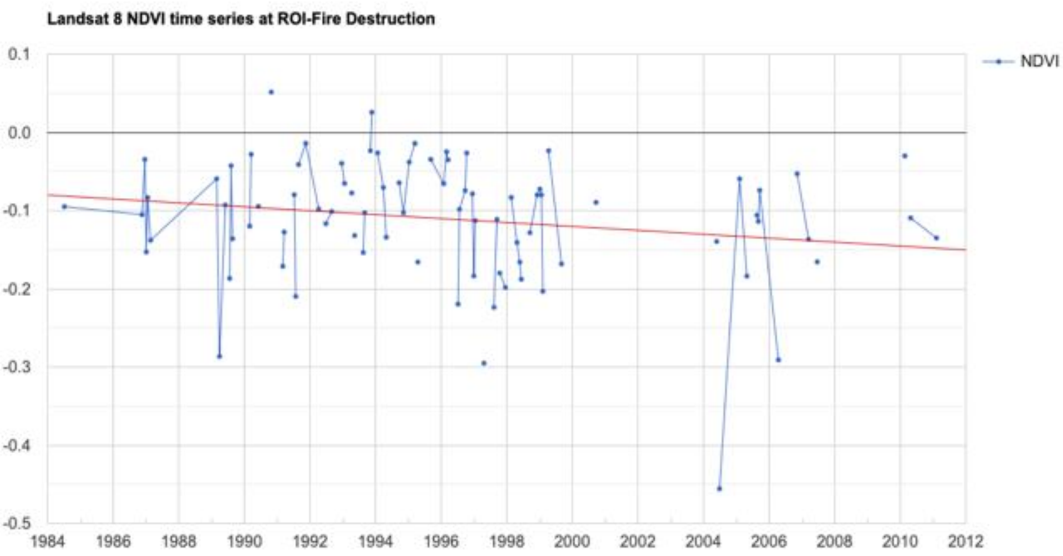


Figure 27: The various ground truthing sites in the Knysna area, taken with a cell phone GPS with the respective line graphs below

a)

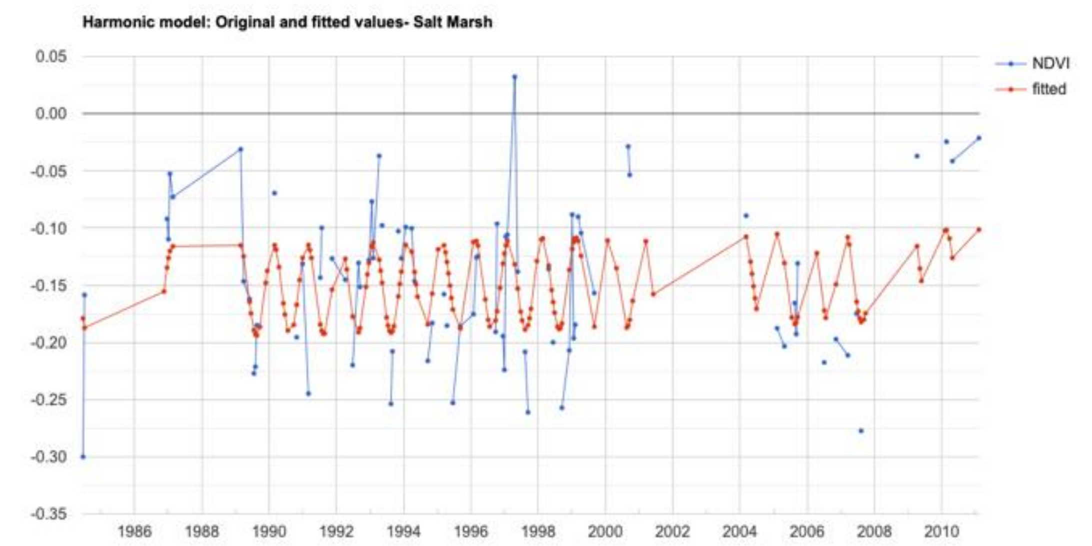


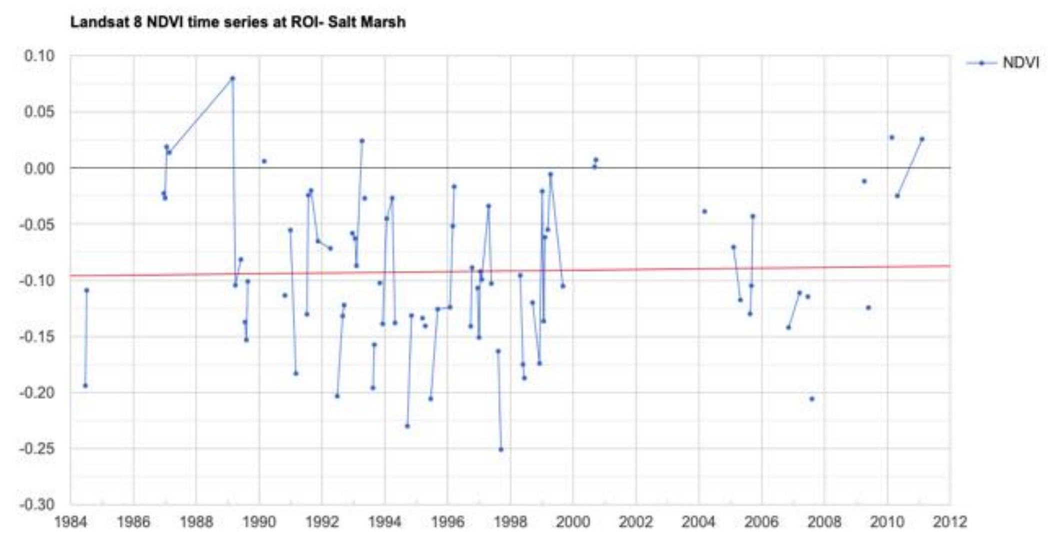
Harmonic model: Original and fitted values- Fire Destruction
NDVI
fitted
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010



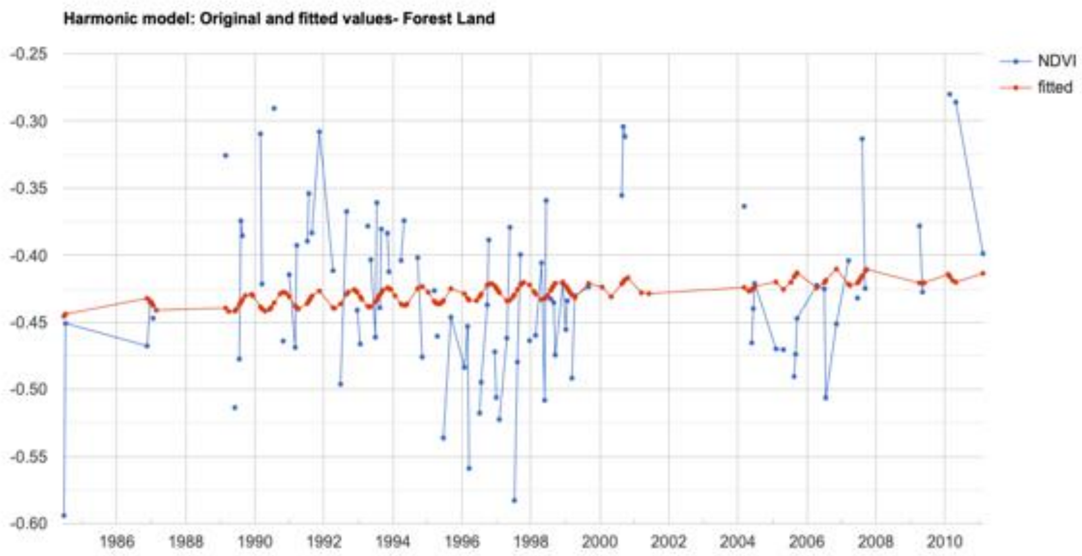
Landsat 8 NDVI time series at ROI-Fire Destruction
NDVI
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012

b)

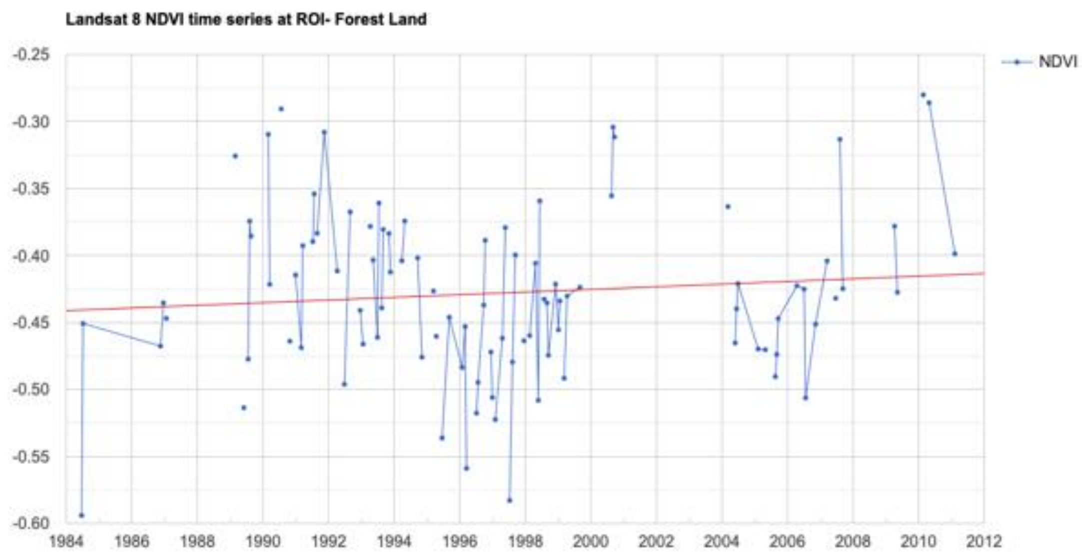

Harmonic model: Original and fitted values- Salt Marsh
0.05
0.00
-0.05
-0.10
-0.15
-0.20
-0.25
-0.30
-0.35
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
NDVI
fitted


Landsat 8 NDVI time series at ROI- Salt Marsh
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
-0.25
-0.30
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
NDVI

c)

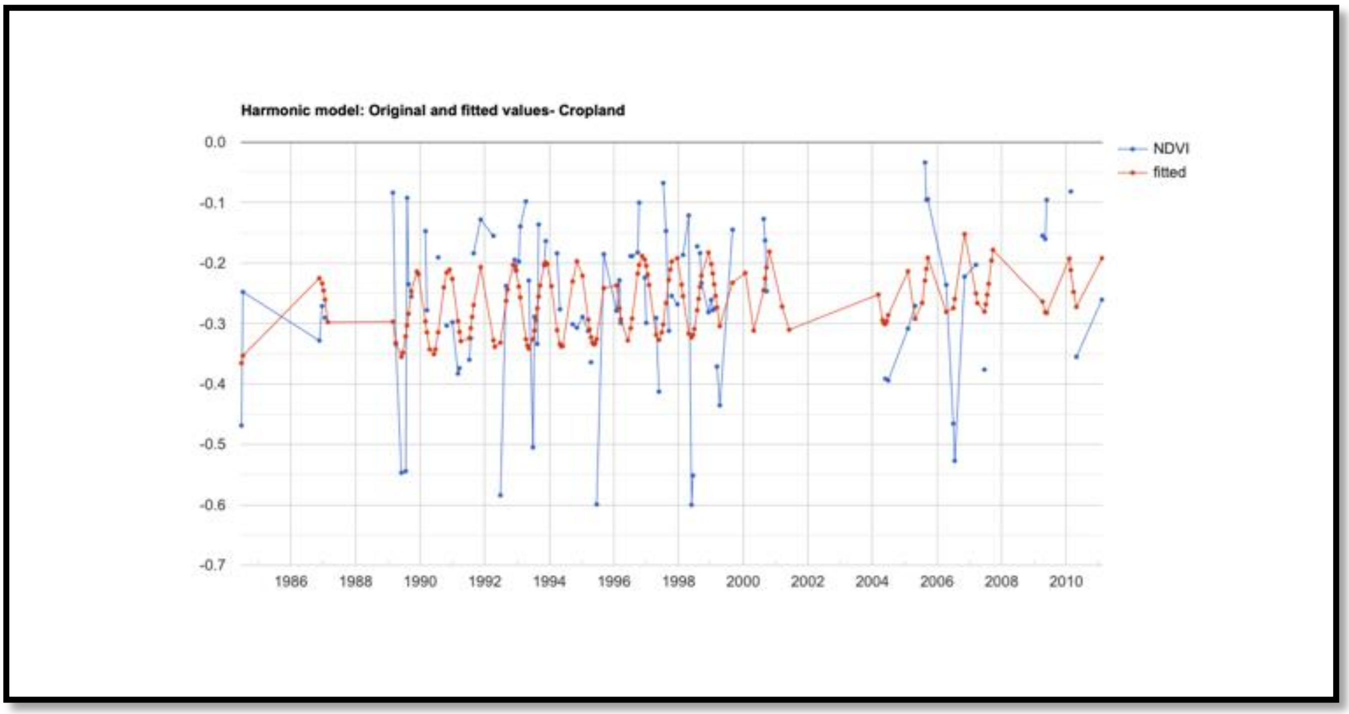


Harmonic model: Original and fitted values- Forest Land
NDVI
fitted
-0.25
-0.30
-0.35
-0.40
-0.45
-0.50
-0.55
-0.60
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010



