TECHNICAL FEASIBILITY OF HEAVY MINERALS IN SOUTHWESTERN AND NORTHEASTERN ONSHORE AND OFFSHORE REGIONS OF SRI LANKA

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Degree of Master of Philosophy

Department of Earth Resource Engineering

University of Moratuwa
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DECLARATION

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ABSTRACT

Beach sediments in Sri Lanka consist of industrial grade heavy mineral occurrences. Most of the previous studies have targeted to identify mineral compositions rather than the provenance of these beach sediments. In this study, the offshore and onshore sediments were collected for identifying heavy minerals compositions. In addition, the long-term coastal morphodynamic changes were analyzed in the coastline of Sri Lanka, with the monsoonal changes. These coastal morphodynamic changes were used to identify the coastal sediment accretion and depositional trends, and its relationship to the heavy mineral provenance. Results suggest the concentration of detrital Ilmenite, Zircon, Garnet, Monazite and Rutile in onshore and offshore sediments in varying concentrations. The heavy mineral potential of the northeastern coast was high (average about 45-50% in the Verugal and 70-85% in the Pulmoddai deposits and 3.5-5.0% in the offshore samples from Nilaveli to Kokkilai (in w/w)), compared to the southwestern sediments (average about 10% in onshore and 2% in offshore Gin River mouth). Therefore, no high economic-grade heavy mineral placers have been discovered by offshore investigations. However, it may be possible to occur concentrated heavy minerals in paleo-river channels that were developed due to glacioeustatic sea-level changes. Observed high concentrated heavy minerals in beach and low concentrated offshore sediments suggest the panning system in the surf zone to form enriched placer deposits. The monsoon-derived longshore currents suggest that the sources of heavy minerals in the Pulmoddai and Verugal deposits may have probably influenced by clastic sediment supply in eastern India and Sri Lanka (the Mahaweli River), respectively. Heavy minerals in the western coast can probably derive from Precambrian metamorphic rocks and supplied to coast through river systems in Sri Lanka. The results obtained are well satisfying for the exploitation of the Verugal deposit and the mine plan was described with the considerations of analytical outcomes.

Keywords: Heavy minerals, Verugal deposit, Mine plan, Mineral economics, Sediment dynamics, Sri Lanka

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LIST OF ABBREVIATIONS

AEA	Atomic Energy Authority
EEZ	Exclusive Economic Zone
GPS	Global Positioning System
GSMB	Geological Surveys and Mines Bureau
HMS	Heavy Mineral Sands
IRZ	Ilmenite Rutile Zircon
MSL	Mean Sea Level
NE	North East
SG	Specific Gravity
SW	South West
UNRFNRE	United Nations Revolving Fund for Natural Resources Exploration

UV	Ultraviolet
ZTR	Zircon-Tourmaline-Rutile

LIST OF APPENDIXES

CHAPTER 1: INTRODUCTION

1.1 Background

Heavy minerals are the natural resources with a specific gravity more than 2.89 g/cm^3 and the hardest and most resistant minerals to abrasion and chemical change. All of these minerals are found in minor amounts as the accessory minerals in the granites and gneisses and the rocks of the highland series. Their chemical resistance keeps them remain unchanged, and due to their higher specific gravity, they are concentrated by the natural sorting action of the waves and are concentrated in bands or lenses more or less parallel to the long direction of the beach.

Sri Lanka as an island having itself the high potential for heavy mineral sand such as Ilmenite, Garnet, Rutile, Monazite, Zircon, with high purity and concentration. All these minerals have high tech industrial applications and have great demand in the world market.

Historical reviews of Sri Lanka beach sand are evidence for the abundance of these heavy minerals. The coastal region of the southwest Sri Lanka has the deposits of heavy sand has been recognized for prolong period and has been exploited cost-effectively during 1918. The deposit at Pulmoddai in the northeastern region of Sri Lanka is currently being mined by Lanka Mineral Sands Ltd, which is the public company of Sri Lanka founded in 1957.

Sri lanka has greater area of exclusive economic zone up to 200 nautical miles which is eight times of its land area. That has a very narrow continental shelf with an area of 31,250 km^2. The EEZ has a more significant potential for these important economic minerals. Further, Sri Lanka has a strategic plan to wide its exclusive economic zone. It is essential to concentrate on marine environment for its mineral requirements and which could support the 'Blue Economy' concept. However, detailed exploration within this continental shelf has not carried out and at present, the country has discovered only the existence of critical marine minerals in beaches and adjacent dune sediments (e.g., Pulmoddai beach heavy mineral deposit).

Therefore, it is necessary to investigate new deposits for the betterment of Sri Lanka. This study explores heavy minerals in both onshore and offshore in the south-western and north-eastern regions. The mineralogical and textural properties of the samples were examined to find the possible source of the deposit and to understand the seasonal replenishment patterns to design a mine plan for the exploitation of the deposit at Verukal, Trincomalee.

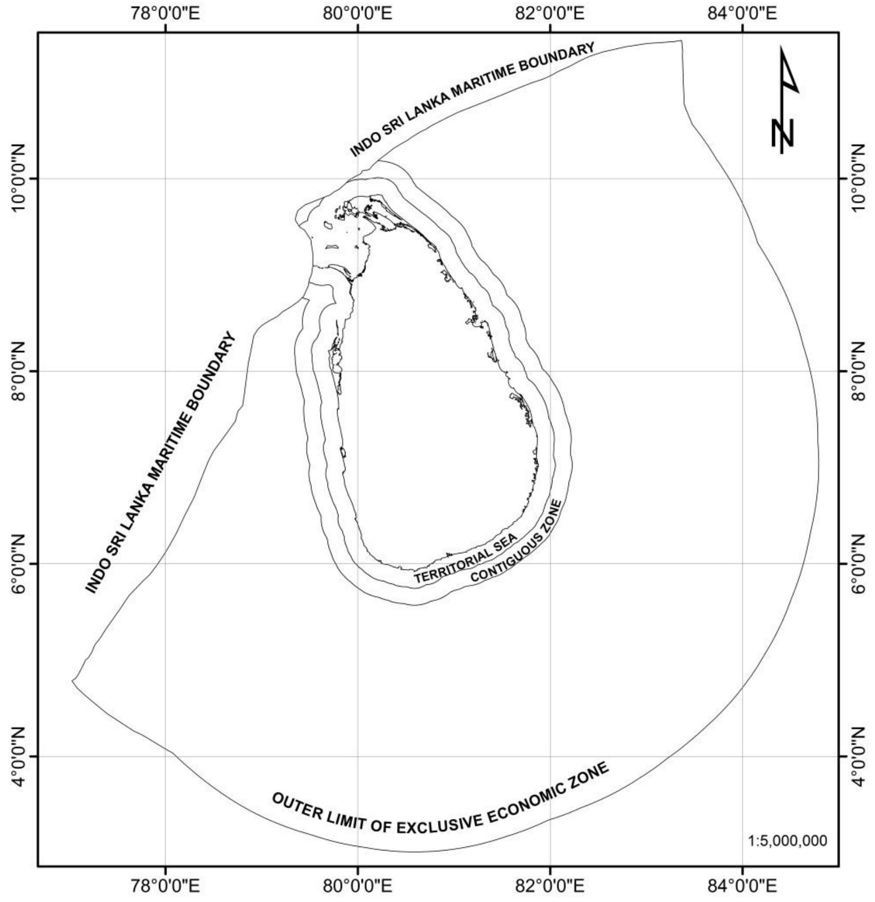


Figure 1.1: Sri Lanka's exclusive economic zone (EEZ)

1.2 Significance of Research

The significance of this research is, finding the possible source of the deposit. In understand the development and current behaviour of the current sedimentary system, identification of the source and depositional area of sediments are important. (J. Alcántara-Carrió, 2010). Understanding the impacts of the seasonal changes also significant aspect because the coastal and marine environment is very dynamic.

Thus, finding the source and understanding the seasonal sedimentation pattern is vital for mining the deposit effectively and efficiently. Not only that but also it will help to protect the deposit and the source by preventing the negative impacts arising from human-made constructions and natural causes. Basically, two concepts for the origin of Pulmoddai deposit, either the sands travel from the continental shelf or the Mahaweli River and heavies brought up the coast due to sediment dynamics. The figures (Fig 1.2 and 1.3) illustrate the significance of finding the source. When the sediment transportation occurs via inland rivers or from a deep ocean basin, then the constructions associated with the streams and coastal conservation actions also affect the replenishment of mineral sand. In the case, if the source is from India the construction across the continental shelf will disturb the replenishment of sediments.

Consequently, it has an impact on international projects like the Sethusamudram canal project. To prove the second theory at Pulmoddai, it was planned for introducing radio isotopes upstream by the Atomic Energy Authority (AEA) and Geological Survey Department (Present GSMB) in the early 1980s but this project was deserted. Although, it was identified construction of dams across the Mahaweli river made the reduction in the heavy sand deposition it is found that settlement of heavy sands has fairly decreased (Jayawardena, 2014). Therefore, to evaluate the economic feasibility of the resource, it is vital to understand the source of the deposit which influences the selection of mining method and mine plan as well.

Objectives

- To explore heavy mineral distribution in the southwest and northeast onshore and offshore regions of Sri Lanka.
- To compare the mineralogical and textural properties to identify,
    - The possible sources of deposits.
    - Seasonal replenishment patterns.
- To quantify the resource and propose a mine plan for exploitation of selected placer deposit in Verugal

1.3 Project Deliverables

- Distribution maps of heavy mineral concentration and identifying their seasonal replenishment patterns
- Mine plan

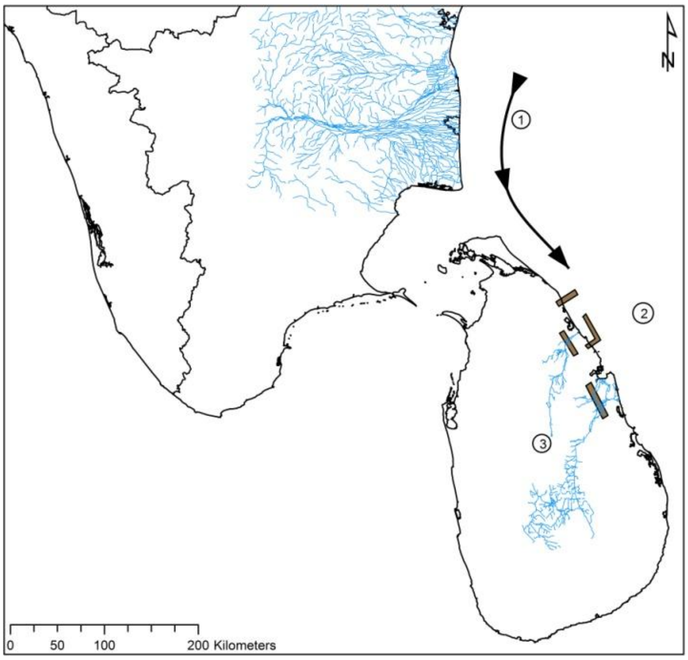
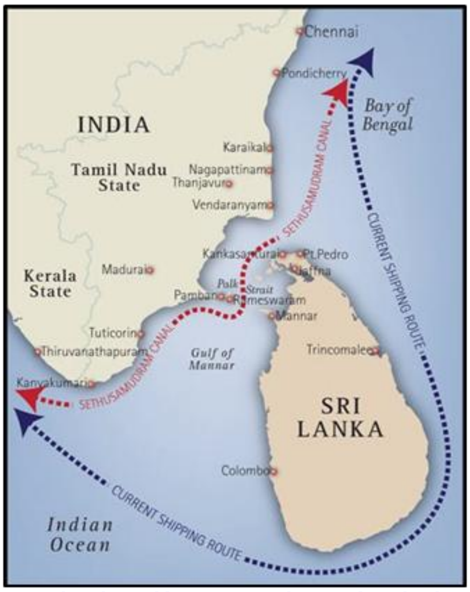


Figure 1.2: Mineral transportation and their disturbance



http://exploretheworldmaps.com/sethusamudram.html
Published January 2010

Figure 1.3: Sethusamudram canal project

CHAPTER 2: LITERATURE REVIEW

2.1 Placer Deposits

Placer deposit is a natural accretion of heavy and valuable minerals formed by gravity separation during sedimentary processes. The weathering process makes the grains to free from their rock matrix. Hence the heavy and stable minerals will slowly be transported and deposited. Higher specific gravity minerals are chemically resistant to weathering and are durable, which form placer deposits.Formation of the placer deposit is the main parameter to catergorize them.

Classification of placer deposits;

- Residual Placers
- Eluvial Placers
- Stream/alluvial Placers
- Eolian Placers
- Beach Placers

There are numerous types of placer deposits; stream and beach placers are economically significant. Beach deposits are formed by the action of waves but alluvial deposits are formed because of running water. Precious minerals of stream deposits concentrated in sand and gravel which are sorted by the actionof the running water. When the velocity of the flow og the stream reduces the heavy mineals are deposited. Therefore it occurs at stream bends (meanders) and at the delta, where the speed is lower. These places can be seen in any beaches because of the shifting of the land and sea during the geological time frame.

Meanwhile beach placers occur along coastlines due to the action of currents and waves. Materials from cliffs by waves or by streams are sorted and deposited according to their size and specific gravity. A longshore drift, parallel to the beach can bring into being beach placer. Significant source of heavies such as Ilmenite, Rutile, Garnet, Monazite and Zircon can be the beach placers. They have been extensively mined in India, Australia, Alaska, and Brazil (Rafferty, 2012).

2.2 Heavy Minerals in Sri Lanka

In general, heavy mineral sands are deposits at beaches and shorelines and other related features such as dune formations. In their physical composition, most beaches are made up of several minerals of varying sizes and shapes which have resulted from the breakdown of rocks, mixed with shell fragments of marine animals.

By far the commonest of these minerals is the ever-present Quartz, but there are other minerals which are not so common and of much higher specific gravity such as Ilmenite, Garnet, Rutile, Monazite, Zircon and many others. These are so-called heavy minerals, all with a specific gravity more than 2.9 g/cm^3, and they represent like the gems, the hardest and most resistant minerals to abrasion and chemical change (Muller & Uptegrove, 1997).

All of these minerals are found in minor amounts as the accessory minerals in the granites and gneisses and the rocks of the highland series (Fernando, 1986). They are set free by mechanical disintegration and chemical decay of the parent rocks. Because of their chemical resistance, they remain unchanged and because of their higher specific gravity, they are concentrated by the natural sorting action of the waves and are concentrated in bands or lenses more or less parallel to the long direction of the beach. These deposits are easily recognisable because of their colour, commonly black due to the predominance of Ilmenite; and at times pink due to the prevalence of Garnet. Beaches of Sri Lanka are rich and one of the most important sources of minerals such as Ilmenite, Rutile, Zircon, Garnet, Monazite and others.

Around the Island has the potential for heavy mineral sand. Such heavy mineral placers on the southwestern coast of Sri Lanka have been known for a long time and have been mined economically since 1918. Many studies of these deposits around the Island (e.g.:Coatess, 1935; Wadia, 1945; Fernando, 1950, 1954) have been made (Wickremeratne, 1986).

The northeast coast of Sri Lanka was identified for an occurrence of the heavy mineral sands by the chief mineral surveyor Dr. Ananda Coomaraswamy in 1904 during the Colonial time (Jayawardena, 2014). The exploration carried out by SIMEC ltd and State mining and Mineral Corporation in early 1981 between

Nilaweli to Mullaitivu proved promising heavy mineral deposits at Pudawaikkattu, Kokilai, Nayaru and Kokuthoduwai. Puduwaikkattu deposit extends inland more than three miles along the old river bed of Kodikkadi Aru. The interesting fact behind these deposits was all were located at the lagoons which are with promontory that might aid for the deposition (Jayawardena, 2014).

Along the eastern coast between Tirukkovil and Kokilai during the years of 2011, many investigations are one by the Geological Surveys and Mines Bureau (GSMB). The Pulmoddai contain an estimated six million tonnes of heavy mineral sands. These reserves are replenishes always during the northeast monsoon period. Sediment of Pulmoddai deposit comprises Ilmenite as the highest percentage ranging of 70-75 %. Second abundant mineral is the Rutile having composition of 10 % while it was 8-10 % of Zircon. In 2011 they have produced 62,955 tonnes of Ilmenite which is 10,000 tonnes higher to the previous year. Rutile production in 2011 was 1970 tonnes, while Zircon was 641 tonnes (Wijesinghe, 2012).

Australia’s Iluka Resources has identified mineral sands of approximately 700 million tonnes has 56 million tonnes of Titanium-bearing heavy minerals in the Puttalam district of the North Western Province, enough for mining life of over 20 years. The principal heavy minerals are Ilmenite and Rutile, with a third potential to Zircon (Jayatilleke, 2016). Silicate mineral sand deposits have been identified in Induruwa, Beruwala, the mouth of the Kelani river , Negombo Northern Zone, Kudiramalai Point, Southkovil and Hambantota (Garnet) (Wijesinghe, 2012).