Landsat 8 NDVI time series at ROI- Forest Land
NDVI
-0.25
-0.30
-0.35
-0.40
-0.45
-0.50
-0.55
-0.60
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012

d)



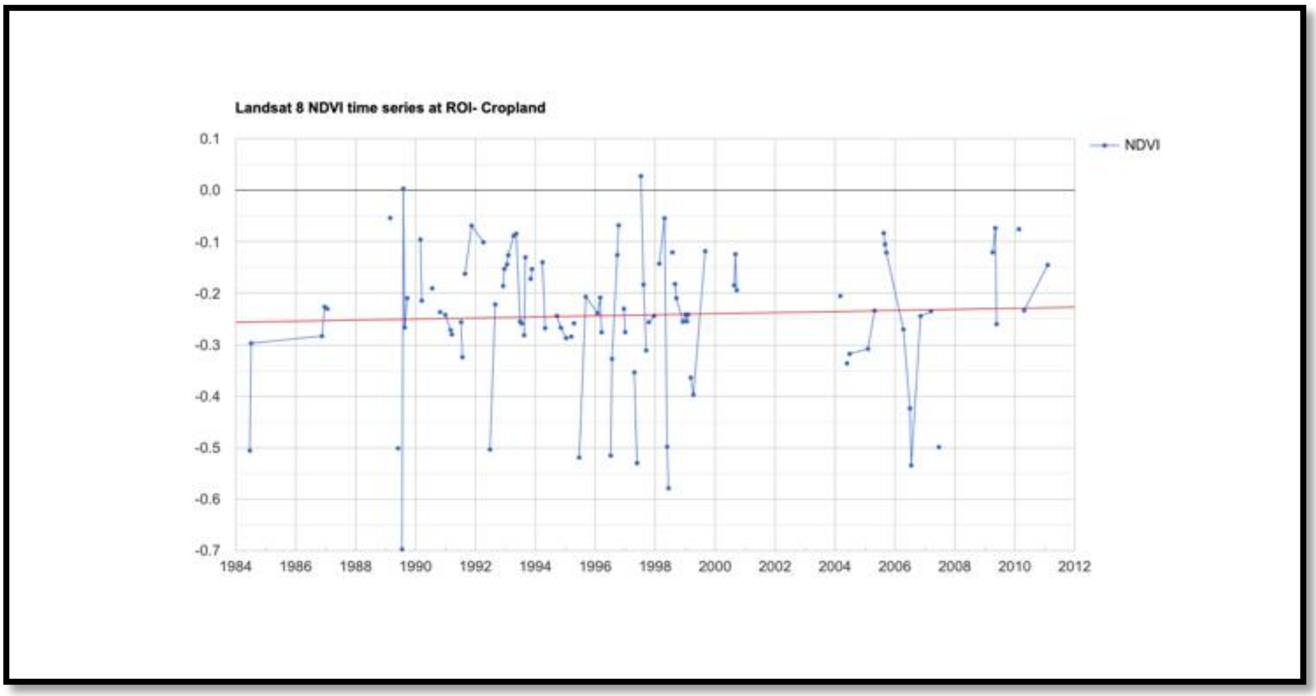


Figure 28: A linear graph harmonic modelling of NDVI (showing seasonality) with original and fitted values for the ground truthing location points accompanied by a linear mean NDVI band values graph showing a decreasing trend. A) Fire destruction, b)salt marsh, c)Forest land and d)Crop land/cultivated land

5.6. ACCURACY ASSESSMENT

The following step within the methodology was the accuracy assessment and error matrix analysis of the data. The standard examination of accuracy assessment data starts with an error matrix, frequently referred to as an arrangement confusion matrix. An error matrix typifies the precise classifications and misclassifications of the individual years. In (Table 8) the accuracy assessment for the supervised classification can be seen from the year 1984 to 2019, while also indicating the various Landsat imagery used.

Table 8: Overall training accuracy according to GEE [code.earthengine.google.com]

YEAR	IMAGE/ LANDSAT	TRAINING OVERALL ACCURACY (%)
1984	5- Surface reflectance	92
1986	5- Surface reflectance	95
1987	5- Surface reflectance	95
1989	5- Surface reflectance	95
1990	5- Surface reflectance	96
1991	5- Surface reflectance	95
1992	5- Surface reflectance	95
1993	5- Surface reflectance	95
1994	5- Surface reflectance	96
1995	5- Surface reflectance	96
1996	5- Surface reflectance	95
1997	5- Surface reflectance	95
1998	5- Surface reflectance	96
1999	7- Surface reflectance	95
2000	5- Surface reflectance	96
2001	7- Surface reflectance	91
2003	7- Surface reflectance	95
2004	7- Surface reflectance	95
2005	7- Surface reflectance	93
2006	5- Surface reflectance	95
2007	5- Surface reflectance	95

2009	5- Surface reflectance	95
2010	5- Surface reflectance	95
2011	5- Surface reflectance	95
2013	8- Surface reflectance	95
2014	8- Surface reflectance	96
2015	8- Surface reflectance	95
2016	8- Surface reflectance	96
2017	8- Surface reflectance	96
2018	8- Surface reflectance	96
2019	8- Surface reflectance	96

The overall accuracy for all the images had a minimum of 91% and a maximum of 96%. Lower accuracy results could be credited to the medium spatial resolution of Landsat data and smaller sizes of the feature areas. Generally, this indicated a great agreement between the maps produced from pictures and the different referenced data (Table 8). The achieved accuracy of the classification had produced a more than satisfactory outcome. Remote sensing and classification can be used as a way to produce precise land cover and land use mapping in the Knysna region. This can also be used for regional analyses allowing for effective environmental policies and resources management decisions with relevant and accurate data.

5.7. VERBAL EVIDENCE

The information retrieved locally indicated that changes in the Estuary had been occurring swiftly (Marker, 2004). During low tide, recreational activities such as swimming within the Salt River Estuary had been possible predominantly during the 1940s (Marker, 2004). Small boats as well as canoes were able to travel at least 1 km upstream at low tide (Marker, 2004). In contrast, people during the 1990s living on slopes above the Estuary expressed their unhappiness with the rate of siltation, as well as the loss of bird life on the Estuary.

According to staff working at the Knysna National Park, *Phragmites australis* had diminished in size and had been lost by the 1970s.

Chapter 6

6. DISCUSSION

The concern with the impact of land use change on the geomorphology of wetland areas has a long history and is of growing prominence (Goudie, 2018). While there has long been a realisation that human activities impact wetland areas, the impacts have become particularly notable with the effects of urbanisation and fires. This also includes the changes in agricultural practices that have altered erosion and sedimentation rates. The Knysna Estuary is threatened by development schemes such as urbanization, barrages and marinas. The decrease in the sediment input in Knysna have occurred because of both the damming of rivers and the reduction in soil erosion in drainage basins, as well as from coastal protection schemes that reduce both onshore and along shore sediment movements. Human activities such as conversion of land for urbanization and industrialization, cultivation, and other agricultural needs also impact the geomorphology of wetland areas as they increase sediment rates within the Estuary.

Estuarine ecosystems do not function on their own as they lie at the junction between marine and freshwater systems. These ecosystems also shape part of a regional, national and global ecosystem where water flows from rivers and streams and mixes with salt water from the ocean. A disruption in one Estuary could impact a large variety of organisms and their habitats in the broader freshwater or marine ecosystems. Therefore, the interactivity between the ecosystems and their users creates an integral balance and the impact on its sustainability that needs to be addressed. In this chapter we will discuss the land use changes on the geomorphology of the Knysna catchment and its impacts on the geomorphological characteristics of the Estuary between 1984 and 2019 (Harvey, 2019).

6.1 LAND USE CHANGE

In the case of urban/built up area, the change was in a increasing trend, ranging from 60100 (2.5%) – (2.8%) during the years 1984-1992, which reached to 70419 (2.9%) to 99915 (4.1%) during the years 1993-2007, and finally augmented to 102844 (4.3%) to 152844 (6.3%) during the years 2008-2019. The main reason behind the drastic changes in the urban area is because of infrastructure extension in the form of transport, markets, settlements, and private companies. It also includes demographic factors that are based on the natural growth of the population, migration, population density, and population distribution. All these activities by human settlements increase the burden on the built up area and increase the pressure on land use area (Latour, 2014).

The fynbos shrub land was recorded to range from 110714 (4.6%) to 140004 (5.8%) during the year 1984 which increased to 250412 (10.3%) to 203053 (8.4%) during the years 1993-2007, and finally reached 245853 (10.2%) to 110714 (4.5%) during 2008-2019. In the case of salt marsh, it ranged from 260120 (10.9%) to 51133 (2.1%) during the years 1984-1992, with 49255 (2.0%) to 92673 (3.8%) during the years 1993-2007 and consequently reached 92873 (3.8%) to 200120 (8.3%) during 2008-2019. The change in the fynbos shrub land use pattern can be observed because of changes in the infrastructure extension, agricultural expansion, wood extraction, demographic factors, economic factors, and most significantly occasional fires (Buckley, 2010).

The land use change was recorded to show increasing trends in the segment of water as 229042 (9.5.%) was recorded during the years 1984-1992 and 633860 (26.7%) during 2008-2019 with water levels was recorded to be 90989 (3.7%) during 1993-2007. The natural wooded land recorded a change from 856501 (36%) during 1984 to 531694 (22%) during 2008 with the natural wooded land level of 167545 (6.9%) during 1993-2007. The woodland land use was impacted by the commercial needs of the human settlements and the rapidly increasing population. The alien vegetation, cultivated land, and shrubland were recorded to be 1151, 987, (47.8%) and 24387 (1%) during 1984-1992, which changed to 324997 (13.4%), 61325 (2.5%), and 23894 (0.9%) during 2008-2019 respectively. The alien vegetation, cultivated land, and shrubland have recorded a change during 1993-2007 with 89248 (3.7%), 166994 (6.9%), and 50389 (2.1%) respectively. Salt marsh was recorded to be 208987 (8.7%) during 1984-1992 and reached 47359 (2.0%), during 1993-2007. Barren land and salt marsh were recorded to be 135139 (5.6%), and 107247 (4.4%) during 2008-2019 respectively.

The above data describes the altering in the land use patterns in the Knysna Estuary over 35 years. The major reason behind the altering in the land use and geomorphology of the Knysna Estuary is human activities that have led to the removal of the wetland sediments by trapping impoundments, sediment reduction because of damming of the upper catchment, land reclamation, and stabilization of dunes. Due to human activities, there has been a limited growth of restricted onshore migration of sediments that led to erosion around the catchment. Apart from this, human activities such as deforestation, urbanization, and barrages and marinas that increased soil erosion in the region (Tang et al., 2016).

6.2 NDVI DATA ANALYSIS

As per the NDVI data analysis, it was found that in the segment of non-vegetation, the NDVI value was recorded to be -1 to 0.199 in the barren areas, road networks, and build-up area. In the segment of low vegetation, NDVI value was recorded to be -0.2 to 0.5 in shrubland, saltmarsh, shrub, and agriculture, while in the high vegetation segment, NDVI value was recorded to be 0.501 to 1.0 in plantation and afrotemperate forests. The vegetation indices are based on a unique analysis of the spectral area of the vegetation in the NIR portions with the help of quantitative assessment and satellite data. It specifically helps in acquiring reliable information related to the spectral transformation taking place in the two or more bands in the terrestrial structural variations. It helps in examining climate trends and estimating the water content of the soils remotely. In terms of using NDVI that has been added in the present study, it is the most routine remote sensing index that helps in estimating the difference between two bands (Near Infrared and Red) of the multispectral images.

The NDVI Analysis of the catchment was conducted and recorded to be averagely mean NDVI 0.4 for east and west catchments of the Knysna Estuary. The western side of the catchment was recorded to be mean NDVI 0.7 and mainly covered with patches of vegetation. It indicated that the plantation has been fluctuating till 2016. On the other hand, the northwest of the catchment was recorded to be consistent in terms of plantation which confirms the classification and assessment accuracy of NDVI analysis. The functioning of the Estuary depended on several factors such as freshwater flushing time, inputs, climatic conditions, tidal range, and others. It was also found that the suspended sediment in the Estuary was impacted by factors such as sensitivity to climate. It highly impacted the decomposition, advection, mixing, resuspension of a particular matter and the rate of sedimentation in the Estuary (Naylor et al., 2018).

6.2.1 NDVI Analysis of the Estuary

Changes in the Estuary can be very dynamic and even a result of tidal fluctuations. The advantage of the NDVI approach is that it integrates changes over a longer period and therefore smooths out some of the shorter term dynamics. NDVI is particularly useful for the monitoring vegetation because it is able to compensate for changing illumination conditions, viewing angles and surface slopes. NDVI is sensitive to underlying soil colour and saturates over dense vegetation; thus, land use classification and NDVI was used in collaboration in this research project.

The NDVI analysis of the Estuary was conducted in which it was recorded that the amount of salt marsh in the Estuary was NDVI 0.2 in the year 1986 particularly in the northwest region of the Estuary. The year 1989 recorded an increase in the encroachment of saltmarsh within the Estuary while a decrease was recorded in the flood plains vegetation. It led to the gradual enlargement of the Estuary which changed its shape from 1991 to 2010. It was recorded that there was the segmentation of the marsh patches into different sections by the year 1993.

There was an amalgamation of Estuary salt marsh patches into larger patches resulting in an increase in the size of the marsh patches indicated by a mean vegetation index reflection of 0.2. The shape of the Estuary increased its size in the southern part by merging salt marsh patches in the centre. The year 1997 also witnessed an increase in the size of salt marsh patches in the distal part with a slight decrease in the centre saltmarsh patch. Apart from this, a gradual increase was recorded In the salt marsh in the distal part in the year 2000 with a complete disappearance in the south region and a significant decrease in the patch size in the centre in the year 2002.

The year 2004 recorded no significant change while in the year 2007 saltmarsh patches increased significantly throughout the entire Estuary. The scattering of salt marsh is estimated by finding out the rate of intertidal accommodation space and is comprised of two fundamental components which are vegetated platform and channel framework (French, 2018). It makes a difference in building up a dynamic balance between sea rise and sedimentation levels. The salt marshes often exhibit resilience against high sea levels and majorly depend on the sediment supply for establishing an equilibrium. It must also be noted that the saltmarshes are different from vegetated wetlands as they are primarily distributed in the upper intertidal region in the Estuary while the vegetated wetlands are specifically located on the lower intertidal zone of the Estuary. As a result, with the high and low tidal range, there is a significant change in the shape, size, and concentration of the saltmarsh (Marker 2002**).**

A decreasing trend was observed in the saltmarsh in 2010 with a significant decrease in 2011. However, an increase in saltmarsh patches was recorded in 2014 especially in the centre and proximal regions of the Estuary. A changing scene was recorded in 2016 with the clearance of saltmarsh patches in the proximal part of the Estuary with a significant reduction in the centre patches. The year 2018 also marked elongated patches of saltmarsh with an average NDVI of 0.4, resulting in a decrease of proximal and distal patches of salt marsh in size in the centre. Based on the above facts, it can be said that the NDVI provides valuable insights about land use classes, waterbodies, urban areas, and vegetation that essentially describe the catchment and shape of the region. By analysing the saltmarsh patches, there is the determination of environmental gradients of salinity and inundation that are recorded within the Estuary (Maree, 2000). Saltmarshes also help in protecting the sediment trap by regulating the water quality. It also helps in stabilizing the coastlines by filtering toxic chemicals, excess nutrients, and disease-causing organisms (Marker, 2004).

6.3 ANTHROPOGENIC INFLUENCES

6.3.1 Population Growth

In 2019 the global population was 7.6 billion (Goudie, 2016), while in South Africa the population was recorded at 58 million (www.statssa.gov.za). In Knysna, in 1996 the total population was 43 000 whereas by 2016 this figure had grown to 73, 835 and in 2020 this number grew to 78, 494 people per annum in the small town of Knysna (Table 9). These increasing numbers have importance for geomorphological processes which include demographic pressures that were implicated in environmental impacts namely urbanisation and deforestation.

With the rapid growth in population, large areas are appropriated to build low cost housing and often this does not allow for soil and erosion protection or substantial rehabilitation. The rapid growth in population is a major issue that plays a vital role in altering both the land cover and use of the Knysna Estuary. The increase in population gives rise to the increase in urbanisation, which in turn has altered the land and impacted the Estuary with the increase in sedimentation rates due to various construction and other socio-economic factors. Currently, some of the most uncontrollable changes in land cover/use are from different socio-economic components such as population development, household incomes and immigration. The result of the increase in urban areas is an increase in concrete and tar surfaces commonly known as impermeable surfaces (Figure 11). These surfaces allow for excess water to be taken directly into the Estuary via sewers and pipes, leading to an increased risk of flooding and an increase in the deposition in the Estuary. The increase in urban areas along the Estuary, particularly the eastern meander is backed up by the 2011 census of the Knysna municipality where the population of Knysna town covered 74% of the population in Knysna (www.statssa.gov.za) (Table 9).

Table 9 indicating the population statistics of the Knysna area from the year 1996-2020(www.statssa.gov.za)

YEAR	***TOTAL POPULATION (PER ANNUM)***
2020	*78,494*
2016	*73, 835*
2011	*68,659*
2006	*65,051*
2001	*52,035*
1996	*43,194*

6.3.2 Built up area / Development

In the present day with rapid urban growth leading to construction for building projects, an extreme increase in man-made impervious or built up areas from the years 2001 onwards can be seen (Figure 25).

Another factor that leads to erosion which should be taken into consideration is the recreational activities of the main channel. Both produce wave activity which impacts the erodible geography of the cliffs and the shorelines, tides, and, in turn, increases the amount of deposition found within the Estuary (Adams *et al*., 2020). Between 1984 and 1986 (Figure 25**)** an increase in urban area can be seen on the eastern side of the Estuary with an annual mean vegetation reflection of 0.0-0.1. This is the main observable change of built up area over the study period (Figure 25) This is due to the increase in population, (Figure 25) rapid urbanisation and possibly also to the abandonment of the Knysna Timber factory, leaving behind machinery and waste dumps that became a health hazard for the eco-sensitive lagoon of Knysna (Adams *et al*., 2020). As a result, there was a decrease in planted forest and alien vegetation towards the north of the catchment in the year 1989. It also decreased the cultivated land from the year 1984-1989 and increased in the year 1989. This can all be observed when looking at the time series map in (Figure 25) and the population statistics (Table 9)

The results of the land cover analysis affirmed the increase of non-vegetative classes as a result of the increase in urban areas. This increase can be credited to quick development operations in and around the study area which driven to extreme deposition within the Estuary.

6.4 CHANGES IN THE ESTUARY

Globally, as the pattern of urbanisation continues to increase, there have been growing concerns over the consequences of urban expansion on wetland areas with great attention on addressing these impacts (Suri *et al*., 2016). One of the most pressing issues that raises concerns were catchment hardening.

The twentieth century was a time for innovative change (McNeil & Engelke, 2016) as cited in (Trischler, 2016). Since World War II concrete has become the main building material. From 1995 -2015, 500,000 Tg of concrete has been produced (McNeil & Engelke, 2016) as cited in (Trischler, 2016). Many scholars such as (Cooper *et al.*, 2002) and (Waters & Zaalasiewicz, 2018) have argued that concrete has been a key factor of the Anthropocene era as well as the construction of major dams (Zarfl *et al*., 2015). This has resulted in various consequences such as the change in river flow, sediment trapping and increased storm water runoff.

The124 manipulations of streams in the Knysna Basin because of hardened banks and other structures has had unforeseen consequences (Marker, 2006). The increased water flowing downstream resulted in bank erosion in the unprotected areas. Cover sands also make the area more vulnerable, while the siltation of the lagoon is an ongoing issue specifically in the Ashmead channel (Adams, 2016).

The Salt River has also been heavily impacted by the Simola development which can easily be seen in the results (Figure 25) Overall the increase in urban areas along the Estuary is a significant factor as it brings along impermeable surfaces once again risking large amounts of depositions and the risk of flooding. The major reason behind it is that both the proximal and distal patches of salt marsh had decreased in size while centre salt marsh patches remained relatively the same. As a result, a visible increase of urban area on Thesen Island in the Estuary since 2016 with a presented vegetation index of 0.1. It is vital to note that we have currently entered a fourth industrial revolution in which advanced technologies such as artificial intelligence has a vast ability to impact the future geomorphological environment (Taylor *et al*., 2015). As discussed by Gedan *et al.*, (2009) the reclamation of land and drainage has resulted in more destruction with large areas of natural wetland resources being lost since medieval times.

Furthermore, if sedimentation and accretion rates at the Knysna Estuary remains constant, some areas around the Estuary could be lost to flooding and, or sea level rise (Figure 25). The major reason behind it is an increase in concrete and tar surfaces in the form of impermeable surfaces because of augmenting population. This led to excess in water flow from sewers and pipes, resulting in an increase in the deposition in the Estuary and high flooding risk. The 1998 time series map indicates the result of an ill-advised development that was impacted by the 1996 floods, (Figure 25) evident on the western end of the catchment. According to Marker (2000), this is a result of the removal of the Simola East golf estate by the triple flood events in October and November of 1996. This is reinforced by the land use change results of 1996 and 2000 (Figure 25) seen on the western end of the catchment.

Sediment is washed into the Estuary as development happens. This peril was forecasted by Reddering (1994) who contended on the vulnerability of the dune sands, particularly the salt river catchment. A side channel on the east of the floodplain had been cut off by a possible flood overflow (Figure 25). Multiple cut offs occurred within the Estuary with regards to the Knysna Salt River, a readjustment of the river meander pattern could be seen in 1997 (Figure 25). The increase in salt marsh particularly in the northwest of the Estuary came about by the removal of the forest adjacent to the Estuary, increasing the amount of deposition, trapping sediment and accretion and allowing for an increase in salt marsh (Figure 25) The fire of 2017 had been one of the largest fires experienced by the town of Knysna. The fire had led to the destruction of the urbanized area as well as large areas of vegetation. With the removal of vegetation, large amounts of deposition entered into the Estuary once again aggravating the geomorphology of the Estuary.

6.5 GLOBAL CLIMATE CHANGE

The outcry on mitigating global warming has gained momentum since the early 1980s. This had a considerable interest in its impacts on the geomorphological impacts (Goudie, 1996) as cited in (Goudie, 2016).There has been a search for particularly sensitive areas with a criteria being their threshold resilience, human actions and climate change, susceptible features - such as being close to the sea level or they exist in harsh climatic areas. Some areas that may, as a consequence, react badly to global warming are low lying coasts such as lagoons, deltas and marshes (Goudie, 2016). Locations such as the Knysna Estuary have been impacted by swift change due to the combined effects of climate change and various other anthropogenic factors as in the case of many of the worlds famous deltas discussed by (Tessler *et al*., 2018).