These heavy minerals have high demand in the world market as these are having vital and vast applications. Further, Sri Lankan mineral sands are high-grade deposits with abundance of Ilmenite, Rutile and Zircon (Ismail, Amarasekera, & Kumarasinghe, 1983; Premaratne & Rowson, 2004). Industrial countries like Russia, Japan, United States and United Kingdom Sri Lankan mineral sand having greater demand (“Lanka Mineral Sands New Brochure,” 2017) also, according to the central bank report the worth of mineral sand had augmented considerably and steadily during the last couple of years (CBSL, 2017). As an example, the price of a metric ton of Ilmenite has increased by 700 % during the last two years. Such these deposits

Figure 2.1: The sediment components of beach

in USA, Australia and China heavy mineral content in sea sand is around 3 % to 5 % while it is more than 80 % in Sri Lanka sea sand (“Features | Sundayobserver.lk - Sri Lanka,” n.d.). But, the tailings of Pulmoddai Lanka Mineral Sands Ltd, Ilmenite Rutile Zircon (IRZ) plant contain more than 3% of mineral sand which are higher than the cutoff grade of mineral sands in the above countries. All these minerals are precious and have important uses with useful physical properties, thus comprise a strategic place in the international mineral market.

According to Sri Lanka Minerals yearbook of 2012, about 325,330 tonnes of Ilmenite, Rutile and Zircon have been sold overseas from 2008 to 2011 which worth Rs. 5,100 million.. The key purchasers were India, Japan, China, Italy, UAE and Singapore.

2.3 Mineralogy of the Heavy Mineral Sands

Mineralogy is the scientific study of minerals, including their distribution, identification, composition, physical (including optical) and chemical properties, and their occurrences. Mineralogy includes the processes of mineral source and configuration, categorization of minerals, their environmental allotment, as well as their exploitation. Optical mineralogy is the learning of minerals and rocks by determining their optical parameters. For this purpose, samples are prepared as thin sections or grain mounts in the laboratory with a petrographic microscope. Optical mineralogy is used to recognize the mineralogical composition of geological materials to reveal their origin and development.

Table 2.1 Properties of Heavy Minerals in Sri Lanka Beaches

	Ilmenite	**Rutile**	**Zircon**	**Monazite**	**Garnet**
Category	Oxide minerals	Oxide minerals	Nesosilicates	Phosphate minerals	Nesosilicates
Formula	$FeTiO_3$	TiO_2	$ZrSiO_4$	$(Ce,La)PO_4$	$X_3Y_2(SiO_4)_3$
Color	Iron-black gray with a brownish tint in reflected light	Reddish brown, Red, Pale yellow, Pale blue, Violet, rarely Grass-green	Reddish brown, Yellow, Green, Blue, Gray	Reddish brown, Brown, Pale Yellow, Pink, Green, Gray	Vitreous to resinous
Luster	Metallic to submetallic	Adamantine to submetallic	Vitreous to adamantine	Resinous, Vitreous to adamantine	Vitreous to resinous
Streak	Black	White	White	White	White
SG	4.70 – 4.79	4.23 – 4.3	4.6 – 4.7	4.6 – 5.7	3.1 – 4.3
Magnetism and Conductivity	Magnetic and Conducting	Non-Magnetic and Conducting	Non-Magnetic and Non-Conducting	Weakly Magnetic and Non-Conducting	Weakly Magnetic and Non-Conducting

2.4 Textural Properties of the Sediments

There are several textural properties relevant to the rocks and sediments. Descriptions of textures provide information on the conditions of deposition of the sediment, the Paleoenvironment, and the provenance of the sedimentary material. Such that textures of mean grain size, sorting, kurtosis, skewness, angularity and sphericity are few of those parameters (Blott & Pye, 2001). The parameter used to describe a grain size distribution fall into four principal groups:

(a) Mean grain size - the average size of the grains

(b) Sorting - the spread of the sizes about the average

(c) Skewness - the symmetry to one side of the average and

(d) Kurtosis - the degree of concentration of the grains compared to the average

Table 2.2 Classification of Mean Grain Size

Descriptive terminology	Grain size	
	Phi	mm/µm
Very coarse sand	-1 – 0	2.00 – 1.00 mm
Coarse sand	0 – 1	1.00 mm – 500 µm
Medium sand	1 – 2	500 – 250 µm
Fine sand	2 – 3	250 – 125 µm
Very fine sand	3 – 4	125 – 63 µm

Table 2.3 Classification of Sorting

Sorting Class	Standard deviation (ϕ)	In micro meters (µm)
Very well sorted	< 0.35	0 – 1.27
Well sorted	0.35 – 0.50	1.27 – 1.41
Moderately well sorted	0.50 – 0.71	1.41 – 1.62
Moderately sorted	0.71 – 1.00	1.62 – 2.00
Poorly sorted	1.00 – 2.00	2.00 – 4.00
Very poorly sorted	2.00 –4.00	4.00 – 16.00
Extremely poorly sorted	> 4.00	16.00 – 64.00

Roundness and sphericity have proven to be useful properties of particles (than sand size) when investigating the transport and deposition of sedimentary material. Roundness of residue particles can be a sign of the remoteness and time involved in the transportation of the sediment from the source area to where it is deposited.

Roundness was defined by Wadell (1932) as the ratio of the average radius of curvature of the corners of the radius of the largest inscribed circle (Wadell, 1932). Although roundness can be numerically defined, geologists usually use a simple visual chart to categorize the roundness:

1. Very angular
2. Angular
3. Sub-angular
4. Sub-rounded
5. Rounded
6. Well-rounded

Sphericity measures the particle spherical shape. It was defined by Wadell (1932) as the ratio of the diameter of a sphere and the diameter of the circumscribed sphere.

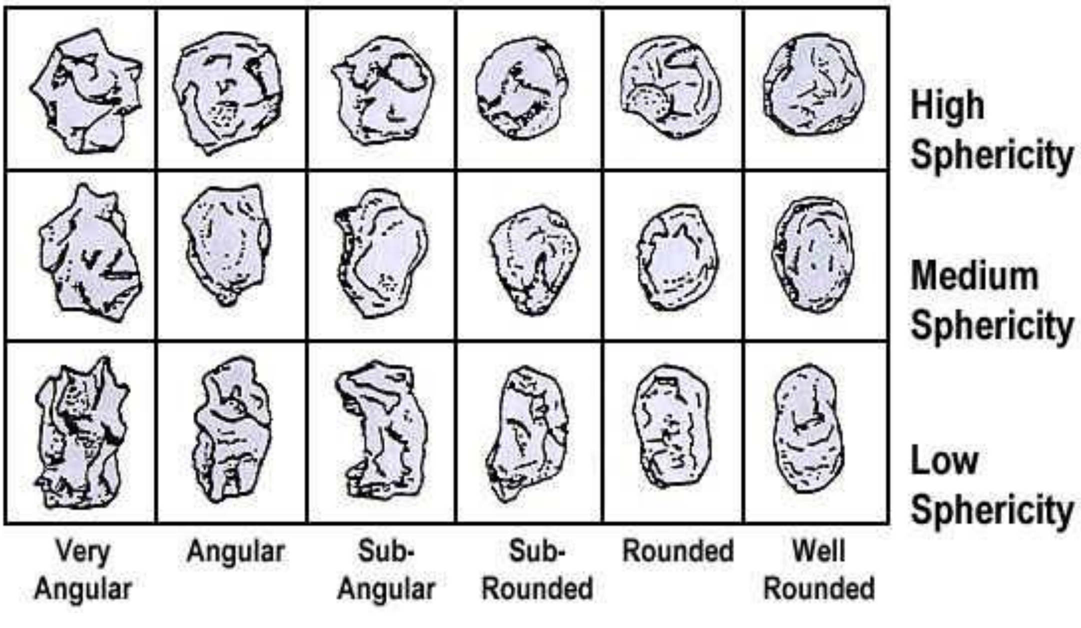


Figure 2.2 Roundness and sphericity

2.4.1 Relationship between mean grain size and sorting

In general, many studies of different sediments revealed that sorting is a sinusoidal function of the mean grain size (Douglas L, 1949; Griffiths, 1951). Hence, well sorted samples will be only medium and fine grain samples while, clays and silts also gravel sediments will be the poorly or very poorly sorted. Frequent normalisation is sorting increases with the sediment transport; this is because of the change in mean grain size of the sediment. Thus, decreasing mean grain size has an improvement in sorting (Folk & Ward, 1957).

2.5 Beach Profile

The measurement of the elevation variation of the beach surface taken along straight lines of perpendicular transacts from the fixed point at dune to the mean sea level and further at the beach can be called as beach profiling. Profiles taken at different periods can be compared to understand and quantify seasonal changes in beach width, slope and shape. The main features of the coast profile are given in figure 2.3 (Alireza, 2014).

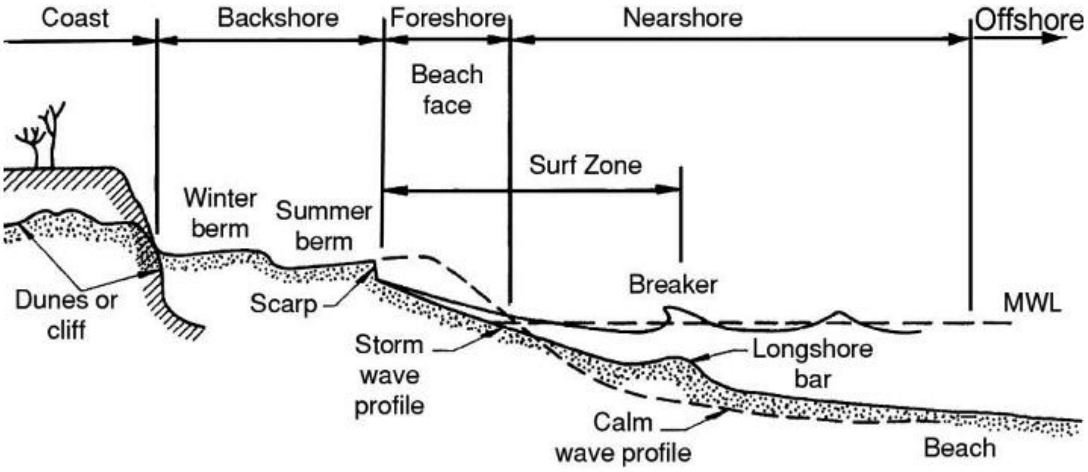


Figure 2.3: Typical beach profile and terminology

2.5.1 Beach face slope

Beach face slope is the measurement of elevation difference from the mean sea level to berm of the location. Beach slope can vary with different parameters such as tidal, seasonal changes, due to storms, or modification to the coast.Slopes also vary alongshore as the beach becomes narrower or wider. Because wave type and swash heights are sensitive to beach slope (Doran, Long, Overbeck, Jewell, & Survey, 2015).

2.5.2 Beach width

Distance between dune crest and shoreline is recongnized as the beach width. Understanding the beach width changes over varying seasons is vital for coastal environment.

2.5.3 Relationship of mean grain size, slope and wave energy

The relationship between mean grain size and the beach slope is well established for the sand beaches. Increasing slope angles are associated with increasing particle size (McLean & Kirk, 1969).

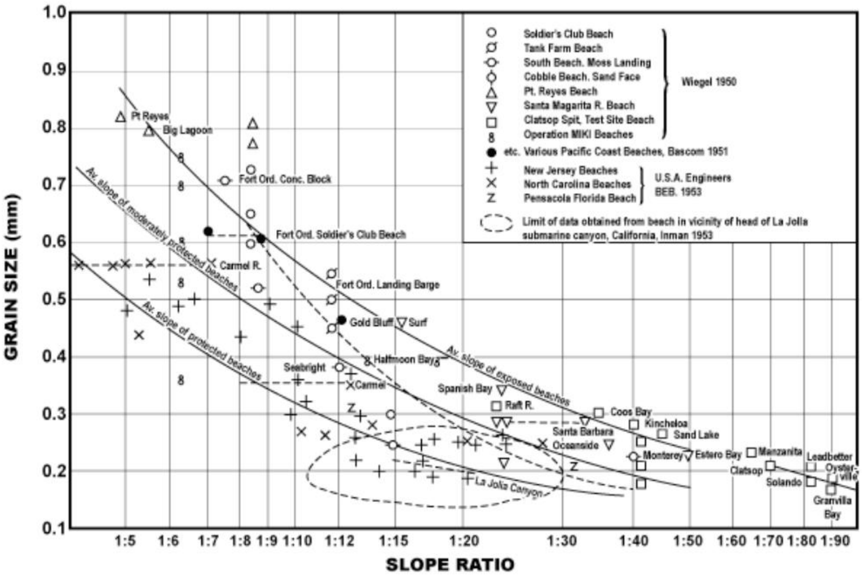


Figure 2.4: Relationship of mean grain size and beach slopes,
Source: Weigel, R.L., 1965. Oceanographical Engineering.

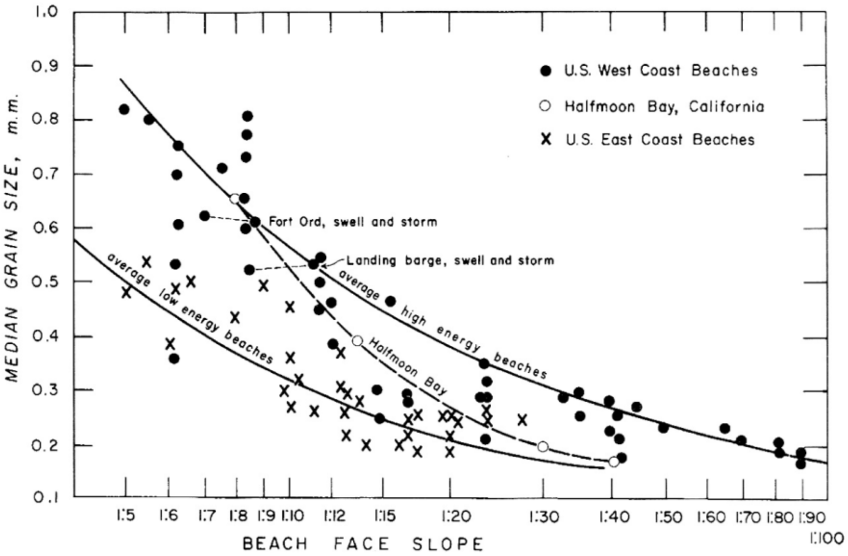


Figure 2.5: Relationship of mean grain size, wave energy and beach slopes
Source: Weigel, R.L., 1965. Oceanographical Engineering.

Swash and backwash of the waves are controlling the slope of the beach. Shoreward up rush strength will be stronger than seaward backwash at the porous beach and the sediments deposited at the beach until a slope support the backwash. Then sediment transport become in dynamic equilibrium and the beach face slope is steady. Thus, coarser beaches backwash is weaker and has a steeper slope than finer sediment beaches.

Figure 2.5 illustrates the phenomenon that, beach angle decreases with decreasing grain size, or increases with increasing grain size. Further it can be seen the high energy beaches to have lower slopes for a given grain size than low energy beaches (Reis & Gama, 2010).

2.6 Seasonal Impacts of Placer Deposits

The placer deposits heavily disturb with the physical forces. The coastal environment primarily depends on sediment transportation. Depositional patterns mainly determined by longshore currents and wave energy.

2.6.1 Monsoons in Sri Lanka

In Sri Lanka there are two main monsoon periods exist. Those are;

1. Northeast monsoon
2. Southwest monsoon

The south-western and north-eastern parts of Sri Lanka have highly influenced areas due to these monsoons (Niranjan, Jayatilaka, Singh, & Bantilan, 2013). Thus, it is essential to study and understand the impacts of seasonal variations. But erosion depends on the monsoon system of Sri Lanka. Existing periods of those monsoons are mentioned in the table.

Table 2.4 Monsoons in Sri Lanka

Type of Monsoons	Period of the year
First Inter monsoon	March to mid-May
South West monsoon	Mid May to September
Second Inter monsoon	October to November
North East monsoon	December to February

The ocean is very rough and stormy in monsoon periods and therefore, the erosion of that coastal area becomes very high in those seasons. The beach erosions can be seen from May to November period on Western and south region of the Sri Lanka. In that period, the width of the beaches is going to be decreased. October to January those types of beaches can be seen in the North and East area in Sri Lanka.