Global warming whether a continuation of the post glacial temperature or human- initiated, is presently causing a nonstop rise in sea level. This SLR has influenced the geomorphology of the Knysna Lower town and the adjoining estuarine coasts by causing a spatial shift of coastal geomorphology, forming through the redistribution of coastal lands forms (Crooks, 2000). As climatic changes are continuous, periodic storms will become more prevalent. Global warming also results in more severe events such as floods and fires. Knysna experienced storm surges such as in 1996 which caused damages to property particularly on Leisure Isle. within the centre Estuary from this storm of 1996 had an expansive amount of sediment entering the Estuary through the salt river. Furthermore, the increase in fires has also had massive impacts on slope processes and runoff (Figure 25). Soil erosion by wind plays an critical part in sedimentation rates, but so may water erosion from agricultural land and the burning and subsidence of peat caused by fires (Goudie, 2020).

6.5.1 Droughts and Floods

Regional climate impacts river flow, particularly in the Western Cape region. This remains highly intricate because of river flow being influenced by precipitation levels, which in turn affect the frequency of floods and droughts. In the beginning of 1996, Knysna experienced one of its worst droughts for roughly 100 years (Marker, 2000). At the end of 1996 three floods occurred between October and November (Marker, 2000). The lower town was flooded on each occasion and these events resulted in extreme runoff transferring sediment into the Knysna Estuary. This increased the amount of sediment within the Estuary and accounts for the increase of water within the catchment area. As a result, there was a reduction in the cultivated land, shrubland, and barren land with -166994 (7%), -50389 (2%), and -47359 (1.9%) respectively.

In the last episode of flooding in November 1996, a whirlwind accompanied the flood, which led to many trees being uprooted. This can be seen when comparing the changes between 1995 and1996 (Figure 25) It led to a reduction in the cultivated land area from 312051 (13%) to 145057 (6%), shrubland area from 70452 (2.9%) to 20063 (0.8%) and barren land area from 250412 (10%) to 203053 (8.4%). The uprooting of trees also allowed for an increase in sediment runoff. This led to an increase in sediment within the Estuary, lowering the water level and increasing the amount of salt marsh present within the Estuary itself. There were flooding events in 1986, 1993, 1996 and 2003 and this can be seen in the results section (Figure 25) and (Figure 28). It is evident that during floods large amounts of sediments are washed into the Estuarine affecting the geomorphology of the Estuary and catchment.

The volume and intensity of precipitation before saturation exacerbates the runoff and sedimentation. In 1999 rainfall average was recorded at a low of 46,6 mm while in 2006 it was recorded at 87,3 mm and in November 2007 average rainfall was recorded at a high of 102,6 mm. High levels of rainfall increase erosion rates drastically while lower levels reduce them (Peizhen *et al.*, 2001). According to Marker (2000), dead timber choked each river mouth within the southern cape. This was one of the greatest deluges of yellow sediment, moreover known as cover sands, that entered through the salt river. The Knysna Estuary had turned yellow-brown in October 1996 (Marker, 2010).

These episodes led to extraordinary siltation as the Salt River Estuary may be an incredible sediment source (Marker, 2010). The record of the Salt Stream Estuary shows that the covered sands have continuously been helpless to erosion. Amid surge conditions this has contributed to the siltation of the Estuary (Marker, 2010). By 1999 areas of brown sediment had held up on banks west of the channel between the Knysna Yacht club and Leisure Isle (Figure 5). There had been multiple floods taking place in the Knysna region and the impact of these floods other than the increase in deposition, was the overflow of the side channels on the east of the floodplain. Numerous cut offs can be seen within the Estuary which accounts for the meandering pattern seen since 1997 (Figure 25). The constant fluctuation in rainfall experienced in Knysna also accounts for the sedimentation patterns or fluctuations identified in the Knysna catchment and estuarine area.

The discharge data acquired from the Department of Water and Sanitation (https://www.dws.gov.za) indicated that the surface water discharge from August to October was 1,834 cubic meters/second. The average exchange in sediment accumulation rates in current decades is roughly 50% more than the levels of the beginning of the twentieth century (Marker , 2010). This brings light to the change in sediment levels found within the Estuary. Changes in the discharge level also reinforce that the increase in built up area and urbanisation have impacted the geomorphology of the Estuary particularly evident towards the east of the Estuary; similar evidence has been found by (Fiket *et al.*, 2013). The increase in the number of dams on flood flows allowed for the reduction in the average yearly flood percentages. This is supported by Fitzhugh and Vogel (2011). In the instance where rainfall levels had decreased but river flow had increased, this is attributed to the discharge of the river from nearby agricultural practices along the river and Estuary (Figure 25).

The fluctuating pattern recorded for river discharge for the shorter and earlier periods such as 2007 up until 2017 reinforced that river flow is affected by the aforementioned anthropogenic factors at various points in time. The sediment patterns for the river flow were recorded to be almost double in comparison to the rainfall. It implies that the variability of river flow may not be entirely controlled by the changes occurring in rainfall. It highlights the presence and impact of other most likely anthropogenic factors. The former studies by (Lakhraj-Govender *et al.,* 2019) and studies on the Cobres river basin in Portugal also confirm that sediment patterns for the river flow and changing rainfall patterns have vital impacts on wetland areas (Lakhraj-Govender *et al.,* 2019).

6.5.2 Fire as a factor

In 1980 the state Department of Forestry implemented policies for controlled fires to rejuvenate fire-dependent vegetation and smaller fuel loads (van Wilgen, 2009). These practices had stopped in 1987 and focuses were shifted to manage fires to protect forestry plantations and urbanised areas (Kraaij *et al.*, 2011). Therefore, there had been a significant build-up of fuel loads in natural vegetation. Large areas of natural vegetation had also been cleared for plantation as well as changes in afforestation of the native shrubland vegetation, urbanization and salt marsh.

All these changes led to landform modifications and alterations in the geomorphology of the catchment areas and Estuary. These changes have also allowed for the increase in fuel loads across the study areas resulting in fires. It remained clear in the supervised classification that a significant amount of damage caused by the fire had been in areas where land change had occurred (Figure 25)

Furthermore, the increase in the Knysna population together with the increase in rural and urban development created an increasing urban-wildland interface (Kraaji *et al*., 2018). This has also come with development in rural areas, increasing the risk of fire, high levels of erosion and deposition. During 2017 the Knysna fire played an extremely important role in the amount of sediment deposition within the Estuary as well as the decrease in urban development found along the Estuary. Evidence of the fire destruction can be seen in the 2018 maps, where the salt marsh fluctuates (Figure 25) and led to the formation of a side channel that marks the previous eastern edge of the salt marsh. The various vegetation types played an important role in the severity of the Knysna 2017 fire. High fuel loads around these urban and rural areas increased the damage done by the fire and ultimately changed the landscape once more (Kraaji *et al*., 2018). Land use changes can occur for multiple reasons, affecting the heterogeneity of the catchment.

However, in this case, it has become increasingly evident that climate change resulting in floods and fires, agriculture along the estuarine banks, deforestation and built-up areas are the leading causes of the change in the geomorphology across the Estuary and catchment areas. These factors increase the deposition of sediment in the Estuary resulting in the change in landform of both the catchment and Estuary. Extreme dips can also be seen in (Figure 28) this attests to the various fires experienced within the Knysna area, attributing to the constant change in the deposition of the Estuary. There have been many cases of siltation of estuaries that brought about from deforestation of the river catchments that nourish them such as in the case of the Knysna Estuary and the clearing of the afrotemperate forest (Goudie, 2016).

6.6 LAND USE

Initially, the Knysna afrotemperate forests covered roughly 25% of the entire catchment where plantation covered 23% and fynbos covered 13%. However, a decrease was observed in the areas covered by afrotemperate forest; these had been declining during the study period because of deforestation and an increase in built-up area. It led to an increase in the amount of sediment in the Estuary due to the lack of natural surfaces. These findings supported Marker (2000) who showed a massive fluctuation in forestry. According to Marker (2000), alien vegetation is notorious for affecting water quantity and quality, resulting in fluctuations of sediment depositions. These fluctuations in sediment deposition resulted in the change of the landform. Prior to 1995, the large removal of afrotemperate forest had also resulted in exposing the soil to large amounts of runoff (Rutherford *et al.*, 2006).

While the removal of the forest led to an increase in deposition within the Estuary, it also led to the growth of vegetation where the forest once stood (Figure 25). This resulted in the binding of the soil, which led to a decrease in erosion in the forest region and ultimately the Estuary. These results have illustrated the linkages between land cover or use, and the part of temporal and spatial scale in understanding the impact of land cover and management of land use activities. The afrotemperate forest is an integral factor in regulating the sediment deposition in the Estuary as forest areas decrease the amount of sediment loss. The major reason behind it is that the Knysna Estuary is also continuously open to tidal influences with the Estuary receiving fluctuations in the amount of deposition and erosion.

There is also the presence of impermeable catchment area, with a steep gradient because of the presence of perennial river flow with historical uplifts leading to the incision. Therefore, the continuous fluctuation in the size of the forest from 1984 up until 2016 has impacted the amount of sediment deposition within the Estuary - particularly on the eastern side of the Estuary (Figure 25). Since the protection of the SANparks organization in 1985, the natural vegetation and biodiversity of the catchment appears to remain constant and in turn decreases the amount of sediment in the Estuary (Raw *et al.*, 2020). As a result, there is a reduction in the Knysna catchment containing natural vegetation, thus reducing the occurrence of erosion.

This is brought to light once again by the increase in salt marsh during 1986 (Figure 25) where the forest laying adjacent to the Estuary had been removed, which facilitated the trapping of sediment and accretion by binding the soil and decreasing run-off. After 1989, an increase in forest areas led to the decrease in deposition within the salt marsh, once again resulting in the overall change in the deposition and sedimentation levels of the Estuary. Particularly in 1989, the encroachment on the salt marsh within the Estuary had become very clear, especially within the centre.

Some of the vital factors that led to the change in sedimentation rates caused by humans at various stages in the Holocene period (Smith *et al.*, 2009). Some of the key points that were raised were, other than the initial clearing of land, are the evolution and development in agriculture. Studies by Carvalho-Santos *et al.* (2005) emphasised how agriculture has led to both slope colluviation and floodplain sedimentation. While according to Dotterweich (2008), the clearing of land particularly during the season of storms would be a powerful impact on the rate of soil erosion and colluviation. These sediments produced by accelerated erosion accumulates in wetland areas such as the Knysna Estuary.

The increase in agriculture near the Knysna Estuary transformed erosion and sedimentation rates. It was also recorded that during 2017 the Knysna Estuary had experienced a severe fire on the western end of the Estuary that resulted in an increase in erosion as well as sedimentation. As a result, annual mean vegetation reflection was recorded to be 0.0-0.1 km^2 between 1984 and 1986. The vegetation index went from a 0.7 km^2 to a 0.4 km^2 in 1989 and remained fairly the same with an index of 0.7km^2 . The vegetation index decreased from 0.7 to 0.4 km^2 on the western end of the catchment as well as in the north east of the catchment in the year 1997. An increase in average NDVI of 0.3 km^2 to a high of 0.5 $km^2$was recorded in 2000 in the northeast catchment. During 2002-2004, an average vegetation index of 0.4 to an average of 0.6 km^2 was recorded along with an index value of 0.7 km^2 during 2008-2010. An average of 0.6 km^2 was recorded during 2013-2016 in the northeast and southwest regions with an average of 0.4 km^2 in east and the west of the catchment area in 2019.

As Marsh (1864) cited in (Taylor *et al.,* 2014) discussed in his study 'the reactivation of dune phases' such as the cover sand in Knysna could also have been caused by humans. Coastal dunes have consistently been favoured for human occupation (Taylor et al., 2014). Be that as it may, to distinguish between areas of increased dune action caused by the change in climate which incorporates windiness and those caused by human affect has never been direct. There's a plausibility that the stages of instability seem to have happened when both climatic and human pressures happened at the same time (Beerten *et al.*, 2014).

It has become evident that the catchment has become influenced by agricultural pressures. Some of the pressures include farmers that have utilized the channel dams on the river and tributaries. The upper Touws and Duiwe catchments both included the increase in the number of dams built (Figure 25). This also leads to an extreme increase in sedimentation in the Estuary. The continuous change of land use together with gentle slopes, decrease the amount of run off in the Estuary; this facilitates the change in the geomorphology of the Estuary.

Agriculture along the Estuary leads to the clearing of land and direct deposition of sediment into the Estuary changing its geomorphology. This is strongly seen on the western end of the Estuary. From 1991 the shape of the Estuary becomes irregular with the gradual enlargement of the Estuary itself. This is the result of the various changes in land use whether it be the removal of the forest, the clearing of land for agriculture or urban areas. The impact on the Estuary became instrumental when the shape of the Estuary itself has changed.

6.7 Conclusion

The present research highlighted the new geological epoch – the Anthropocene (Oliveira, 2015) that describes the change in the global environment, coastal ecosystems, and estuarine.

It includes all the changes that occur in the natural settings because of changes in the physical, chemical and biological processes (Steffen *et al*., 2002). Where human force clashes with nature, it is influencing the earth system (Steffen *et al.,* 2010) by bringing the geomorphological changes. It not only highlights the human interference in the natural ecosystems but also describes the implications on all ecological systems and living beings that are impacting earth systems adversely (Goudie, 2016).

Presently, we have insufficient or limited knowledge about the workings of the earth system and seek learning to provide definite answers. It increases the need for intricate feedback between geomorphic systems and humans so that there is the determination of large gaps or uncertainties in knowledge. As mentioned by Chin *et al.,* (2014) feedback within geomorphic systems will help in obtaining significant learning about human changes such as the affected geomorphic systems and in return its effect on humans. The impacts of anthropogenic climate change have become increasingly evident as we are now facing a faster change in response to both climate and land use change (Goudie, 2016). A sensitive location such as the Knysna catchment and Estuary need to be identified and make clear the importance of our discipline towards the conservation of the Earth.

Chapter 7

7. CONCLUSION

The Knysna area is located in an area known for its rich biodiversity. The pressures caused by various anthropogenic factors are a growing concern that we may be at a point where key natural elements are about to be lost, if they are not lost already. Ultimately, there is an intricate interaction between land use, climate change and geomorphological impact (Choukri *et al.*, 2020). Climate change can affect the change in land cover by impacting the thickening of vegetation as well as the underlying surface impacting climatic conditions. Thus, it is tough to separate the impacts on land use change and climate change entirely. In this study, the contributions can be used to compare the impacts of land use change and climate change on coastal environments (Hou *et al*., 2021). Furthermore, land use change has progressed more drastically than climate has over the past few decades (Peng *et al.*, 2020). However, rapid urbanization within the Knysna area together with climate change and rapid population increase has led to greater impacts which was proved by this study.

Land use and climate change are some of the most crucial factors driving the change in estuaries (Leh *et al.,* 2011). Even though many case studies have been carried out to determine the impacts of land use change and climate change on various ecosystem services, few can distinguish between the two (Leh *et al.,* 2011). This study on the Knysna Estuary addressed land use change and its impact on the geomorphology of the Estuary between 1980 and 2019 through various studies methods while geomorphic and urban development zones were further compared. The results indicated that in areas distinguished by land use change, the change in sediment was dominated by climate and various anthropogenic factors.

As a comparison, the result of land use change on the Estuary indicated great impacts on urban development zones indicating high sensitivity to anthropogenic influences. Some of these anthropogenic factors included the clearing of land particularly during the season of storms that have affected soil rates and ultimately accumulated in the Knysna wetland. Similar studies have been conducted by (Dotterweich, 2008) who concluded that powerful impact on the rate of soil erosion and colluviation accelerated erosion accumulates in wetland areas. Furthermore, Kaplan *et al.,* (2009) has also stated that there has been an acceleration in slope erosion produced by agricultural activities while Naylor *et al.*, (2018) has concluded that the increase in floodplain sediments has been caused by human activities. Moreover, scholars such as Cooper *et al.,* (2018) and (Waters & Zaalasiewicz, 2019) agree with the finding of this study that built up areas or urban developments near wetland areas has been a key factor of the Anthropocene and resulted in various consequences such as sediment trapping (Zarfl *et al.,* 2015).

A long-term land use change analysis was carried out to identify and describe as well as map the landscape dynamics in the Knysna region and ultimately to discuss the impacts it has had on the geomorphology of the Estuary. Multiple environmental drivers of change within the study areas were explored. Urban land cover grew over the past few years and is expected to continue to grow in the coming years, presuming the nature of development remains the constant. Overall, the overpopulation and other anthropogenic factors such as agriculture explained the greatest increase in urban areas as well as the impact on the geomorphology. This study shows the link between land cover/use and the geomorphology and the role of temporal-historical data analysis in understanding the effect of land cover and climate change on land use activities on sedimentation. The results appear that when heterogeneity of the catchment was modified, whether by human initiated activities such as farming or by natural events such as fire and floods it affected the amount of stream flow which in turn had follow on effects on the geomorphology of the Estuary.

The Changes in Land Use within the Knysna area have included the reforestation of the local vegetation of Fynbos bushes with non-native pines, the associated invasion of shrubs through pines extends from plantations and security of firefighters from Fire Inclined shrublands from fire (Kraaij *et al*., 2018). All of these changes have brought about in increased fuel loads within the locale. The development of the human population has been accompanied by an expansion of provincial areas and an increment within the urban-wild boundary, expanding the chance of exposure to fires (Kraaij *et al*., 2018).

These components, coupled with exceptionally high fire danger climate conditions preceded by dry season, driven to damaging fires in 2017. Such occasions are sporadic and individuals can rapidly lose interest in executing firefighting practices. firefighting and become willing to put amenities in high-risk areas. for long periods between fires Possible valuable reactions may include the reintroduction of prescribed burning programs as well as fire concealment in key regions, effective programs to control the spread of alien invasion species, consideration of economic sustainability as well as ecological development of commercial planting of invasive alien species, exotic trees in fire prone areas and strong regulations of residential and other developments and the interface between the city and wild lands (Kraaij *et al*., 2018).

Changes in land management might have a significant impact on the development on the Estuary and the catchment. Various stages of government have the responsibility to manage this natural environment within the Garden route National Park. As tourism in the areas is also a key income base, it makes even more sense to protect and monitor the garden as this is the key element that also draws tourists from all over the world.

People control much of the Earth's environment, however we depend on the running of normal environments for numerous pivotal services, which include the provision of food, clean water, air and recreation. Hence, it is basic that association is formed to connect science and management to modern paradigms around how these biological systems work with plans that will guarantee the continued provision of the vital system benefits on which we as people depend (Ewel *et al*., 2001).

The challenge management faces with regards to coastal wetlands are to conserve the biological and sedimentary resources while simultaneously tapping into the economic potential of the wetland. Each area of a wetland needs individual attention and consideration; however, there is a danger that badly coordinated small-scale systems will result in equally damaging circumstances.

7.1. RECOMMENDATIONS

With regards to the Estuary, a team effort is required between scientists and management to designate effective reserves while determining specific management practices, improving the understanding of individuals on how wetlands operate. Secondly, with regards to the restoration of ecosystems and the establishing of new ones, scientists need to focus on educating individuals on how wetlands function while also communicating that information to stakeholders and finding ways of joining that knowledge into a system that can also be utilized by supervisors (Ewel *et al*., 2001). Scientists should weigh the pros and cons of their demands, as well as recommendations to assist the needs of managers, taking into consideration the political implications of their requests. Managers for their part need to welcome the change of management strategies whereas being open to suggestions from researchers, indeed on the off chance that it means permitting for a short-term risk to attain a long-term objective of maintaining the health and integrity of an ecosystem. Only when scientists and managers have worked together and stakeholders become actively involved can we ensure that wetlands will continue to thrive.

Management plans for creating areas that have estuaries and lagoons should have a approach of no net misfortune of saltmarshes. Several agencies need to get on board and become involved with protection, restoration projects and programs. A policy of security and rebuilding ought to be received within the Knysna area as an aim to preserve these wetlands. Educating and promoting the benefits of wetlands enables the public to get involved in various ways on how to help save and conserve these wetland areas. The Thesen Environmental Studies Laboratory could focus on research and training of a wide variety of young individuals starting from school groups to PhD students to give these individuals first-hand experience on the importance of the wetland as well as the importance of estuarine ecology. This laboratory could also raise awareness with the local community on how to conserve and protect the environment while also involving the locals in specific research fieldtrips.

Studying the history of these crucial ecosystems permits us to put recent and continuous changes to coastal wetlands into point of view; it permits us to receive a more proactive approach to the Estuary and land management in which flexible management can be implemented. Persistent human occupation and land use changes around the Knysna Estuary and lagoon as opposed to SLR and other environmental impacts have resulted in the most severe impacts on coastal ecosystems. This study has quantified losses and gains in the catchment area and identified the various land use changes from 1980-2019 around the Knysna catchment area.

7.2. LIMITATIONS

While the approach taken in this study has resulted in an accurate map of estuarine dynamics in relation to land use changes, it is vital to note the limitations of the study. One of these limitations include data before 1980 that were not available. The inclusion of more data focuses within the entire study would improve the accuracy of the yearly maps. This would at the same time allow for an improved assessment of anticipated performance through time. With that being specified as the spectral signature of these particular classes are improbable to have changed through time, the forecast of the study is likely to remain the same. Besides, the study also depended on visual assessment of high resolution imagery to create training data. Ground truth data had to be performed as it was not readily available. Without this, misclassification could occur.

Furthermore, depending on a single image to show an entire year period disregards the fact that certain training data points may pass between classes based on the changes in season or weather (i.e., soil might be in full bloom during spring and bare during winter). Thirdly, the classes number were restricted to 8 which may limit the study itself. With accurate data for more classes, it may be possible to produce maps with more than 8 classes. Even though the study included limitations, the approach taken and model validation results show that the maps shown within the research had a high forecast of precision. Future studies are able to expand on this study and apply this approach to create worldwide scale land cover.