2.6.2 Coastal erosion

Understanding the phenomenon of coastal erosion is important for many reasons. In general, erosion may lead to groundwater contaminant, sea level rise and a threat to the structures nearby beaches. Particularly, for the mining of sand from the beach, this is critical to study the erosion and accretion so that to design and develop the mine plans accordingly without the economic and environmental adverse effects. However, the rate of erosion depends on the followings:

- Breaking point of a wave
- Wave steepness
- Depth of sea and direction of fetch
- Supply of beach material
- Beach morphology
- Rock resistance
- Erosion control structures and methods

2.6.3 Coastal erosion in Sri Lanka

The Sri Lanka coastline is about 1,760 kilometres and this entire length is subject to accelerated erosion. In Sri Lanka it has found that the most severely affected part as the southwestern coast. The northern coast is the next most affected area and there are several other localities where coastal erosion is considerable. This problem is least experienced in the northwest and the southeast, and more especially, these two coastal segments, or rather, accretion environments showing growth of beach. It has been estimated that over 50 – 55 percent of the shoreline is subjected to coastal erosion. The largely decisively affected areas are between Kalpitiya in the Northwest and Matara in the South.

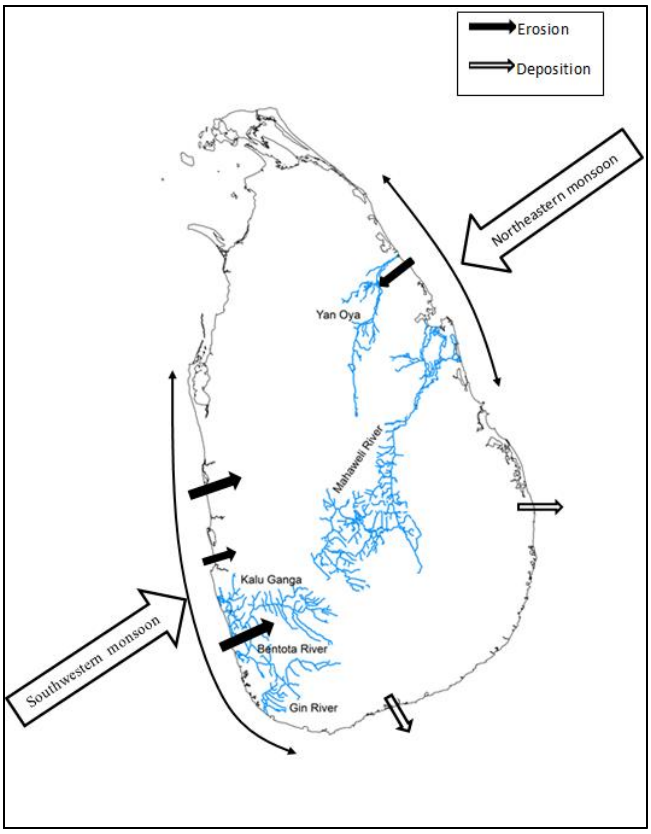


Figure 2.6: Coastal Erosion and Accretion of Sri Lanka

2.7 Coastal Sediment Dynamics

2.7.1 The process of heavy mineral deposition

Basically a placer material must be dense and resistant to weathering processes. The accumulation in placers can only be happened if the mineral particles are significantly denser than that of Quartz (Roy, 1999). When considering about the origin of placer deposits, it occurs as a result of panning process at surf zone and minerals such as Rutile, Ilmenite, Magnetite, Monazite, Garnet and Zircon are some of those minerals that are depositing as a placer. When panning process is happening, both heavy and lighter particles come together. The volumes of lighter particles have a relatively higher value than that of higher density particles. As a result of having higher volume, the upthrust acts on these particles are relatively higher than smaller higher density particles. Therefore, the tendency to flow the lighter particles is higher during the backwash than that of smaller particles. This panning process is shown in the below diagram.

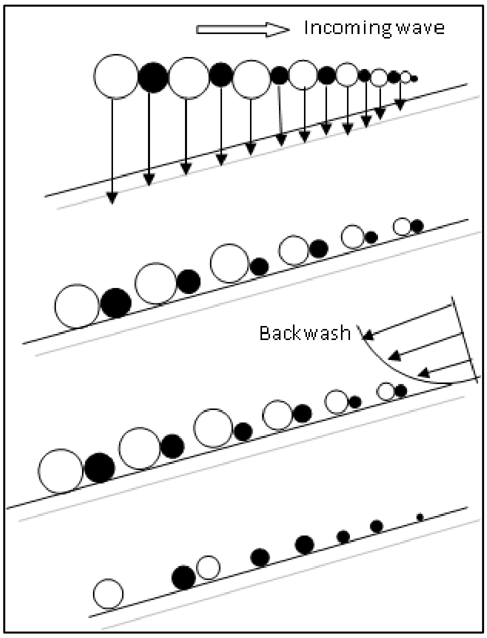


Figure 2.7: Panning Process

2.7.2 Sand budget

The concept of the sand budget is discussed about the sand input to the beach and sand output from the beach. The sand receiving methods are cliff erosion, river transportation, longshore current, cross-shore currents, wind transportation, etc. The sand output methods are cross-shore currents, longshore drift, etc. It will help to identify the erosion or deposition going on the beach area.

INPUTS	+	OUTPUTS	=	BALANCE
Longshore transport into beach		Longshore transport out of beach		Accretion
River supply		Offshore transport		Erosion
Cliff erosion		Wind transportation into dunes		Steady state
Onshore transport				

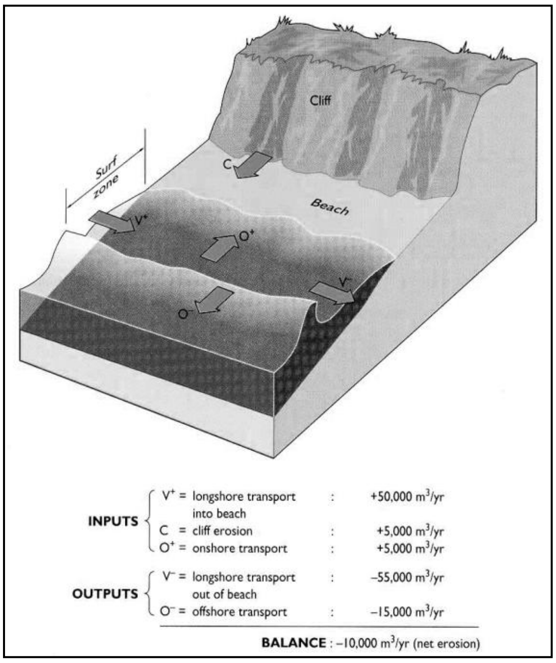


Figure 2.8: Sand budget of the coast

2.7.3 Sediment transportation methods

The sand is the dominant sediment on the beach and they are moving place to place because of several reasons. Waves and Currents are the major sediment transporting method in the sediment dynamics.

Waves

Waves are the forward progress of the ocean's water due to the frictional drag of wind on the water's surface. Waves have crests and troughs. The wavelength is determined by the horizontal space between two crests or two troughs. Waves can be classified according to their physical properties.

Deep-water waves

The depth of the ocean deeper than L/2 that is called deep water waves, so they don’t feel the bottom at all because of that, they can’t move the sediment at the bottom of the ocean.

Shallow-water waves

The depth (d) of the ocean is less than 1/20 the wavelength (L) that waves are called shallow water waves. They are also named as long waves.
Tsunamis and tides are shallow-water waves because they have a very long wavelength (L).

Transitional waves

If the wavelength is greater than two times but less than 20 times of depths (d) that types of waves are called transitional waves. They have properties somewhere between deep and shallow waves.

2.7.4 Currents

Currents in the ocean are several types. Current is a continuous movement of sea water those are longshore currents, rip currents and cross-shore currents.

Longshore currents

A long-shore current is an ocean current that moves parallel to shore. It is caused by waves reached to the beach with an angle and water is moving on the beach with that angle. After breaking the waves the energy of the waves is transferred to the water. Then the water molecules are proceeding with the surrounding sediments. The water and sediments are moving along the beach with the reached angle. But in the backwash is done perpendicular to the beach under the gravitational force. That water molecules are going in the zig zag way.

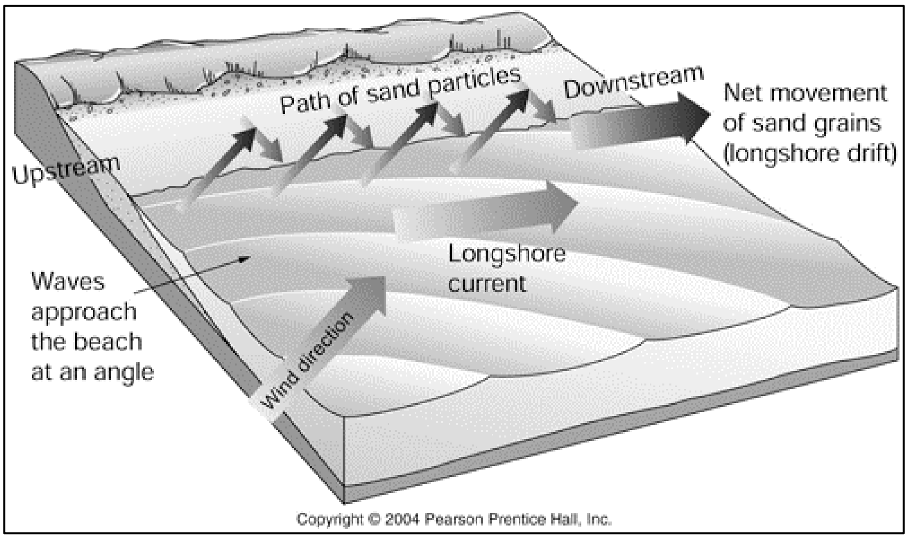


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Figure 2.9: Movement of sediment in a longshore current

Longshore drift

The process by which longshore currents move sediments along the shoreline along a surf zone called as longshore drift. It can be seen some island and deltas are created because of this longshore drift process in Sri Lanka. Longshore drift is generating

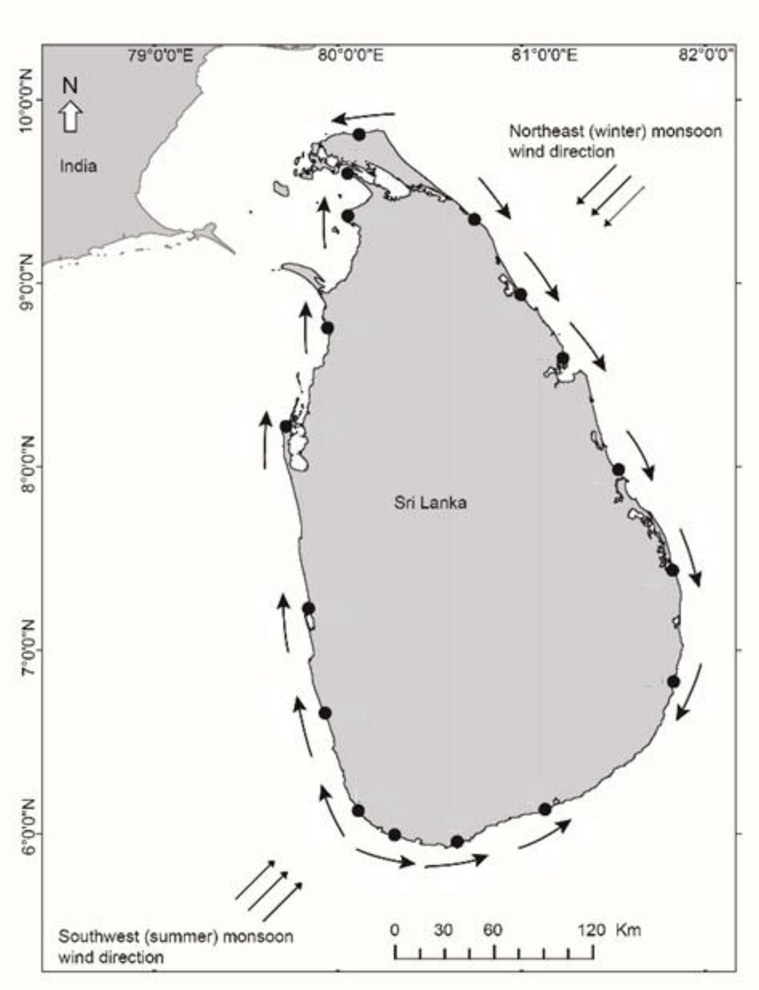


Figure 2.10: Long Shore Drift in Sri Lanka

south to north direction in Sri Lanka under the southwestern monsoon period. North to South direction longshore drift can be seen in the northeast monsoon period.

Cross-shore currents

The wave energy is different from time to time in the year. When the waves have a long period and low height waves, the power of the wave is less and calm and fair weather can be seen. If the wavelength is short and height is high, the energy is very high during those periods and stormy type seas can be seen. Because of that, releasing the strength of the broken wave water is different. The erosion and sedimentation of the beach are varying according to the period of the year. The calm period sediments are coming from the ocean and settling on the shores. But in the storm period, wave energy is higher and the beaches are eroded into the ocean.

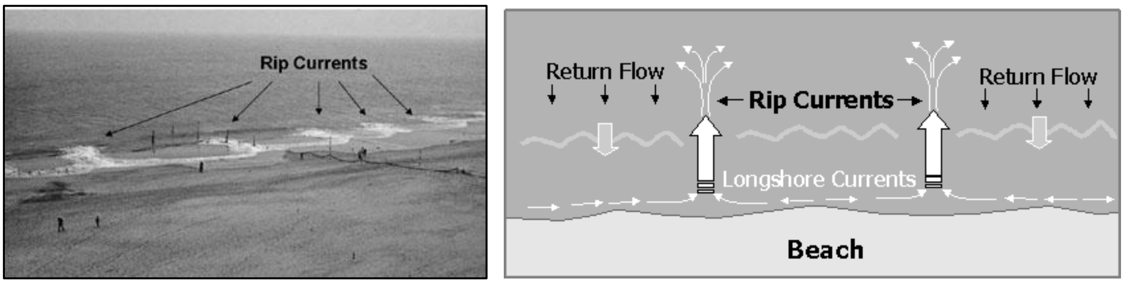


Figure 2.11: Rip Currents

Rip Currents

Rip currents can be occurred along with any coastline. When waves break in and having different of their power, creates water circulation. Rip currents are narrow, fast-moving belts of water traveling offshore. The sediment transportation is less in rip current condition comparing other currents.

2.8 Finding the possible source of alluvial deposits

2.8.1 Source rocks of heavy minerals

Heavy minerals form as accessory minerals in many igneous and metamorphic rocks,these minerals occur as detrital accumulations in beach placer deposits (Eric R, 1991). Weathering of the source rocks and particles will be transported through the streams and finally in to the ocean. However, eventualy they become economical to utilize and attain commercial grades. Understanding the characteristic of these minerals also help to reveal the source rock and sediment dynamics. This process influence the formation of sedimentary rocks and heavy mineral deposits (Ravindra Kumar & Sreejith, 2010).

Granite is the basic source of Monazite, Rutile, Zircon, and Ilmenite in some cases. The source of Ilmenite and Garnet is ultramafic and mafic rocks. Garnet can be found generally at metamorphic rocks such as Garnet silimanite gneiss, Garnet silimanite graphite gneiss etc. Rutile, Zircon and Monazite are derived mainly from metamorphic rocks and ilmenite may come from igneous rocks.

In this study, another key work is to find the source of the Verukal deposit. Comparison of average mineralogical data of source with deposit is important to understand the provenance of the deposit, because they have similar mineralogical assemblages (Okay & Ergün, 2005). Accordingly, the analysis was done to find the similarities and patterns of mineralogical and textural variations of the tested samples with the probable source locations.

Investigating the source and depositional areas of sediments is important to understanding the development and behaviour of the sedimentary system (Alcántara-Carrió, Fernández-Bastero, & Alonso, 2010). Identification of the source of the placer deposits is very important, because these deposits are dynamics due to wave actions. Offshore erosion, seasonal changes, wave energy are the main factors which contribute to the dynamic nature of the placer deposits. Source of origin is significant for mining as well. Source of origin gives knowledge about the maximum concentration of heavy minerals on the beaches. This information helps to calculate the assay value of the deposit and it provides information about the economic feasibility of the deposit as well as lifetime which deposit can be extracted.

Textural property of mean grain size gives possibilities for identification such as; the direction of the sediment transportation can be seen in mean grain size and skewness. Other one is improvement of sorting comparing the source and deposition area o (Gao & Collins, 1992). Also, the mineralogy is used for the same purpose, mostly similar between the sediments and the source.

2.8.2 River water discharge and sediment transportation

All streams do not carry sediments as they not erode the bedrocks. Usually streams are flow over the rock of different hardness and resistance to mechanical weathering. However, long reaches of the channel may not bring sediment at all (Gao & Collins, 1994). The removal and transportation of sediment due to erosion and deposition is the process of the transportation and settlement of sediments. Competence, capacity and sediment supply are determining the amount of sediments transport via streams. (van Rijn, 1993).