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9. APPENDIX

Creating the region of interest (ROI) of the study area.

```
/ Define a region of interest as a point.  Change the coordinates
// to select an ROI in your area of interest.
// You can use the inspector tool to find your coordinates
var roi = ee.Geometry.Point(23.054, -34.0482);
```

Loading and filtering the image collection

The *first* or least cloudy image was arranged and selected from '*Image Collection'.*

```
// Load Landsat 8 input imagery.
var image = ee.Image(ee.ImageCollection('LANDSAT/LC08/C01/T1_SR')
 // Filter to get only images under the region of interest.
  .filterBounds(roi)
  // Filter to get only one year of images.
  .filterDate('2018-10-01', '2018-10-30')
  // Sort by scene cloudiness, ascending.
  .sort('CLOUD_COVER')
  // Get the first (least cloudy) scene.
  .first());
Map.addLayer(image, {bands: ['B5', 'B4', 'B3'], max: 0.5, gamma: 2}, "L8 Image");
      // Merge points together
```

Collecting the training data

Map.addLayer(image, {bands: ['B5', 'B4', 'B3'], max: 0.5, gamma: 2}, "L8 Image");

// Merge points together

Var newfc =

Water.merge(naturalwoodlands).merge(plantedforest).merge(builtuparea).merge(cultivatedl

and).merge(fynbosshrubland).merge(waterbodies).merge(saltmarsh);

print(newfc, 'newfc');

// Select the bands to be used in training

var bands = ['B2', 'B3', 'B4', 'B5', 'B6', 'B7'];

Sampling Images at Training Points to create training datasets

```
// Select the bands to be used in training
var bands = [‘B2’, ‘B3’, ‘B4’, ‘B5’, ‘B6’, ‘B7’];
// Sample the input imagery to get a FeatureCollection of training data.
Var training = image.select(bands).sampleRegions({
  collection: newfc,
  properties: [‘landuse’],
  scale: 30  // should reflect the scale of your imagery
 });
```

Training the classifier

```
// Make a classifier and train it.
Var classifier = ee.Classifier.randomForest(10).train({
  features: training,
  classProperty:  ‘landuse’,
  inputProperties: bands
```

Classifying the image and displaying the results

```
// Classify the input imagery.
Var classified = image.select(bands).classify(classifier).aside(print);
// Define a palette for the Land Use classification.
```

Var palette = [

'#0a9917', // naturalwoodlands (0)

'#00f7f7', // water (1)

'#fffcb0', // cultivatedland (2)

'#d7d8ff', // builtuparea (3)

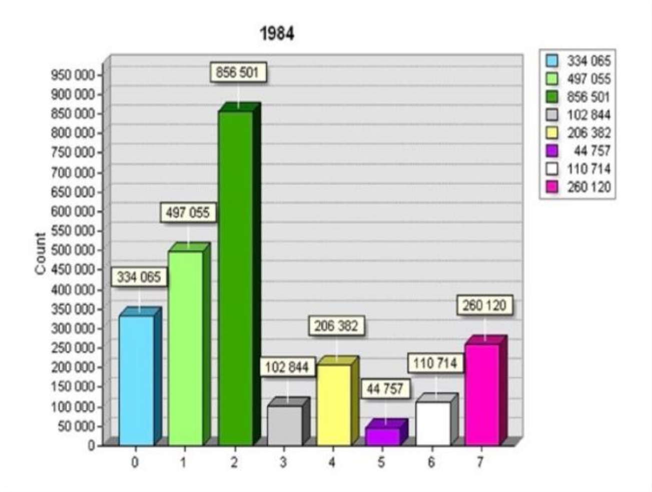
'#1aff0b', // plantedforest (4)

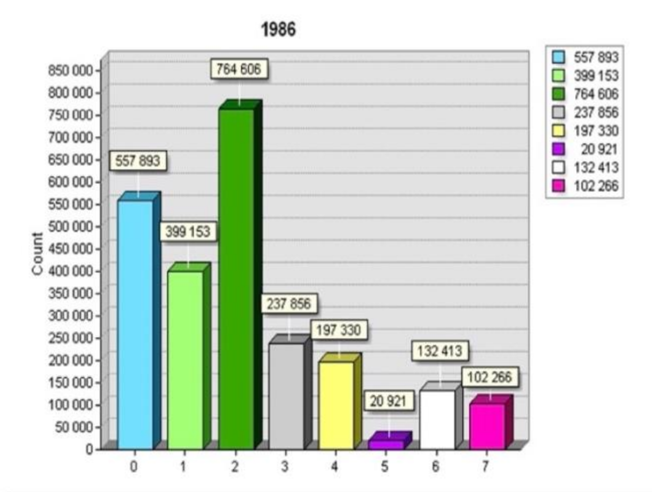
'#e766ff' , // fynbosshurbland (5)

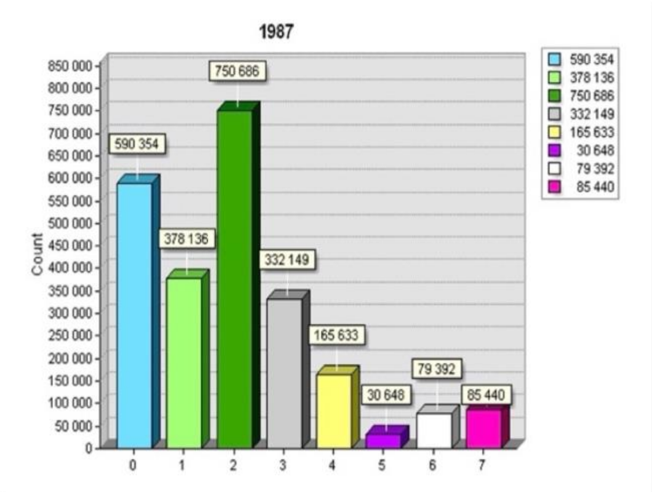
'#1612f7', // barrenland(6)

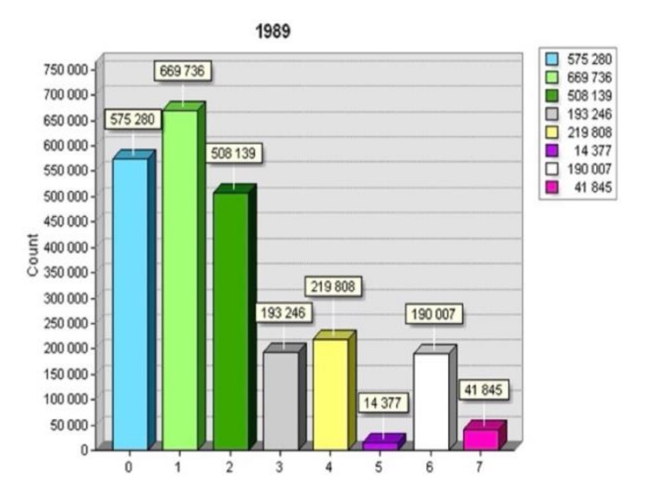
'#a054ff',// saltmarsh(7)]