When considering the geological existence of Pulmuddai and Verugal area, is located above and below the Trincomalee bay. It is the place where Mahaweli river meets the Indian Ocean. Verugal Aru is the south most river fall of Mahaweli river as well as delta type river fall of Mahaweli river causes considerable river sediment input to the Trincomalee area. The river inputs of Mahaweli river may come to Pulmuddai and Verugal area due to the longshore currents. It is possible to have a clear idea by identifying the exact current direction at the area and the variation of these currents with the seasons of the year. There is a possibility to transport sediments of Indian rivers such as Ganga river to these deposits. Because these rivers come across a vast area of land and it may consist of higher percentages of minerals. Sea currents can be caused to transport these heavy minerals towards Sri Lanka. Below diagram shows the river input around Pulmuddai and Verugal area.

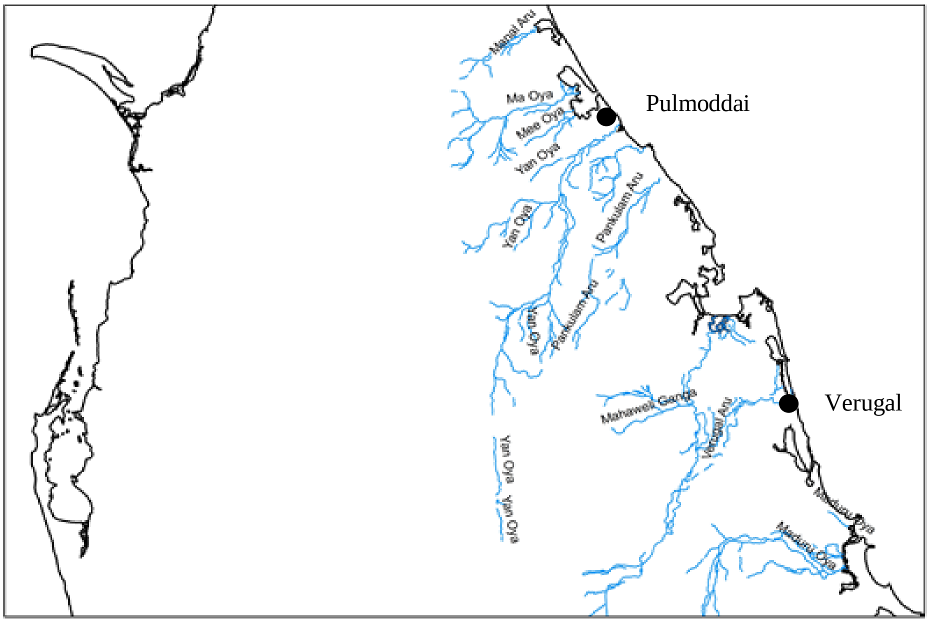


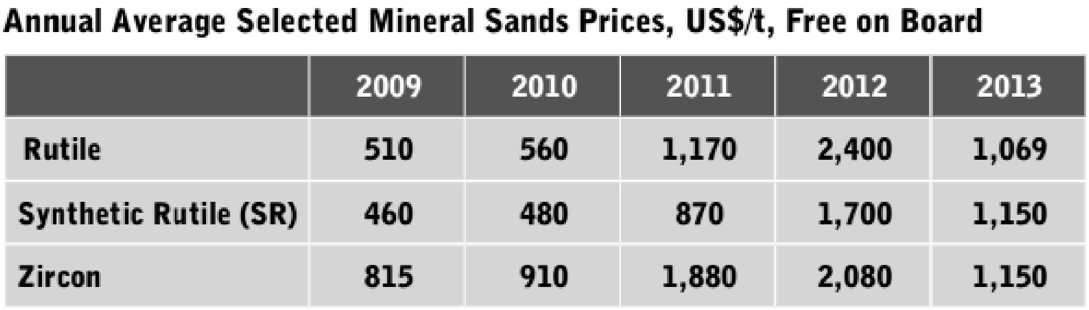
Figure 2.12: River input around Pulmuddai and Verugal area.

2.9 Mineral sand market and economical aspects

Most of the big companies are dealing with the extraction of mineral sands due to the higher amount of profit margin that can be achieved through this industry. The countries like Australia and the United States of America are the two of the main suppliers in the world mineral sand market. Demand for Titanium minerals and Zircon are stable, Increasing demand is observed over the recent past in the developing countries.

Table 2.5 Market Prices

Product	Price in US$ (Metric ton)
Ilmenite	150-180
Rutile	480-500
Zircon	800-900



Annual Average Selected Mineral Sands Prices, US$/t, Free on Board

	2009	2010	2011	2012	2013
Rutile	510	560	1,170	2,400	1,069
Synthetic Rutile (SR)	460	480	870	1,700	1,150
Zircon	815	910	1,880	2,080	1,150

Pulmoddai plant in Sri Lanka export mineral sands of Ilmenite, Rutile, and Zircon at it's with poor infrastructure. The production of Ilmenite to 6000 tons, 1,800 tons of Rutile and 600 tons of Zircon from the Pulmoddai plant was recorded. The price of Ilmenite in the international market dropped down to US$ 92 per ton from $ 320. Rutile take a cost of $ 700 a ton and Zircon $ 850. The company has taken a strategic decision to limit Ilmenite production and to increase the production of Rutile and Zircon to meet global price fluctuations. Sri Lanka is earning millions of dollars in foreign exchange from the export of these three minerals without value addition and the cost of the refining of mineral sands is low. The company has recorded a profit of Rs.253 million after tax in 2013. The revenue was Rs. 947 million. The profit of the

Pulmoddai mineral sands company which was Rs. 239 million in 2009 has recorded a new high of Rs. 7 billion in 2011.

2.10 Mining method to extract heavy mineral sand

Heavy mineral sands are mostly deposited as placer deposits, usually in beach environments by concentration due to the specific gravity of the mineral grains. Follow by the discovery of deposit, it is estimated and the most appropriate mining method is selected based on technical, economical and environmentally accountable consideration. In selecting the most appropriate mining method have to compare the economic feasibility of extraction of the deposit.

2.10.1 Selection of mining method

Selection of the proper mining method is the most important because of wrong mining method cause additional cost and also additional time consumption. Before select the proper mining method, it is essential to consider many factors. Those factors are related with not only geological and economical but also sociologically related. According to those factors, the better mining method should be decided. The elements can be divided as follows.

- Type of minerals
- Replenishment rate of material per year. (This rate is calculated according to the observations and data of several years.)
- Required annual quantity. (This quantity is decided according to the plant capacity, extraction rate and demand of the domestic market and world market)
- Mining locations. (If enough quantity of minerals is existed, then it is profitable to carry out the mining activities from those places).
- The location of mining equipment installment (land or sea).
- Proper mining equipment or manpower (need to select in a way to match with the required production rates).

- Excavated material transportation system (dump truck or wagon system).
- Weather condition of the mining area. (Mining sequence and mining rates need to be decided by considering these factors).
- Environmental affect (From the machineries and the behavior of people)
- Mining system.

2.10.2 Types of mining methods

Wet or dry mining methods are in use of mineral sand extraction. Wet methods are advisable for huge quantity, low clay content ore. Dredging can be done in where the landscape and the water access is suitable for the process only. In a wet mining operation, a floating dredge in the ocean breaks the material and pumps the slurry to the land or floating ship. Wet mining method is done as mechanically or hydraulically.

Mechanical dredgers are:

- Bucket ladder dredge
- Grab dredger
- Dipper
- Backhoe dredge

Hydraulic dredgers are:

- Plain suction dredge
- Cutter dredge
- Trailing suction hopper dredge.

In dry mining, if scrapers are used, the ore is mined from the top of the face to the toe of the face. Dry methods employing earth moving are used to excavate and transport the sand for the processing plant. There are some advantages and also disadvantages of dry mining methods when compared with the wet mining method. These can be listed as below.

Advantages:

- Low cost to extract.
- No additional cost to transportation through pipelines or from barges.
- No additional cost to dry heavy mineral sand.
- Low cost for processing because of the minerals at dry conditions.
- This method is better to low quantity of deposits.
- The Initial investment is low.
- Low risk.

Disadvantages:

- The Production rate is low.
- Annual production quantity is low.
- Can be applied only for limited mineral resources.
- Can be applied only for the limited place/area.
- Political and social factors are directly affected.
- Environmental regulations and limitation are high.
- Environmental conditions are directly affected.
- Geological conditions are directly affected.

Therefore, it is essential to compare the advantages and disadvantages of each method and select the most appropriate method for an extraction operation.

2.10.3 Improvement of mining method

To improve production of heavy mineral sand, there should be a proper plan for the whole process. That proper plan should be consisted of the following details.

- Should gain a detailed idea about the replenishment process by doing a qualitative and quantitative analysis of replenishment and erosion. (Should be recognize the ways of the replenishment process happened with monsoon, rivers, storms, etc.)

- Use proper techniques to increase replenishment and decrease erosion. (Groynes are the most suitable structure to decrease erosion and increase sedimentation of heavy mineral sand)

- Decide a better mining method to extract the optimum quantity of heavy mineral sand with the lowest cost and also it should be an environmentally friendly one.

- Decide on a proper transportation system from extract place in the processing plant. (This transportation system should be applicable well for all places and also it should cost effective)

- Exploration should be wide till the nearshore zone or offshore zone for recognizing if there is another considerable deposition.

Plan a method to reduce the waste during the extracting process (maximum extract quantity of heavy mineral with the lowest contamination)

2.11 Environmental Effect of Sand Mining

Beach sand is an important resource for a country. However, this practice of extracting beach sand is becoming an environmental issue as the beach sand mining and its associated activities can be responsible for the considerable environmental damage.

Beach mining has a different kind of environmental effects when compared with other mining areas such as mining in the land, mining in the ocean and sand mining in the river areas. Beach mining has a direct relation to the ocean. Detail description of the environmental impacts that caused due to beach sand mining is mentioned below.

2.11.1 Beach erosion

Beach erosion is the major environmental effect of beach mining (Borges, Andrade, & Freitas, 2002). Study of coastal engineering issues it was found that the causes of erosion vary greatly from one location to the other and the causes identified include;

- beach sand source may loss
- Increased exposure to the incident wave climate
- Changes in the nearshore current pattern
- Due to natural causes or man-made changes, such as the construction of coastal infrastructure and also installed sand processing plants
- Changes in the natural sediment balance

Beach erosion can create lots of other environmental problems such as;

- Destroys fisheries, causing problems for people who rely on fishing for their livelihoods.
- Impacts the local wildlife.
- Causes turbidity in the sea water which is harmful to organisms such as corals, phytoplankton that need sunlight.
- Removal of physical coastal barriers leads to flooding of beachside communities.
- The removal of heavy mineral sands from the beach and their replacement with lighter beach sand would mean that the potential for longshore transport on the existing beach alignment would increase by a factor of 1.2 – 1.5. Need to compensate this increased capacity to move the lighter sediments.

Unsustainable beach sand mining can cause disturbance of coastal marine ecosystems and change the ability of natural marine processes to replenish the sand. Therefore, it is essential to concern about these factors while carrying out the activities relating to the extraction of beach sand to achieve optimum production targets with the smallest possible environmental damage.

2.11.2 Effects on the ecosystem

Dredging is a general mining method in beach mining. Dredging can be causing the changes in nearby coastal areas as mentioned below;

- Physically disturbs or removes the bottom substrate
- Deposits sediments on the substrate
- Suspends sediments in the water column and reduces light penetration into the sea water
- Changes circulation of considerable area
- Reduces dissolved oxygen and increases nutrient levels in the water column
- Direct elimination of benthic habitat in the dredged area

It is essential to consider all these factors while initiating a new production process.

2.11.3 Health hazards

Health hazards of the mining activity are of least concern for most of the authorities. This can be mentioned as most critical side of the beach sand mining processes. In most of the cases, beach sand mining deals with the extraction of minerals that are having radioactive reactions. If the proposed mining area having high natural background levels of radiation this issue was concerning both occupational health and safety aspects of the proposal and public health implications. This can lead to severe health problems for the entire community who is living around those areas. The following facts can also be mentioned as the potential risks of beach sand mining operations.

- Dust generated by mining will be cancerous
- Noise pollution caused by the mining machinery and transport of heavy mineral concentrates.

- Wastewater of the processing plant can be moved to pure water bodies (water well, water streams, etc.). It may dangerous to the human body and also living organisms

2.11.4 Hydrological effects

Mining and dredging activities poorly planned stockpiling, uncontrolled dumping of overburden and chemical or fuel spill will cause to reduce the water quality of shallow sea water as well as pure water in the coastal area. It directly affects aquatic life and beachside peoples. Impacts on groundwater extraction for mining and processing would affect other bores in the area. The immediate result of the implementation of beach mining will be the salinization of groundwater in the considerable area. The people have to face lots of troubles as a result of using salinized water.

- The construction of the for dune, primary dune and secondary dune to the desired size, shape and location, using processed clean sand from mine residue
- Re-vegetation and with ecologically similar species, re-contouring of the land to its original shape, including dunes, and management of groundwater resources.
- Monitor dune stability and beach erosion and take remedial action if necessary.

CHAPTER 3: METHODOLOGY

The research was constructed with extensive literature review and development of acceptable standard methodologies for the exploration and data analysis. Further, it was structured as the findings of southwestern regional studies can be applied for the study of heavy mineral potential and their sources to the northeastern region. Therefore, heavy mineral concentrated locations were identified and selected based on the previous studies and suitability of the objectives. The study area at offshore and onshore in the South-Western and North-Eastern regions of Sri Lanka has been illustrated in figure 3.1. The impacts of seasonal variations on the depositional pattern and possible sources of the deposits were discovered to ensure effective mining.

3.1 Locations

The five main study areas were selected as follows;

1. Northeastern Onshore –Verugal
2. Northeastern Offshore – Kokkilai
3. Southwestern Onshore – Panandura to Telwatte
4. Southwestern Offshore – Beruwala and Galle
5. Along Mahaweli river

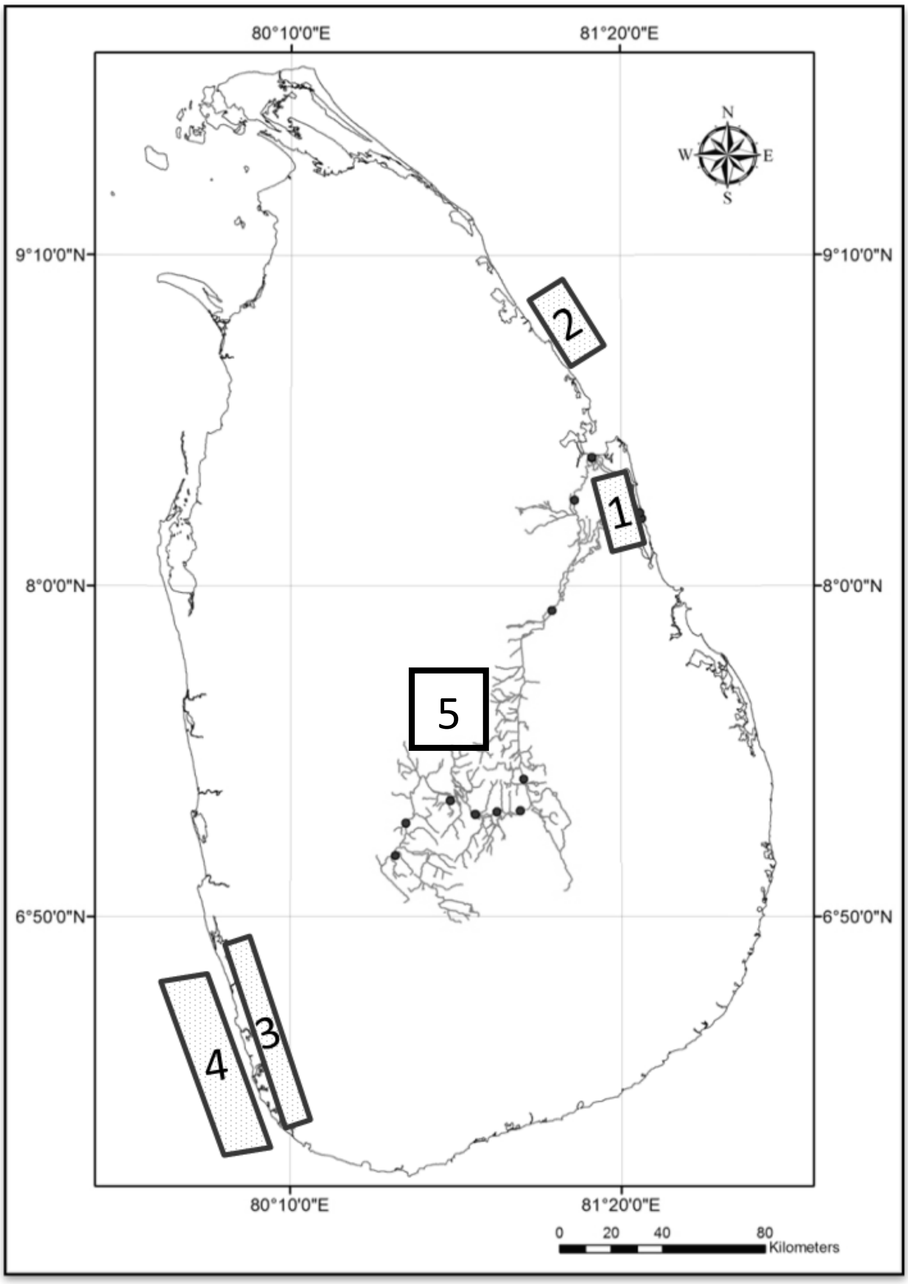


Figure 3.1: Major study locations of heavy mineral exploration

3.1.1 Northeastern Onshore –Verugal

The sampling points of the northeastern Verugal area are plotted in figure 3.2. This study area is covering the Verugal River and the nearby beach. Here, samples were collected on six lines parallel to the east-west direction from mean sea level (MSL) point at an offset distance of 500 m and 1000 m.