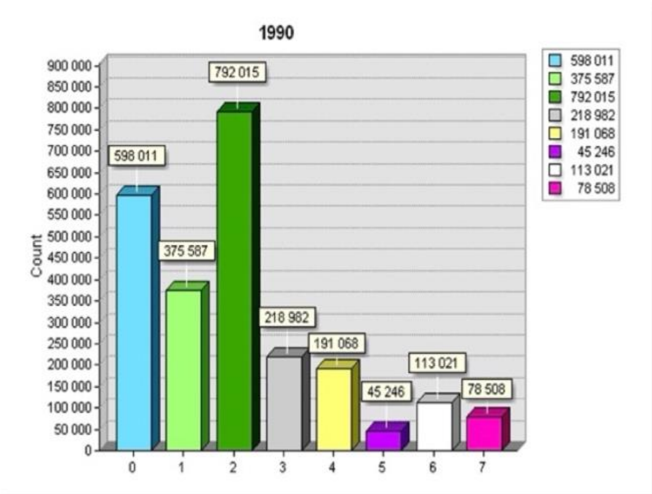
<u>Supervised classification graphs</u>

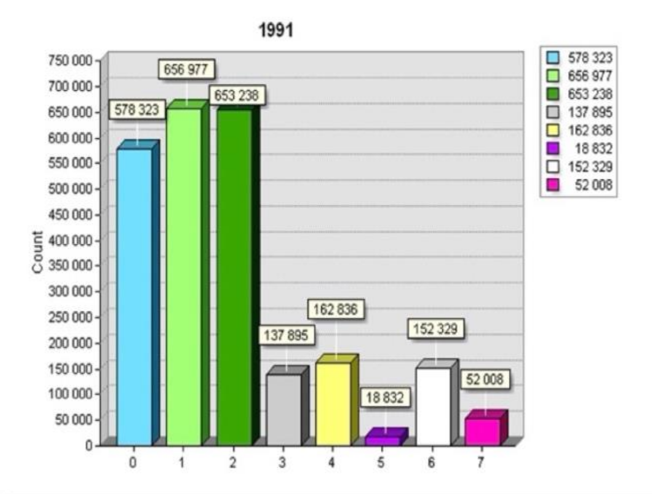

1984
Count
334 065
497 055
856 501
102 844
206 382
44 757
110 714
260 120
0 1 2 3 4 5 6 7

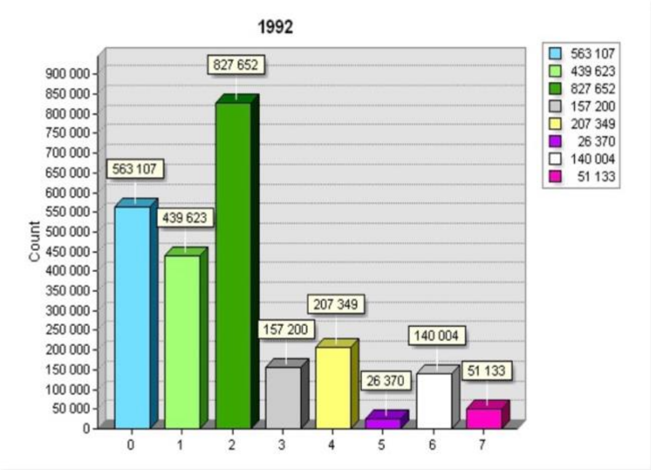

1986
Count
557 893
399 153
764 606
237 856
197 330
20 921
132 413
102 266
0 1 2 3 4 5 6 7

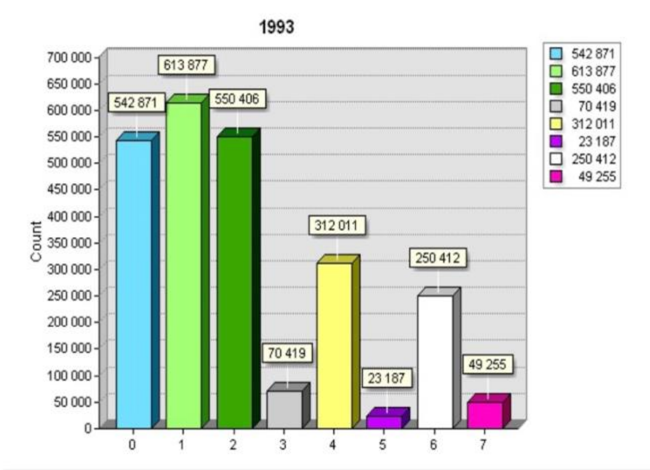

1987
Count
590 354
378 136
750 686
332 149
165 633
30 648
79 392
85 440
0 1 2 3 4 5 6 7

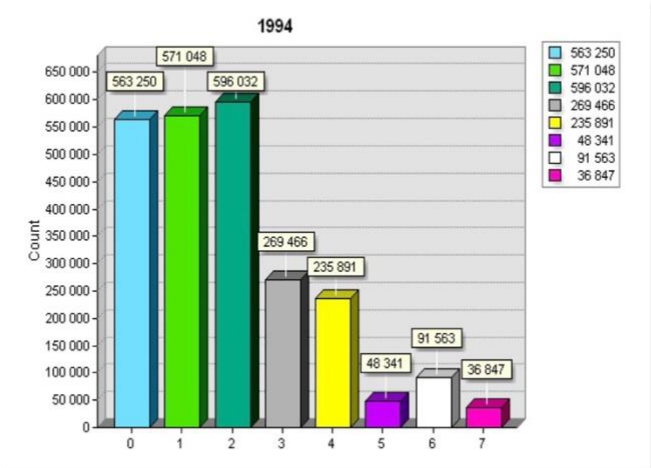

1989
Count
575 280
669 736
508 139
193 246
219 808
14 377
190 007
41 845
0 1 2 3 4 5 6 7

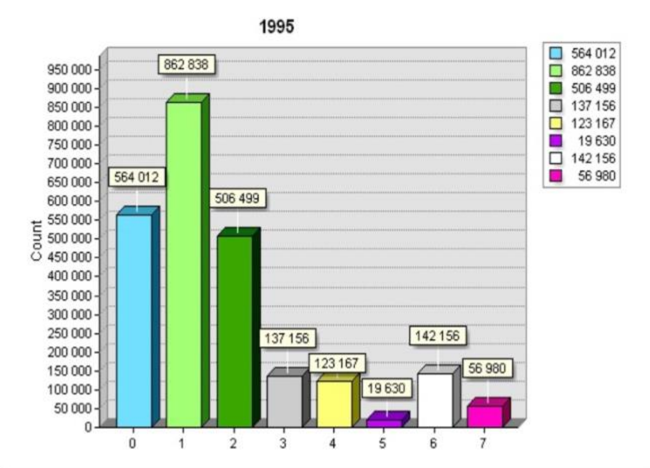

1990
Count
598 011
375 587
792 015
218 982
191 068
45 246
113 021
78 508
0 1 2 3 4 5 6 7

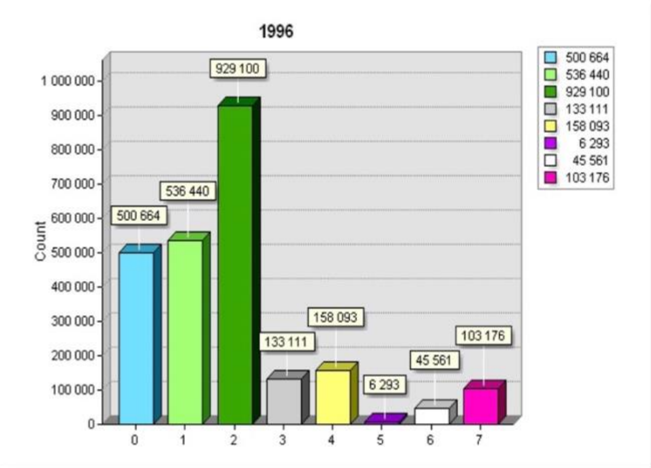

1991
Count
578 323
656 977
653 238
137 895
162 836
18 832
152 329
52 008
0 1 2 3 4 5 6 7

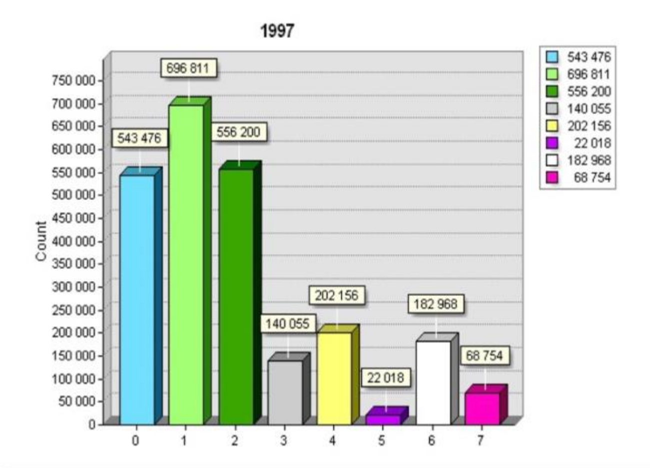

1992
Count
563 107
439 623
827 652
157 200
207 349
26 370
140 004
51 133

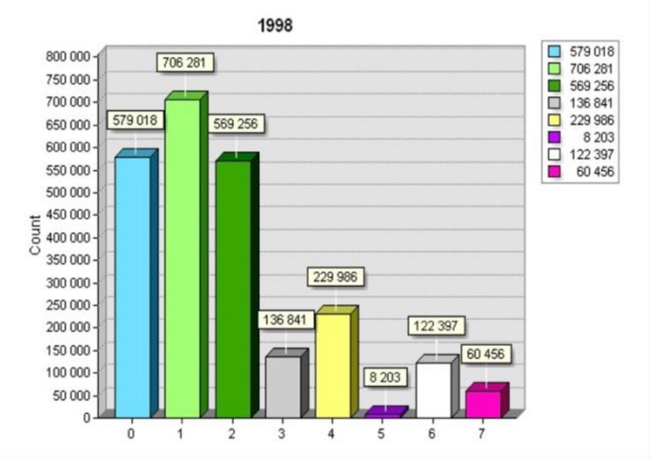

1993
Count
542 871
613 877
550 406
70 419
312 011
23 187
250 412
49 255

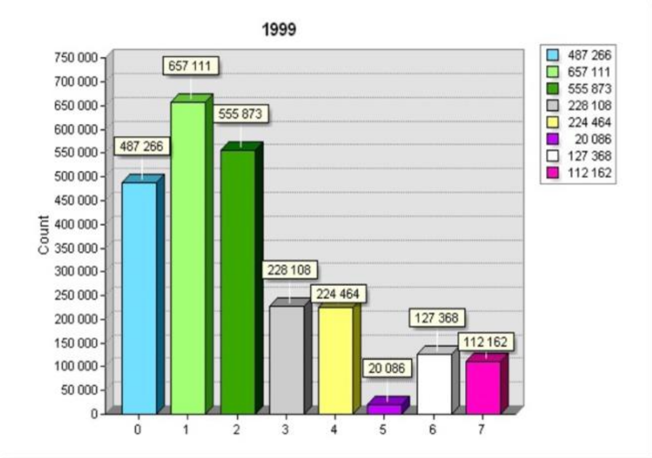

1994
Count
563 250
571 048
596 032
269 466
235 891
48 341
91 563
36 847

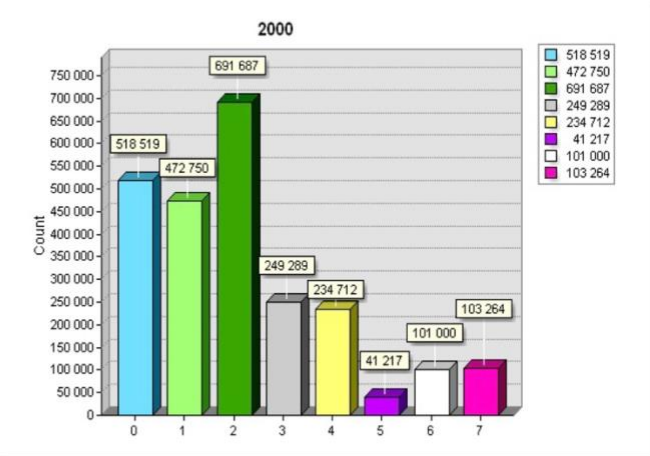

1995
Count
564 012
862 838
506 499
137 156
123 167
19 630
142 156
56 980

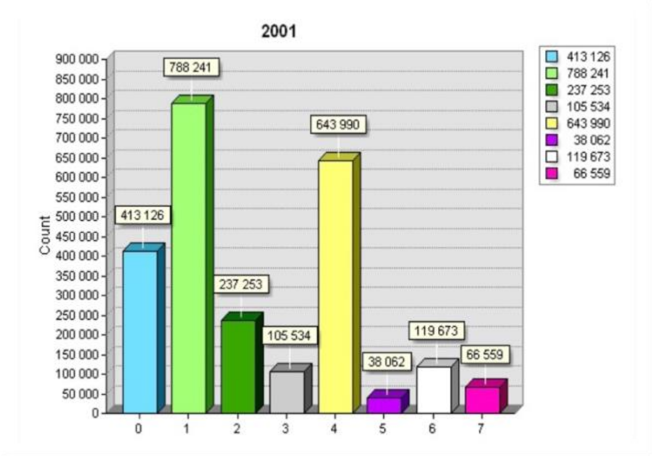

1996
Count
500 664
536 440
929 100
133 111
158 093
6 293
45 561
103 176

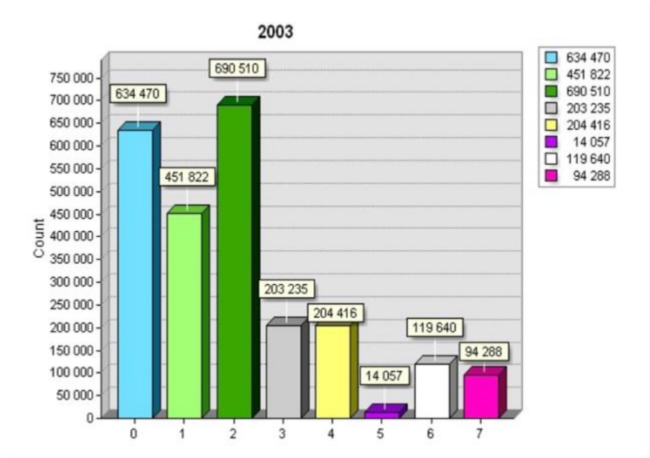

1997
Count
543 476
696 811
556 200
140 055
202 156
22 018
182 968
68 754

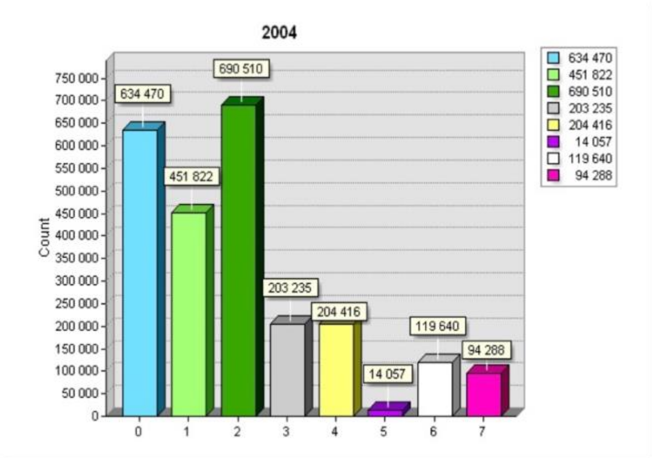

1998
Count
579 018
706 281
569 256
136 841
229 986
8 203
122 397
60 456

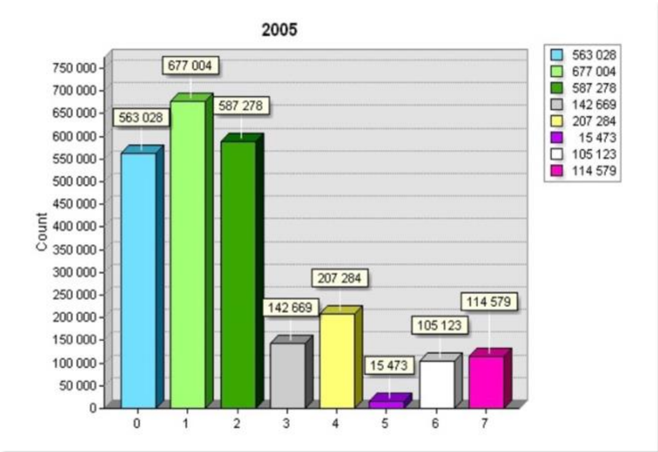

1999
Count
487 266
657 111
555 873
228 108
224 464
20 086
127 368
112 162

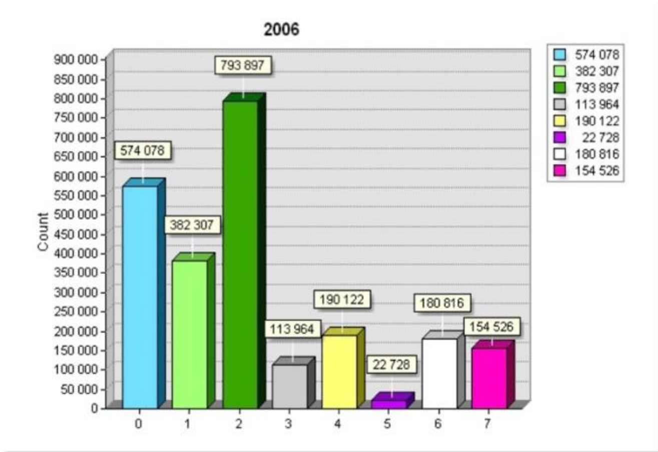

2000
Count
518 519
472 750
691 687
249 289
234 712
41 217
101 000
103 264

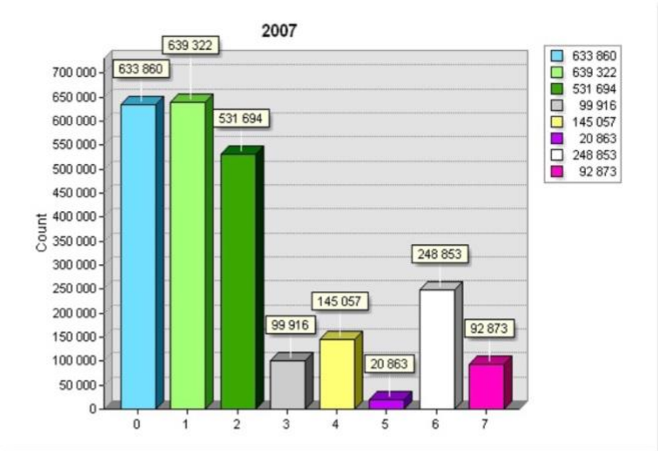