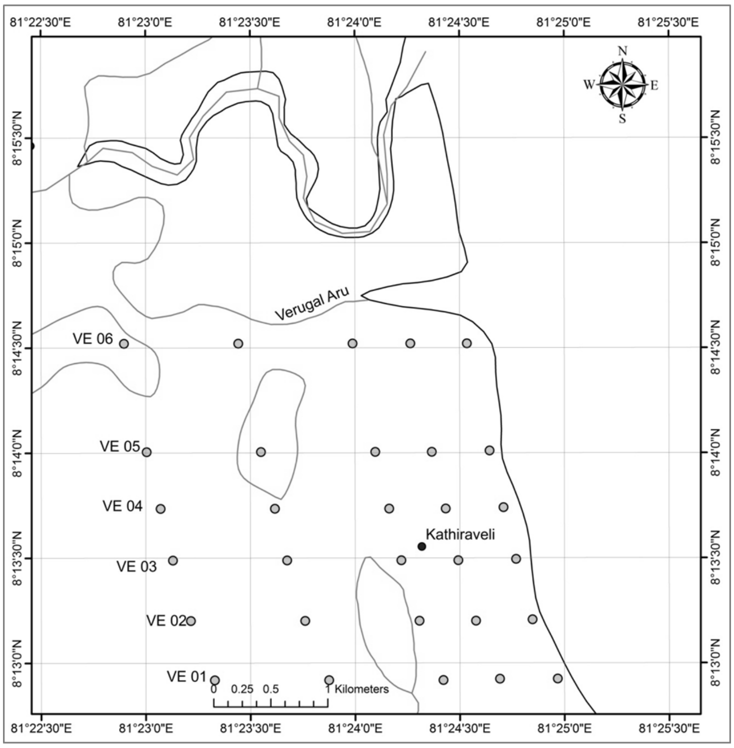


Figure 3.2: Sampling points at the northeastern onshore Verugal

The above image illustrates the points with their locations where the sampling was done; however, the map is exaggerated 100 times horizontally to keep the image to be visually enabled.

3.1.2 Northeastern Offshore – Kokkilai

The published research data of Kokkilai was used for offshore of northeastern region (Jinadasa & Wijayadeva, 2013). The multi-day boat is used for sample collection at the below indicated points (Fig 3.3). The area consists of around 95 km^2 with an average depth of 30 m.

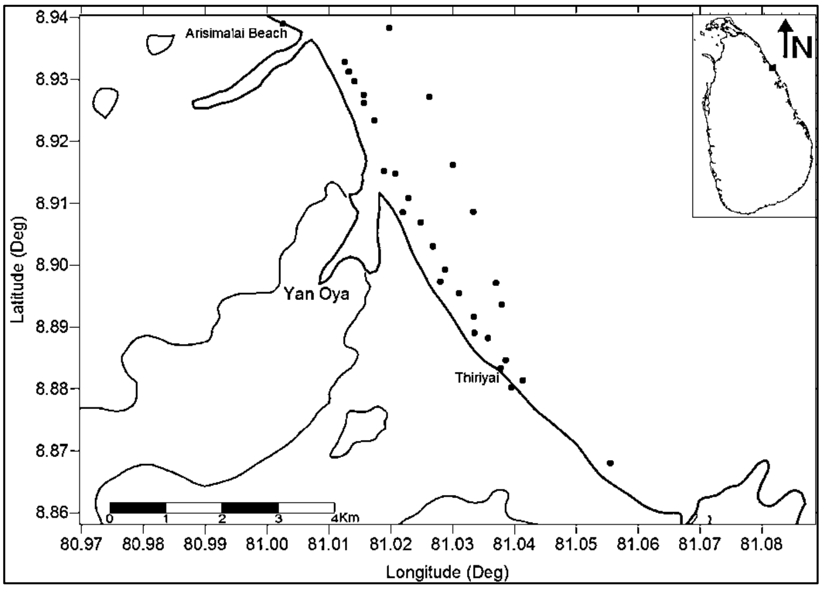


Figure 3.3: Sampling Points at the Northeastern offshore Kokkilai

3.1.3 Southwestern Onshore – Panandura to Telwatte

The southwest onshore sampling locations were determined by the considerations of historical evidence for provenance, access to the beach and distance to adjacent sampling points. The coordinate points of fourteen sampling locations from Panandura to Telwatta were listed and each point was sampled during all field visits.

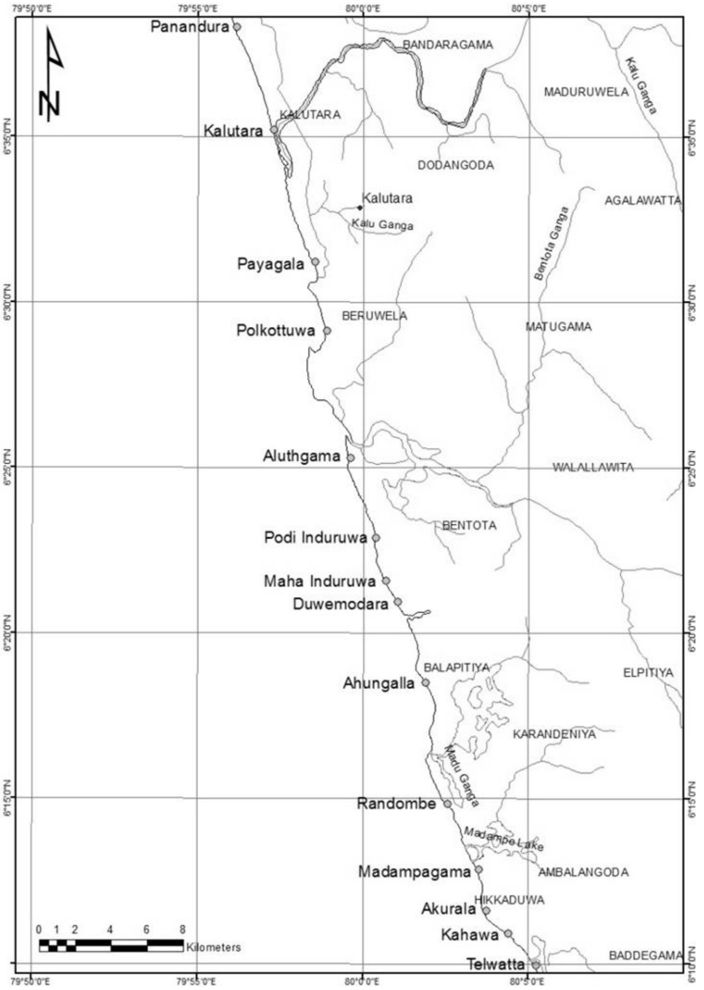


Figure 3.4: Sampling Points at the Southwestern Onshore

3.1.4 Southwestern Offshore – Galle

The study area of Galle offshore was selected with the consideration of regional development and accessibility to the ocean. Sampling locations were determined by way of covering the Gin river outflow at the grid points with 500 m X 500 m distance. (Fig 3.5)

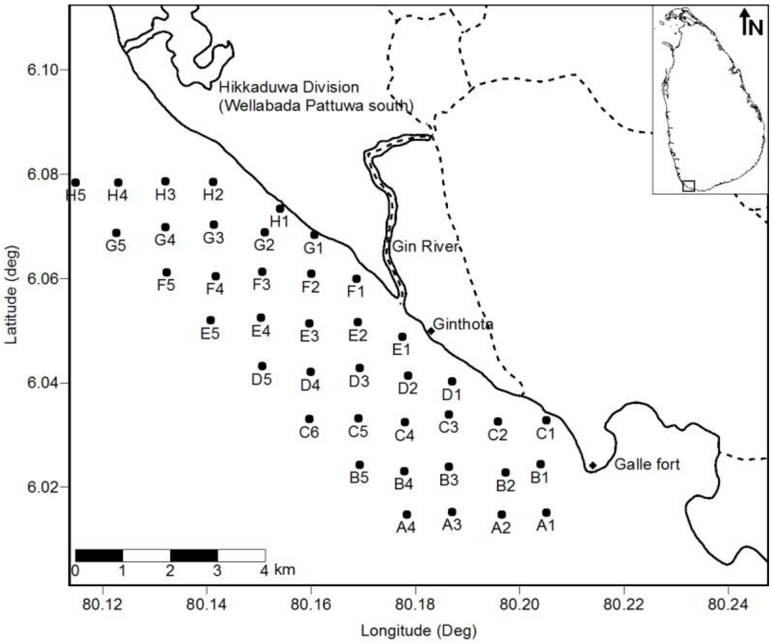


Figure 3.5: Sampling Points at the Southwestern Offshore –Galle

3.1.5 Southwestern offshore – Beruwala

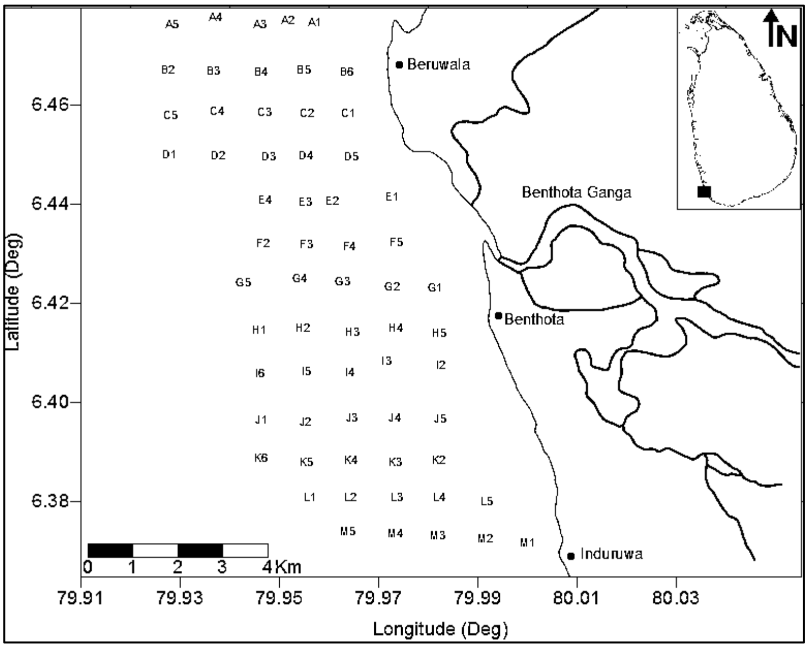


Figure 3.6: Sampling points at the Southwestern offshore –Beruwala

Another location at southwest offshore region was studied covering the Beruwala – Induruwa area, including the Bentota river mouth. Sampling points were selected at 1 km X 1 km grid plan. This area is one of the famous locations for heavy mineral sand deposit in Sri Lanka and the area is overlapping the explored region by United Nations Revolving Fund for Natural Resources Exploration (UNRFNRE).

3.1.6 Along Mahaweli River

The longest river in the country and which is also falling on the northeast coast was sampled at below mentioned places(Fig3.7). Sampling locations were initially selected using satellite images and topographic maps. Sediment samples were collected along the rivers taking into account sediment deposition at the meandering points of the rivers since most of the heavy minerals are deposited at the point bars of the rivers. Sediment samples along the Mahaweli river were collected by referring three topographical locations such as locations above the dams of Mahaweli river, locations at the dams of Mahaweli river and locations below the dams of Mahaweli river.

A total of 35 sediment samples were collected along Mahaweli River and Verugal River (last branch of Mahaweli river) and among them 12 samples along the Mahaweli river and11 samples along the Verugal river were taken.

Four to five kilograms of bulk samples and three replicate samples were taken from each location. Sampling was carried out in March 2014. Firstly initial observations of elevation and the physical environment were noted down and all samples were located using GPS within an accuracy of ±5 m.

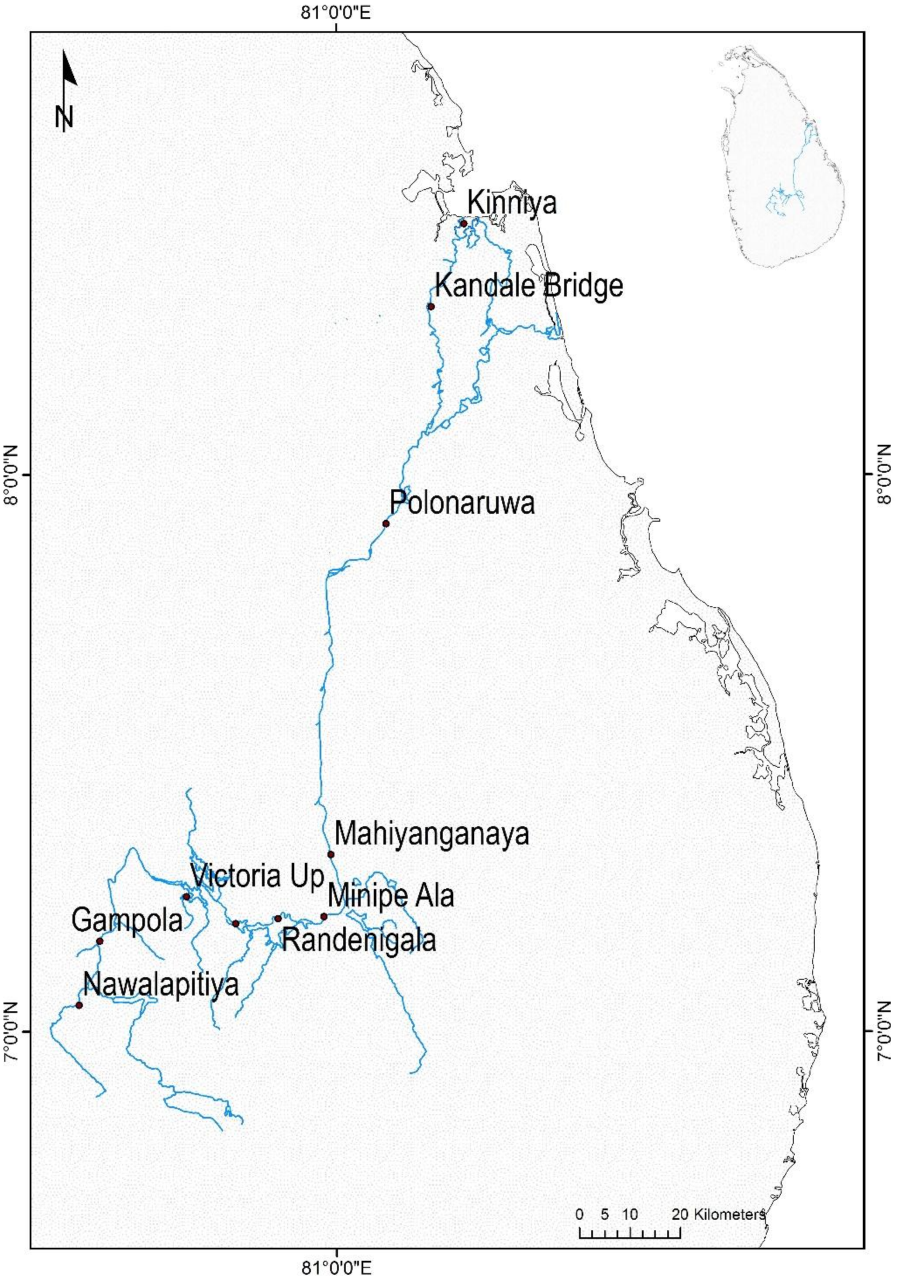


Figure 3.7: Sampling Points at the Mahaweli river

3.2 Sampling at Offshore

The sampling at offshore was done in both northeastern and southwestern regions. Initially, the area and the sampling points were specifically determined and the field map was prepared with the coordinates. In both regions the bottom surface sediments were collected by grab sampler. The collected samples were visually analysed and packed with sufficient detailed sample label (Annexure 1).

3.2.1 Southwestern offshore - Galle

The offshore field visit was carried out on the 31st March and 01st April 2012 during the inter-monsoon period. Research vessel of Baticlova-1 belongs to the Ocean University of Sri Lanka was used for the exploration visit.. Predetermined sampling locations were identified with the aid of the inbuilt Global Positioning System (GPS) navigation system (FURUNO GP-1850W C-Map NT). The Nansen type grab sampler was used to collect forty sediment samples from the surface of the seabed from a 500 m × 500 m grid. About 2 kg weight of the sample was collected at each point. The geographical coordinates of sampled locations are given in Annexure 2. Each sample was investigated on-board for physical and visual examination of geological, mineralogical and other properties. All samples were put in the sample bags and sealed with a label before transferring to the laboratory. The water depth of each sampling point was recorded using echo sounder.

3.2.2 Southwestern offshore - Beruwala

The offshore field visit was conducted and a total of 63 samples (Annexure 3) were collected from the seafloor of Beruwala to Kalutara in early November (1st and 2nd). The grid was prepared with 1 km x 1 km grid and at each point, surface samples were collected using a grab sampler.

3.2.3 Northeastern offshore – Kokkilai

The published data was used for Kokilai (Jinadasa & Wijayadeva, 2013). That was done with 30 bottom sediment samples collected in northeastern offshore part covering the area of 25 km^2 with an average depth of 30 m (Annexure 4). The manually operated small grab sampler was used for sampling. The 200–300 g sample was collected in one lowering.

3.3 Sampling at Onshore

Sampling at onshore differs from offshore sampling method. The northeastern and southwestern coasts were sampled at MSL, berm and dune. The points were accessed through predetermined coordinates using a GPS instrument.

3.3.1 Northeastern onshore –Verukal

Sampling at northeastern onshore locations was carried out on 25th August 2013 and 24th January 2014. During 1st field visit samples were collected at the depths of the surface, 0.3 m, 0.7 m and 1.0 m, at the distances of 5 m, 10 m, 20 m and 30 m from the MSL. Sediment samples were collected by digging the beach to the needed depths and at each depth about 1 – 2 kg sand was collected into the sample bags. The GPS points of collected sample points are given in Annexure 6.

3.3.2 Southwestern onshore – Panandura to Telwatte

In these, all locations sampling and beach survey were conducted several times and the data were analyzed from 2007. From July 2007 to Jan 2008; Oct 2009 to June 2010; Dec 2013 are the periods this study was conducted and the data were analysed. The samples were collected at MSL, Berm and Dune points of the beach at the surface level during all the field visits (Annexure 7).

3.4 Beach Profile Survey

The beach survey was done in the northeast and southwest coasts to understand the coastal sediment dynamics and the seasonal depositional patterns. Accordingly, beach width and beach profile were measured using surveying instruments (leveling instrument and leveling staff) (Annexure 8).

On each sampling point, a perpendicular transacts to the beach profile was surveyed. The beach profile was measured at each location from two meters seaward from the MSL to a fixed point in the backshore. The measurement was taken in every one-meter distances until prompt changes existed and if the change is not significant within a metered space the heights were obtained at reasonable distances.

3.5 Mineralogical Study

The mineralogical investigation was done to reveal the heavy mineral composition of the samples. 200 grams of each 02 kg sample was extracted by cone and quartering method to obtain a representative sample. That was subjected to panning process and concentrated the heavy mineral sand.

3.5.1 Panning

36-inch diameter plastic gold pan was used for panning each sample and concentrates were oven dried at 100 °C until getting the constant weight. The dried sand grains were weighed using electronic balance. This result reveals the weight percentage of the heavy mineral content of the samples.

3.5.2 Petrographic Study

Concentrated heavy minerals were examined through a reflected microscope and subjected to grain counting to determine the heavy mineral content of the samples (Henley, 1983). Around 200 grains were counted three times for each concentrated sample mounted on a gridded thin glass plate (Mange and Maurer, 1992, Dryden Jr, 1931). The grains were identified as a particular mineral with their colour, opacity, shape and lustre. The volumetric percent of each heavy mineral sand in the samples were calculated (Annexure 9).

3.5.3 The accuracy of the measurement of heavy mineral content using panning by dense media separation

Dense media separation was performed for two representative samples using bromoform to ensure the accuracy of panning process (Mange and Maurer, 1992). As the bromoform having the specific gravity (SG) of 2.8 g/cm^3 the lighter (floating) and heavier (sinking) minerals can be separated. Therefore, the heavy minerals (SG.2.8) were separated by this method. The samples VE 03/20m/1m and VE 01/05m/1m were tested. The test result and panning process data are given below (Table 3.1).

Table 3.1 Comparison of Panning and Bromoform Test Data

Sample	Heavy Mineral Percentage from Panning (%)	Heavy Mineral Percentage from Bromoform Test (%)	Accuracy (%)
VE 03/20m/1m	75.4	80.78	93.34
VE 01/20m/1m	87.6	90.00	97.33

Further to this, the same test for the surface sample of Verugal aru and Peradeniya samples were tested to the panned fraction. It was 99.7 % and 99.8 % accurate to the panning process. Both types of results ensure the panning results are within acceptable accuracy.

3.6 Textural Study

The sieve analysis was done to all samples to study the textural properties of mean grain size and sorting of the samples. The collected samples from offshore were brought to the laboratory and kept in the deep freezer at -4 ^{0}C. The onshore and offshore samples were air dried followed by oven dried at 120 ^{0}C for 24 hours to remove the moisture. After obtaining 500 g through cone and quartering, samples were sieved using BS EN 933-1:2012 with 2.00mm, 1.40mm, 1.18mm, 850µm, 500µm, 425µm, 355µm, 250µm, 212µm, 180µm, 125µm, 106µm, 75µm and 45µm seivers for 10 minutes at constant vibration (Guagliardi, Apollaro, Scarciglia, & Rosa, 2013). Statistic package GRADISTAT version 4.0 (Blott & Pye, 2001) is used for data analysis. The grain size distribution, mean size, sorting ($\sigma_g = \exp [\sqrt{\sum} f(\ln m_m - \ln \bar{x}_g)^2 /100)]$ and cumulative particle size distribution maps were generated (Annexure 10) (Folk & Ward, 1957).

3.7 Assessing the Resource

Quantify the resource and assess the economic feasibility of Verukal placer deposit is essential for mine plan. The obtained results were analysed and ore reserve estimation was done. The mine plan was developed with the considerations of replenishment dynamics, economics, environmental impacts and easy technology. The maps and models of the deposit were generated using surfer software. Two main groups of traditional resource estimation;

1. The scalar geometric methods
2. The spatial (Geostatistical) methods

    - The scalar geometric methods can be further subdivided into:

        - Block method
        - Triangle method
        - Polygonal method
        - Graphic method (Isochors planes)
        - Triangle Method

Triangle methos is actually a variant of the polygon method. A series of triangles are developed with the bore holes at the apices. Drill area is divided into triangles by connecting adjacent drill holes with construction lines.

The significant benefit out of this method is that the calculation refers to three point values of thickness and grade. Material quantity is calculated for the more than cut off grade for each bore hole point. For the purposes of this problem, each drill hole is presumed to have the average grades and thicknesses.

CHAPTER 4: RESULTS

4.1 South-Western Region

The primarily south-western region was investigated covering both onshore and offshore areas. The study region of the southwest is given in Figure 4.1.

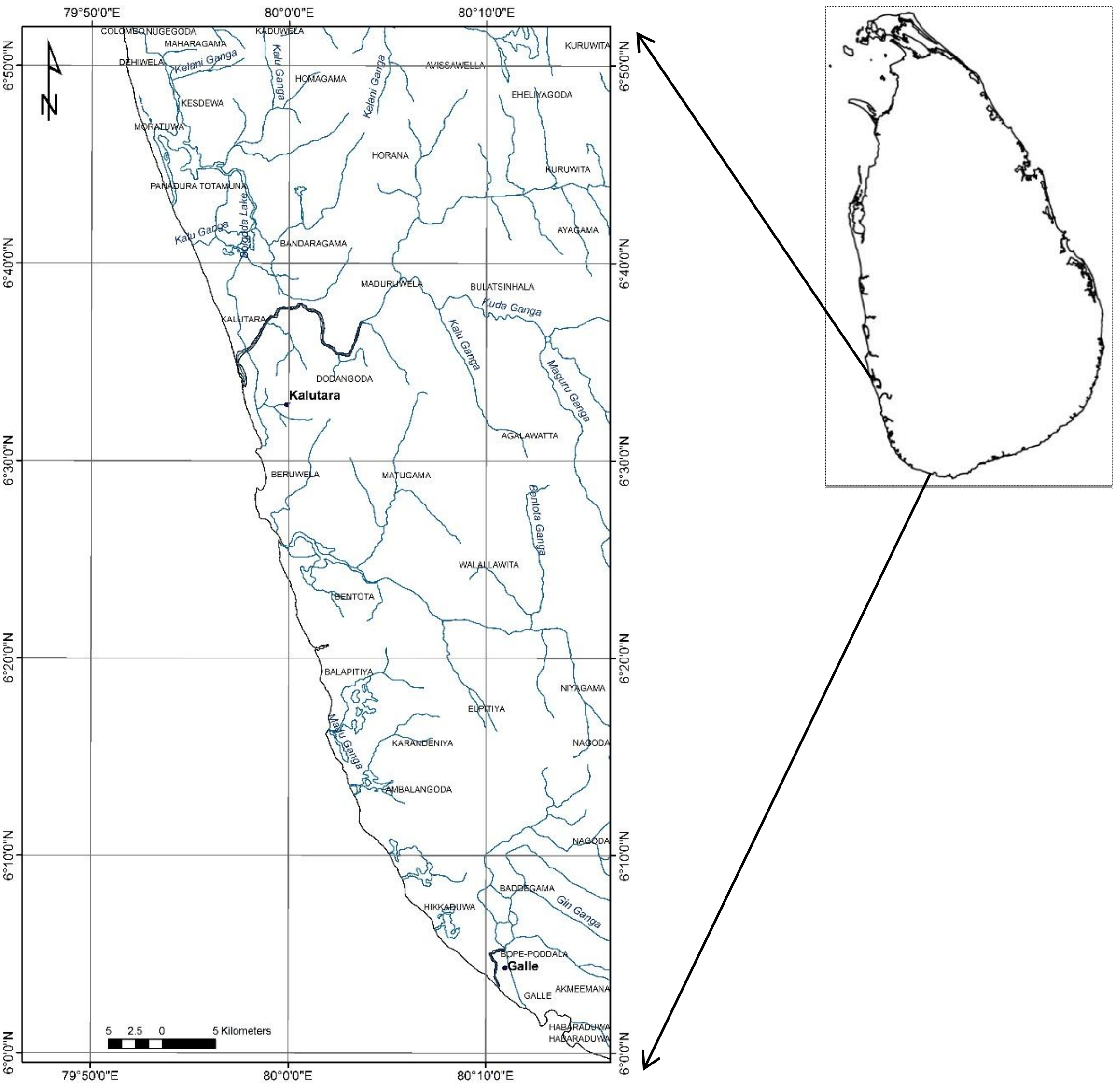


Figure 4.1: South-western study region

4.2 South-Western Onshore Analysis

The onshore region of the south-western part was studied during both monsoon periods and the results were compared. The beach slope, beach width, mean grain size, sorting and heavy mineral distribution were compared with the seasonal changes.

4.2.1 Beach angle of the southwest coast

The beach profile was measured using the levelling instrument and the slope was calculated during the southwestern (SW) and northeastern (NE) monsoon periods. The angles obtained in each location were plotted in Figure 4.2.

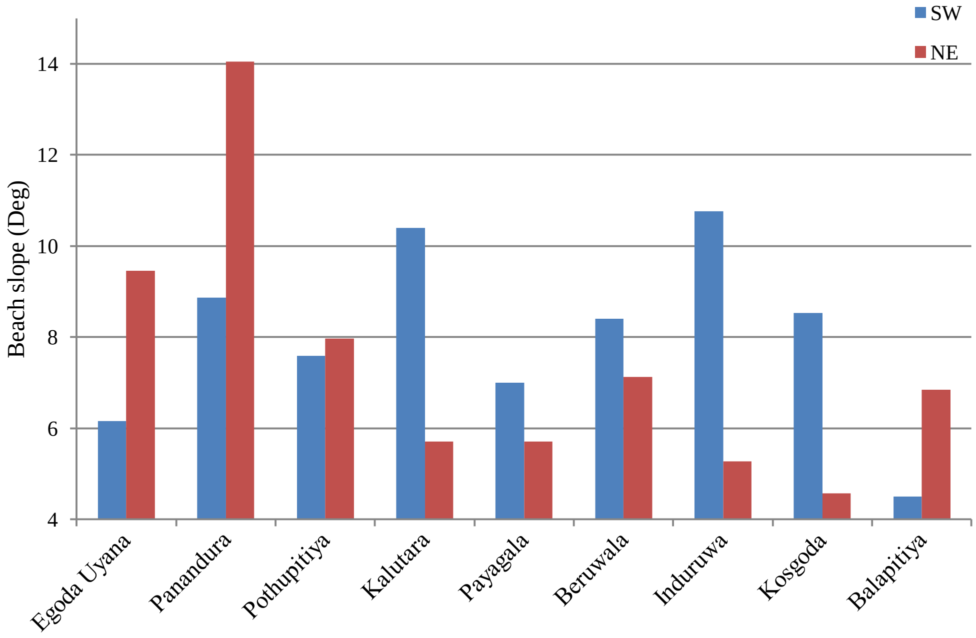


Figure 4.2: Beach angle of the southwest coast during both monsoon periods

The slope is gentle during the northeast monsoon period compared to the southwest monsoon period. The average slope of the beach during the southwest monsoon recorded as 09 degrees while it is 06 during the northeast monsoon period. However, Egoda Uyana, Panadura and Pothupitiya locations have a higher slope during the northeast monsoon than southwest monsoon period.

4.2.2 Beach width of the southwest coast

Beach width variation is given in Figure 4.3. The result is given concerning the beach width obtained during the southwest monsoon. Beach width data was collected two times during the northeast monsoon period and the pattern remains the same but the marginal differences in values from the other.

The maximum beach accretion was observed at the Panandura having 13 m increment compared to the southwest monsoon period. At Kalutara it was seen that heavy erosion happened with 10.5 m but it might be due to any artificial impact as that result not match with the trend. Generally, the southwest coast gets accrued during northeast monsoon period however, the decreasing trend was observed towards the south from the west coast. The beach width is decreased relative to the beach width during the period of southwest monsoon at down south from Beruwala to Galle. Meanwhile, the accretion was taken place during the northeast monsoon period from Beruwala to Egoda Uyana.

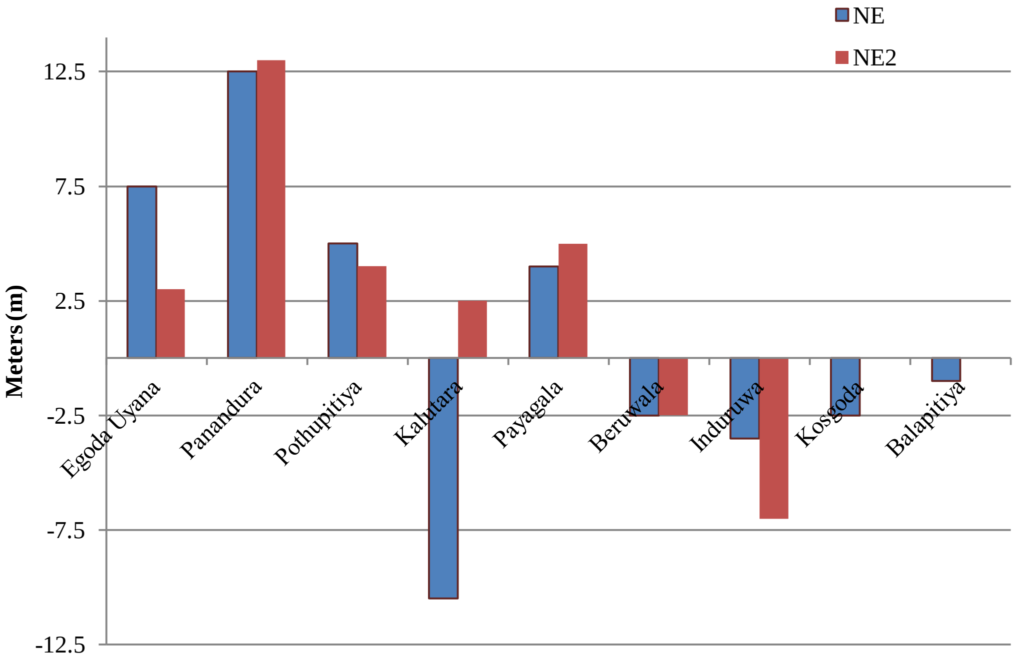


Figure 4.3: Beach width variation of southwest coast relative to the southwest monsoon

4.2.3 Mean grain size of the southwest coast

The beach sediment samples were collected at the mean sea level (MSL), berm and dune. Around a kilogram of such sand samples were subjected to the sieving process and using the GRADISTAT package the mean grain sizes were obtained. The mean grain sizes of each location were calculated and illustrated on Figure 4.4 on both monsoons. The pattern is similar in both monsoons and having the average size range between 250 – 500 microns thus, sand can be classified as medium grain size. From Aluthgama to Randompe mean grain sizes are smaller during northeast monsoon than southwest monsoon period.