2001
Count
413 126
788 241
237 253
105 534
643 990
38 062
119 673
66 559

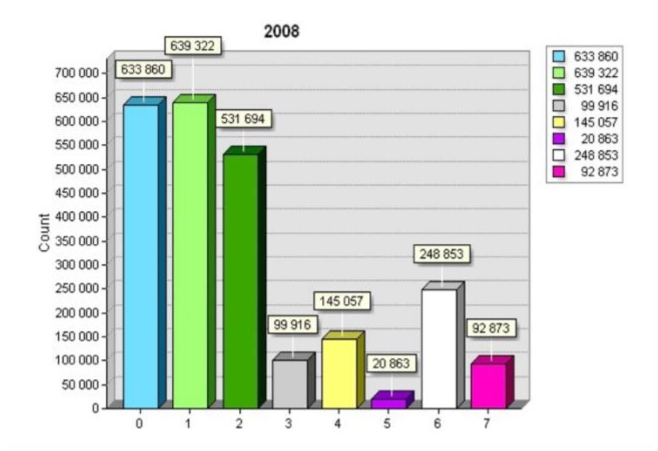

2003
Count
634 470
451 822
690 510
203 235
204 416
14 057
119 640
94 288

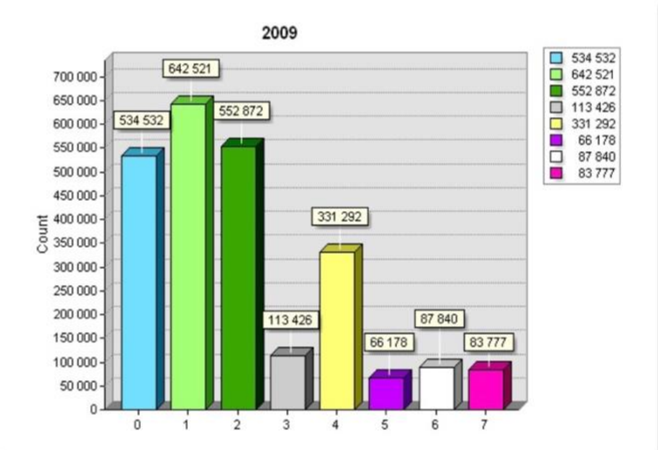

2004
Count
634 470
451 822
690 510
203 235
204 416
14 057
119 640
94 288

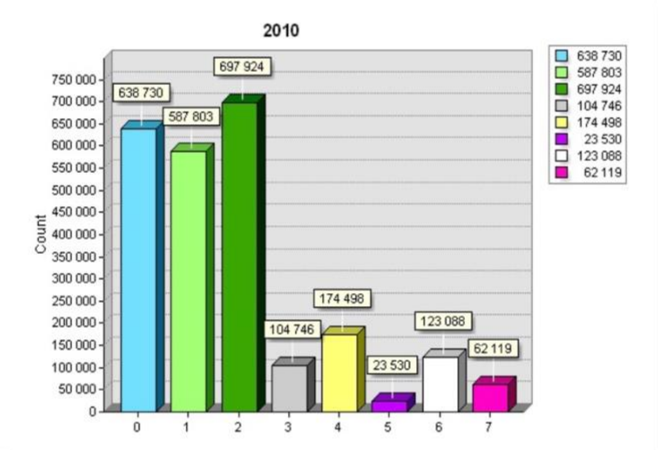

2005
Count
563 028
677 004
587 278
142 669
207 284
15 473
105 123
114 579

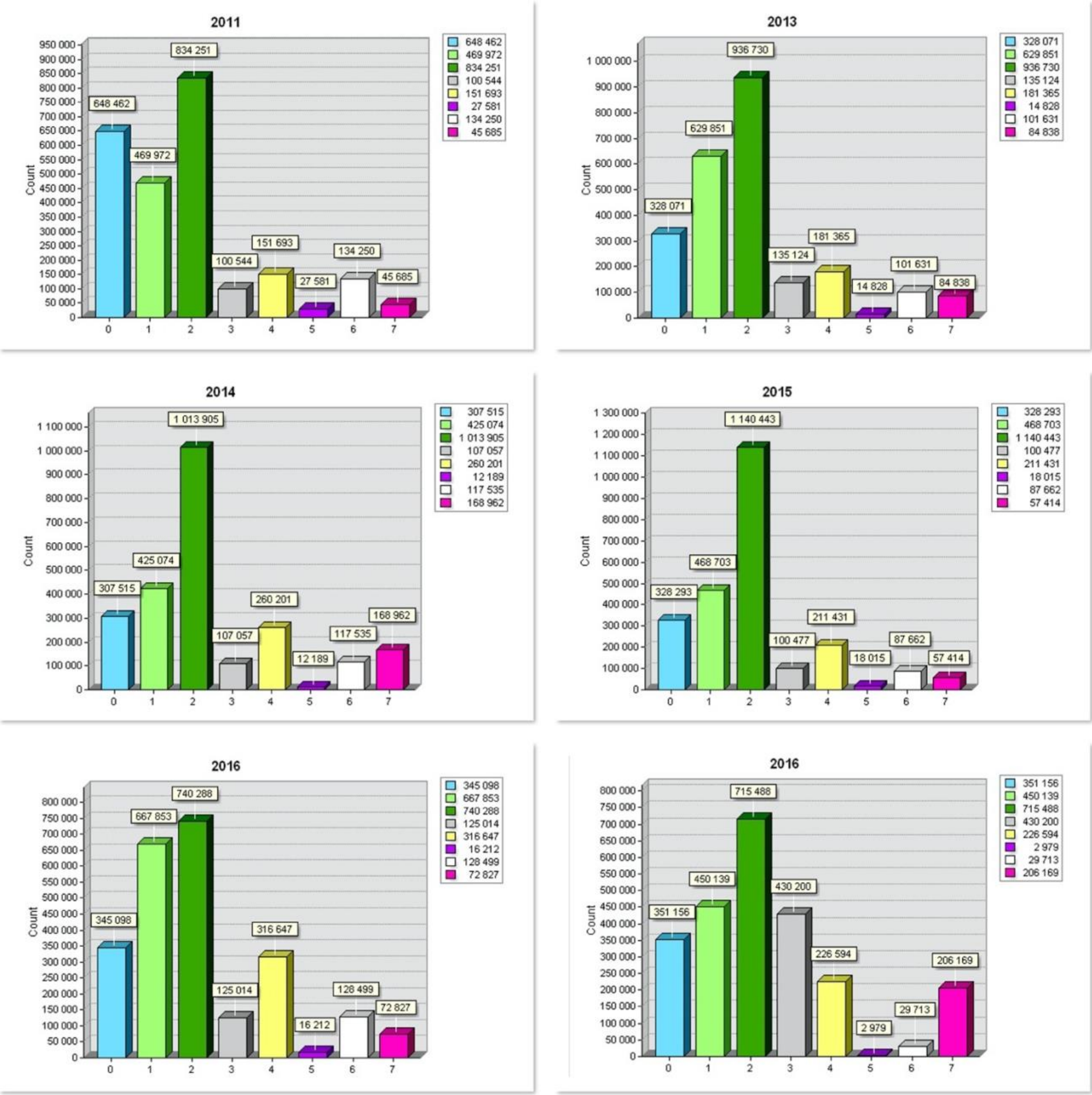

2006
Count
574 078
382 307
793 897
113 964
190 122
22 728
180 816
154 526

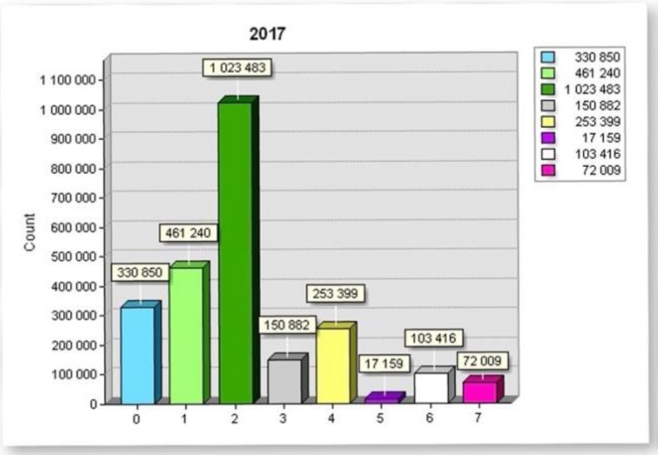

2007
Count
633 860
639 322
531 694
99 916
145 057
20 863
248 853
92 873

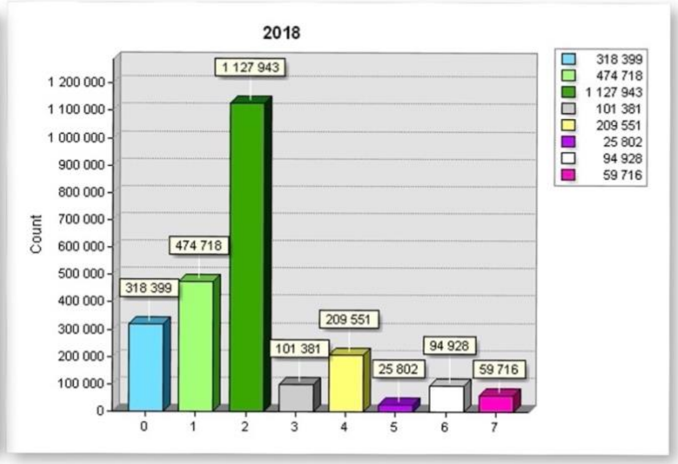

2008
Count
633 860
639 322
531 694
99 916
145 057
20 863
248 853
92 873

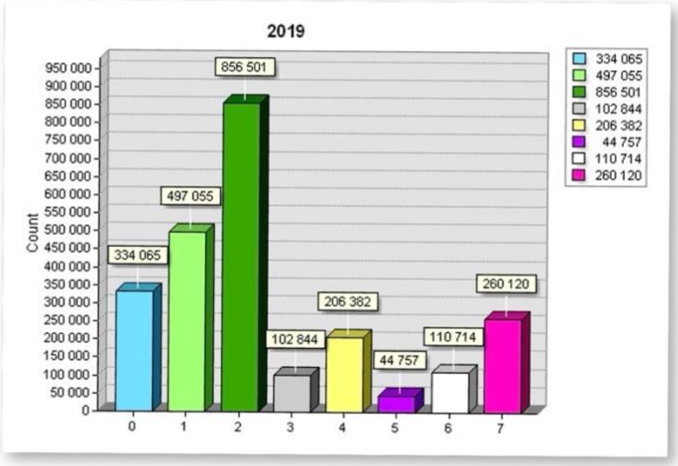

2009
Count
534 532
642 521
552 872
113 426
331 292
66 178
87 840
83 777


2010
Count
638 730
587 803
697 924
104 746
174 498
23 530
123 088
62 119


2011
648 462
469 972
834 251
100 544
151 693
27 581
134 250
45 685
Count
2013
328 071
629 851
936 730
135 124
181 365
14 828
101 631
84 838
2014
307 515
425 074
1 013 905
107 057
260 201
12 189
117 535
168 962
2015
328 293
468 703
1 140 443
100 477
211 431
18 015
87 662
57 414
2016
345 098
667 853
740 288
125 014
316 647
16 212
128 499
72 827
2016
351 156
450 139
715 488
430 200
226 594
2 979
29 713
206 169
0 1 2 3 4 5 6 7


2017
Count
1 023 483
461 240
330 850
253 399
150 882
103 416
72 009
17 159
330 850
461 240
1 023 483
150 882
253 399
17 159
103 416
72 009


2018
Count
1 127 943
474 718
318 399
209 551
101 381
94 928
25 802
59 716
318 399
474 718
1 127 943
101 381
209 551
25 802
94 928
59 716


2019
Count
856 501
497 055
334 065
206 382
102 844
44 757
110 714
260 120
334 065
497 055
856 501
102 844
206 382
44 757
110 714
260 120


Legend
Water
Natural Woodland
Planted Forest/ Alien Vegetation
Built Up Area
Cultivated Land
Grassland
Barrenland
Salt Marsh