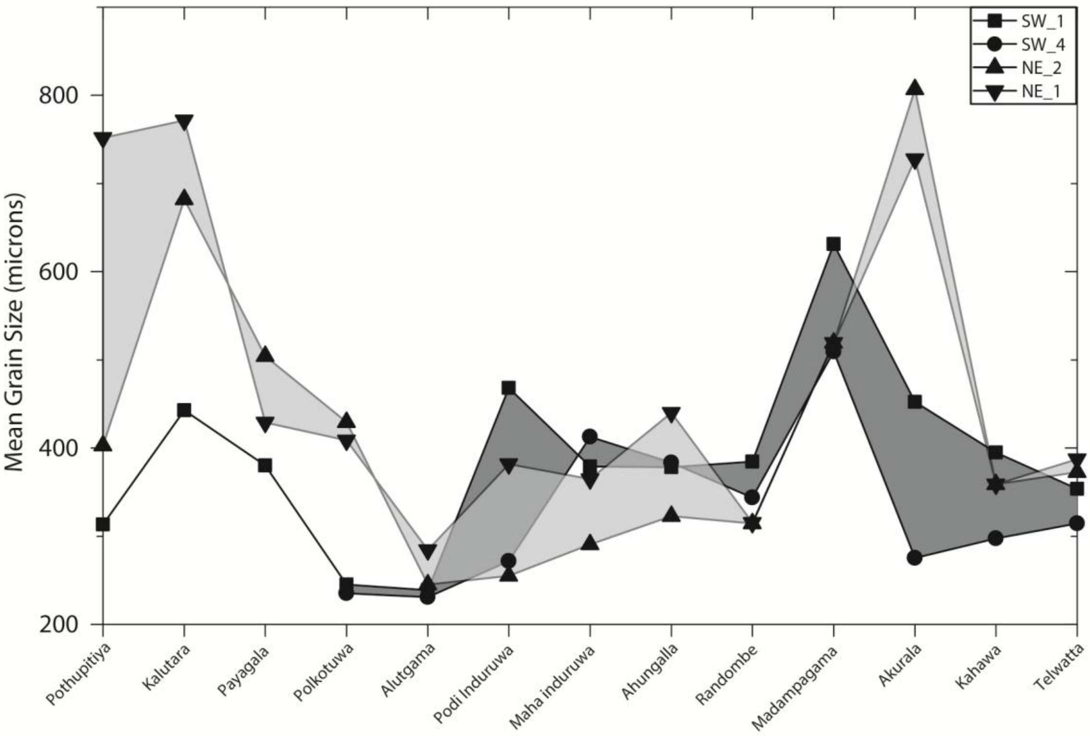


Figure 4.4: Mean grain size variation of the southwest coast sediments during southwest and northeast monsoon

4.2.4 Sorting of the southwest coast

The metric values of sorting indexes were obtained through the statistical package and results plotted in Figure 4.5. Sorting of both monsoon periods was in the range of well sorted (1.27 – 1.41) to moderately well sorted (1.41 – 1.62) and the pattern matches in general during both monsoons while values lesser during the southwest monsoon period. Poorest sorting encountered at the Payagala during northeast monsoon and at the Akurala two readings during the northeast monsoon period are in opposition with having highest and lowest values of the location.

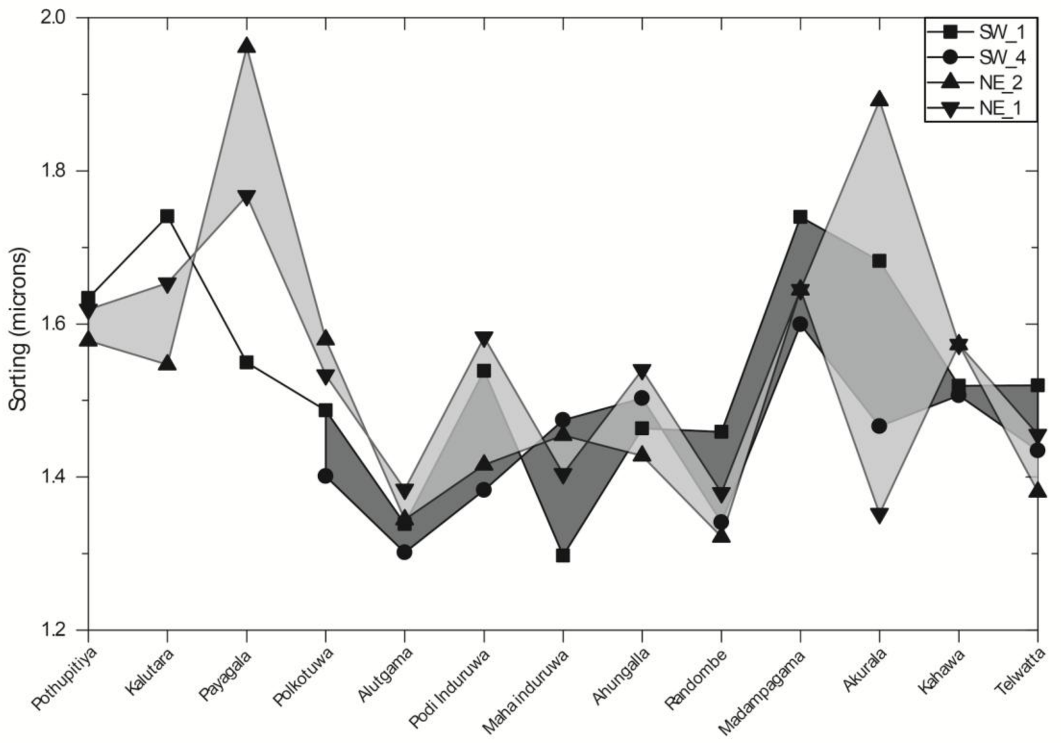


Figure 4.5: Sorting of the southwest coast sediments during southwest and northeast monsoon

4.2.5 Mineral Composition of the southwest coast onshore samples

Southwestern coast is well-known for the Monazite deposition throughout the history hence, studies initially focused on the abundance of the Monazite. Southwest coast onshore samples were tested for the Monazite content and the results were compared for both monsoon periods. The samples were collected separately on MSL, berm and dune at each location. The results were obtained separately and the values for each location were compared with seasonal changes (Fig 4.6). Results showed some anomalies at Maha Induruwa, Podi Induruwa and Polkotuwa locations and also during the southwestern period, the accumulation of Monazite was many times higher than north-eastern monsoon period (4 – 18 % during southwest and 1 – 3 % during northeast monsoon). However, most of the locations were did not reveal for any Monazite or had very less amount but the pattern matched during both monsoons.

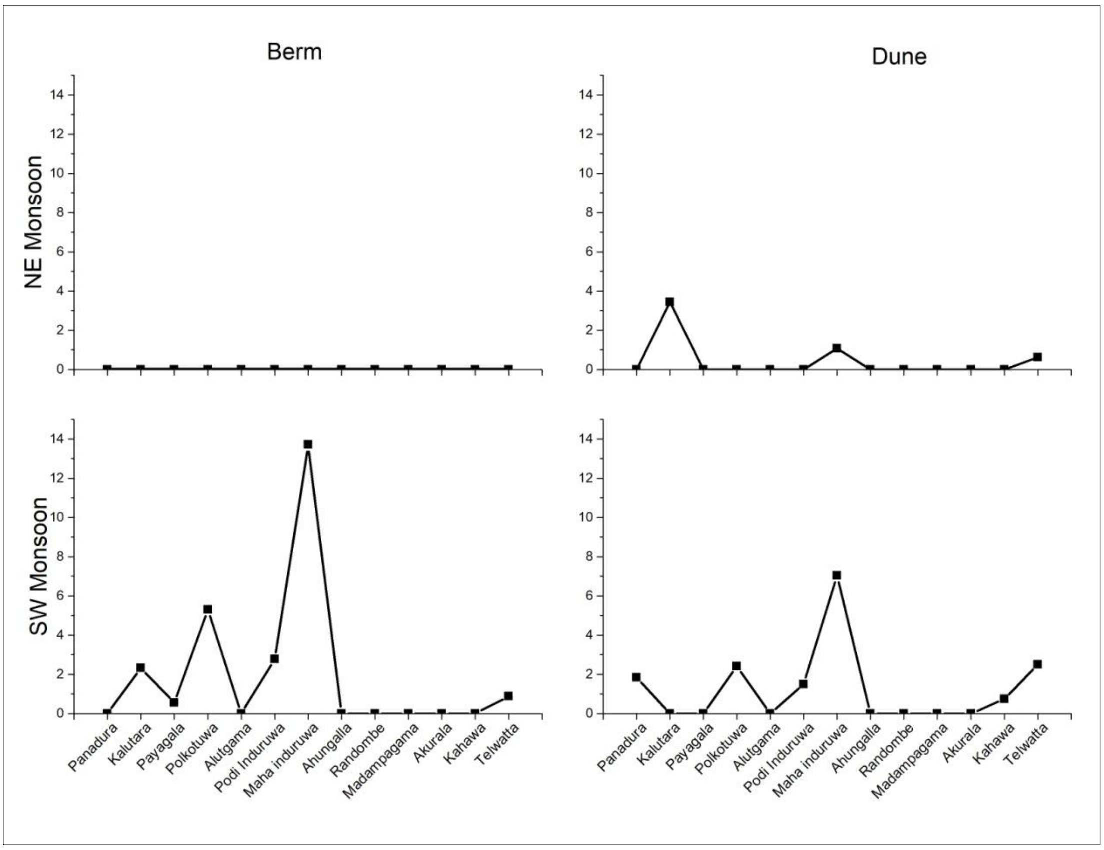


Figure 4.6 Monazite percentage variations along the south western coast during both monsoon periods at berm and dune

Figure 4.7 shows the distribution pattern of the constituent of the heavy mineral component. It can be seen the abundance of Ilmenite with an average of 60% while the Monazite showing average of 01 % with a maximum of 18%. Zircon is the second most abundance among those samples. The heavy mineral content was zero in many locations at the dune samples and the content of the Ilmenite was increased while other elements were reduced towards landward samples (dune and berm).

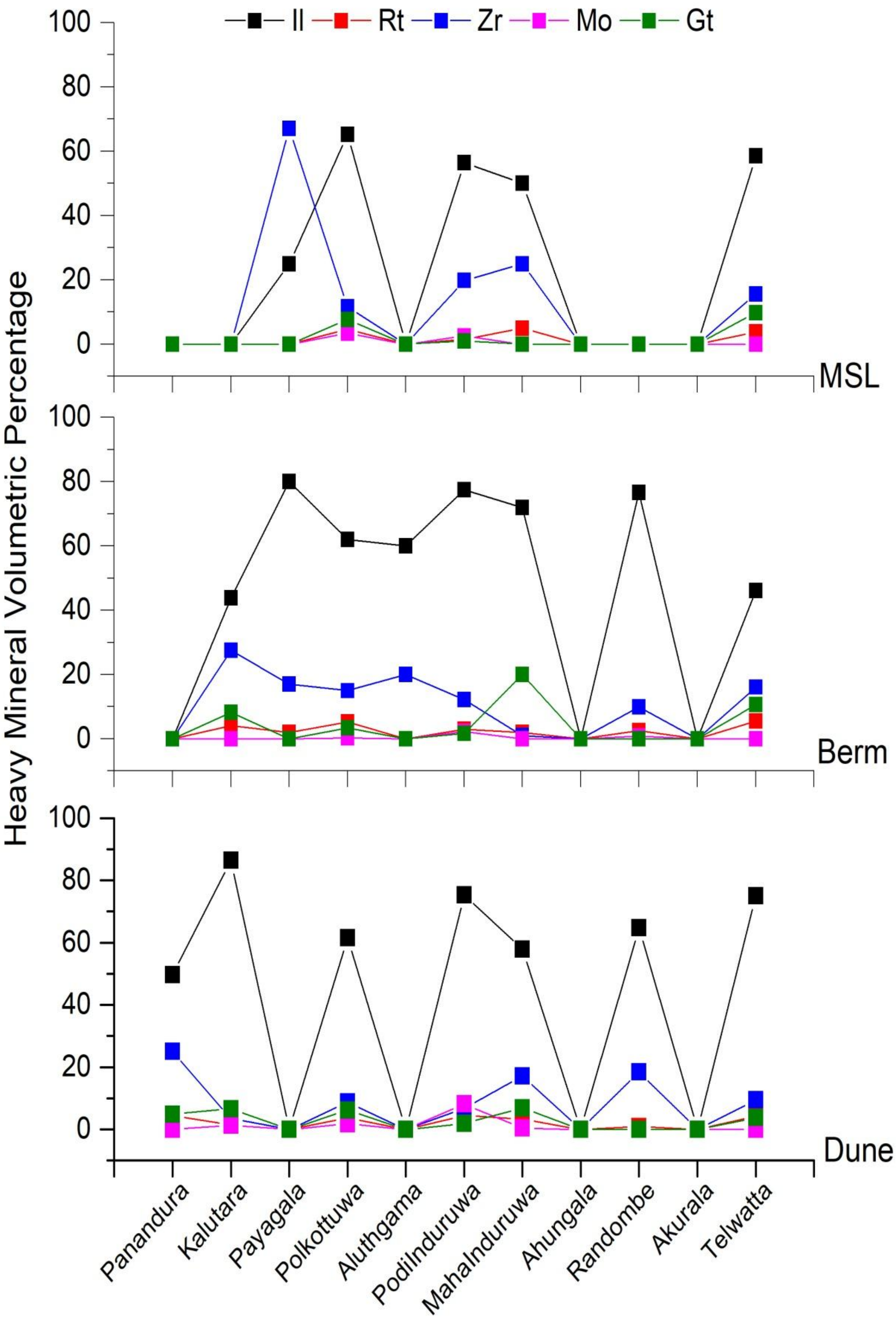


Figure 4.7 Heavy mineral sand composition variations along the southwestern coast during northeast monsoon

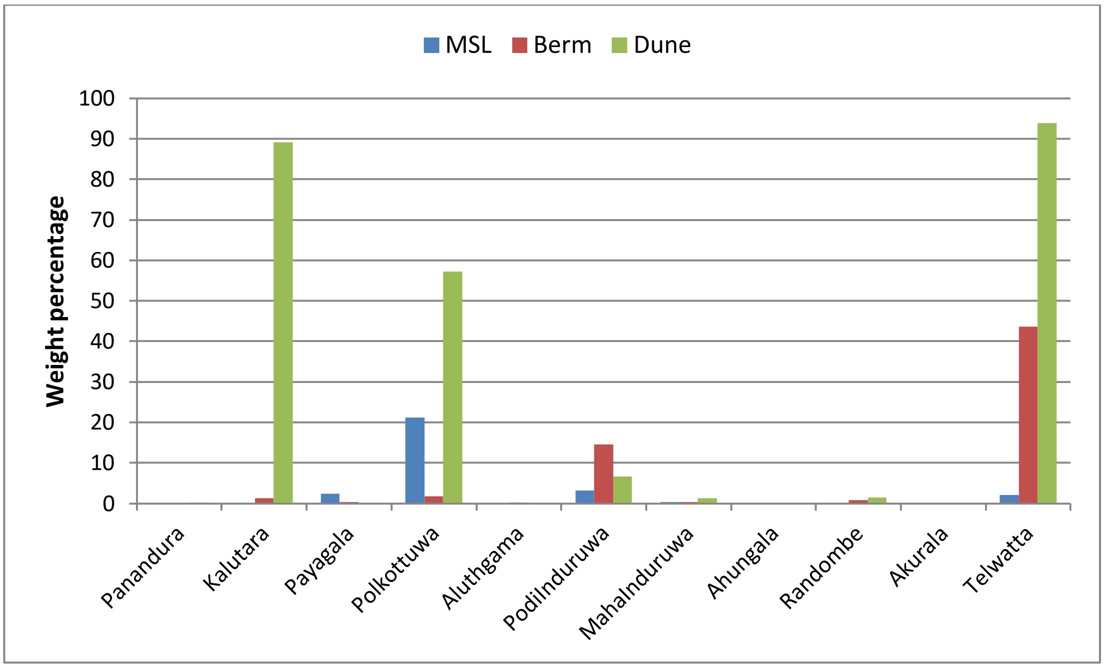


Figure 4. 8: Total heavy mineral weight percentage of southwest coastal sediments

Heavy mineral content of the samples of southwest coast has around 90 % at the Kalutara and Telwatta while it is of 57 % at Polkottuwa.

4.3 South-western Offshore Analysis

The offshore region of southwest coast studied during the first and second inter-monsoon periods. The inter-monsoon season was selected to avoid the rough sea and the sedimentation at the sea bed will not be affected by the monsoon changes. The offshore analysis in the southwestern region was carried out in two different locations adjacent to each other, one is from Beruwala to Induruwa covering Benthota river mouth and the other one is from Rathgama to Galle Harbour. Textural and mineralogical properties obtained from the collected samples.

4.3.1 Geological classification of the sediments from offshore study area in the south-western region

The half of the offshore samples from the Beruwala field is decided as the clay sediments and the 20 samples were identified as sand. On the Benthota River mouth, it is seen that the sediments are mud and the sand band found on the north and south sides of the river mouth.

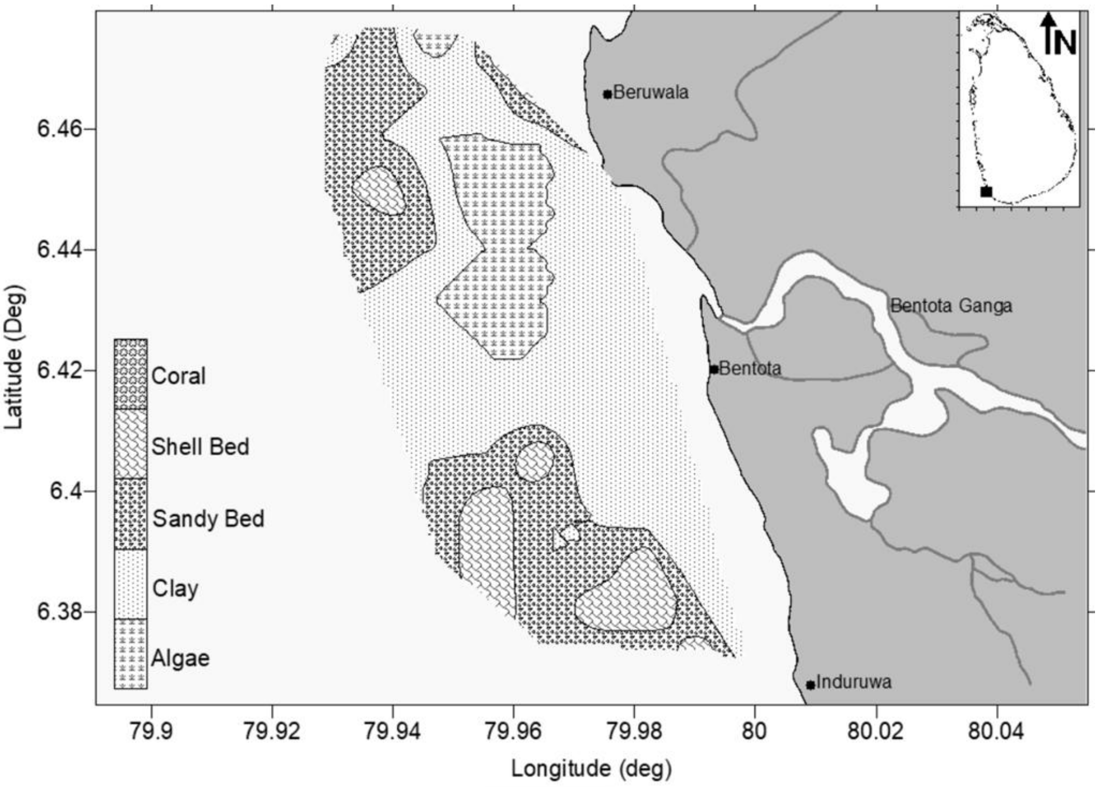


Figure 4.9: Geology of the Beruwala offshore samples

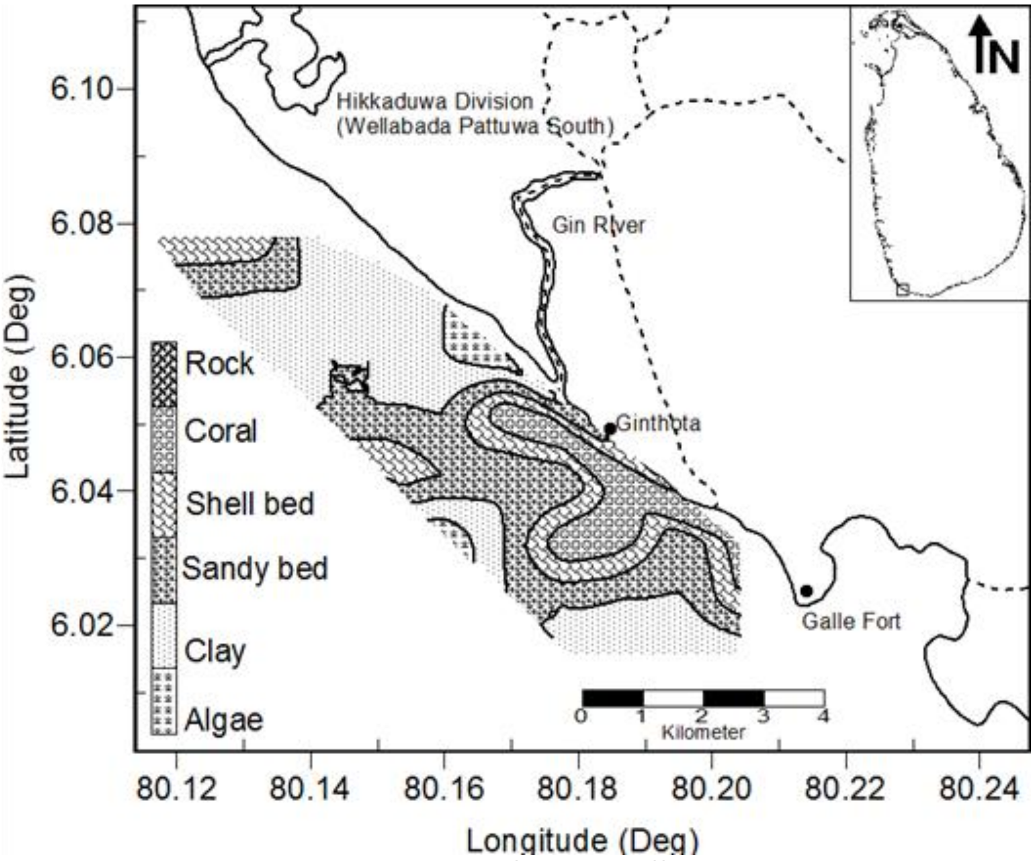


Figure 4.10: Geology of the Galle offshore samples

Most of the Galle offshore samples are classified as sand and the clay was found on the north of the Gin River mouth while southward sand band suggests the river flow path and sediment transportation. The sand deposition was not close to the beach but the coral and shells abundantly found nearby the beach.

4.3.2 Mean grain sizes of the samples from offshore study area in the south-western region

The many of the sea bed surface samples of the Benthota area were classified as clay and corals such samples were not tested for sieve analysis. The results of the mean grain size of the 20 samples were put into Figure 4.11. Benthota region mostly had the mean grain size in the range of 500 - 2000 microns thus, coarse sand to very coarse sand. Similarly, the tested samples of Galle offshore also shown the coarse to very coarse sand.

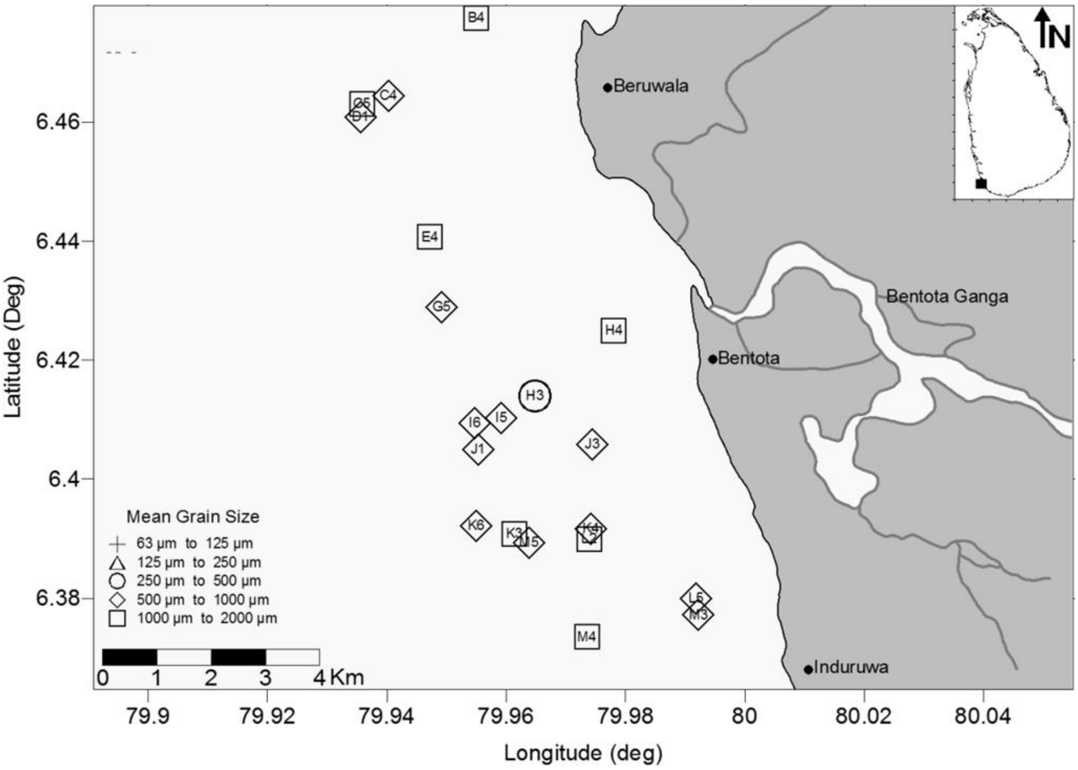


Figure 4.11: Mean grain size of the Beruwala offshore samples

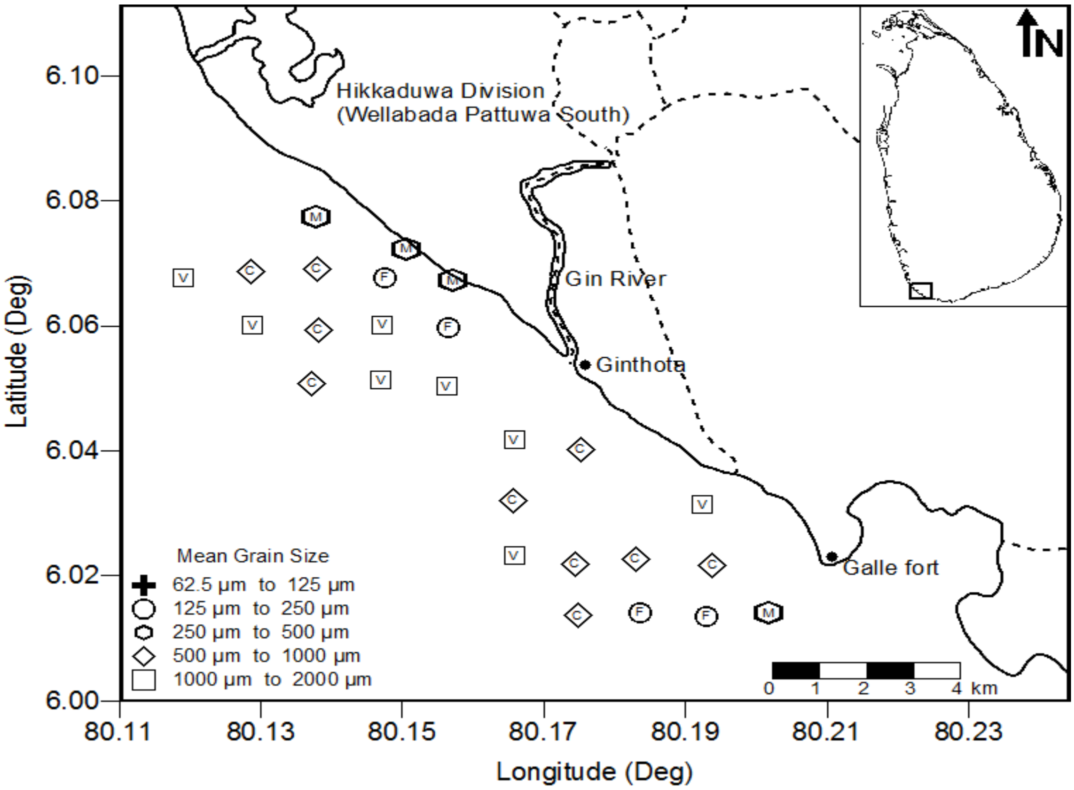


Figure 4.12: Mean grain size of the Galle offshore samples

4.3.3 Sorting of the offshore study area in the southwestern region

Offshore samples of Benthota region were tested for sorting indexes and found that those are moderately sorted in most locations and few with moderately well sorted (Figure 4.13). Galle regional samples were classified as moderately well sorted to well sorted equally with accompanying poorly sorted and well sorted in the north of the river mouth area. That top half study area has a mixture of the well sorted to poorly sorted samples. Figure 4.14 shows the sorting pattern of Galle region. In both regions the north of the river fall area is lower in sorting compared to the south side and the sorting is mixed up with wider range of the indexes.

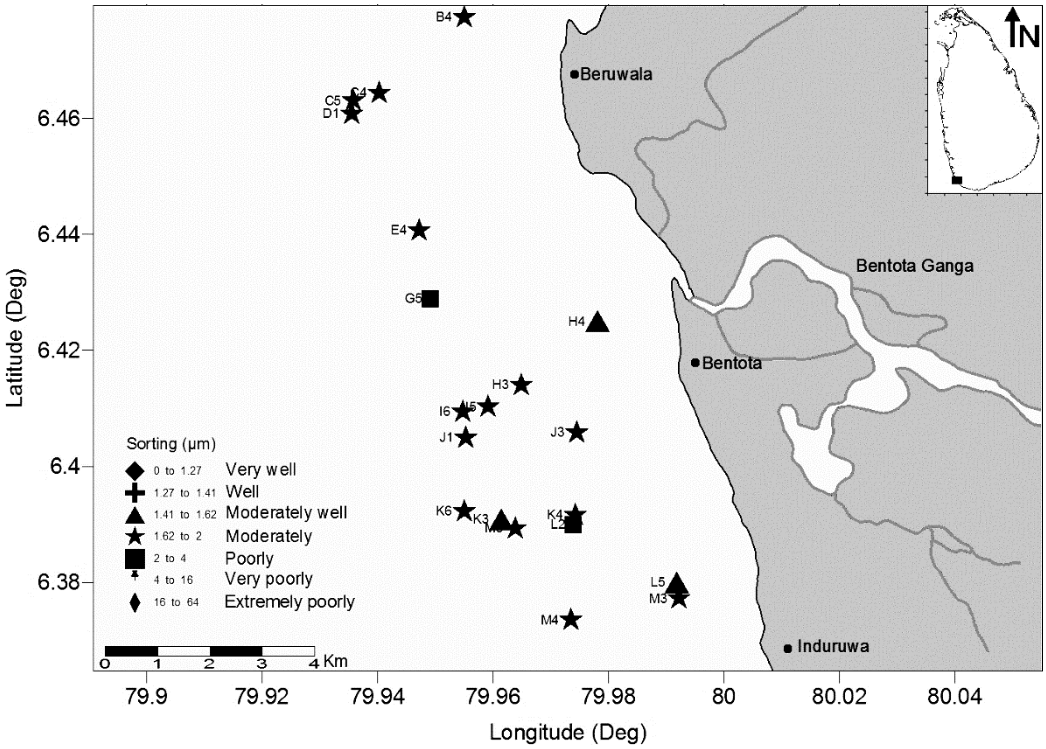


Figure 4.13: Sorting of Beruwala offshore samples

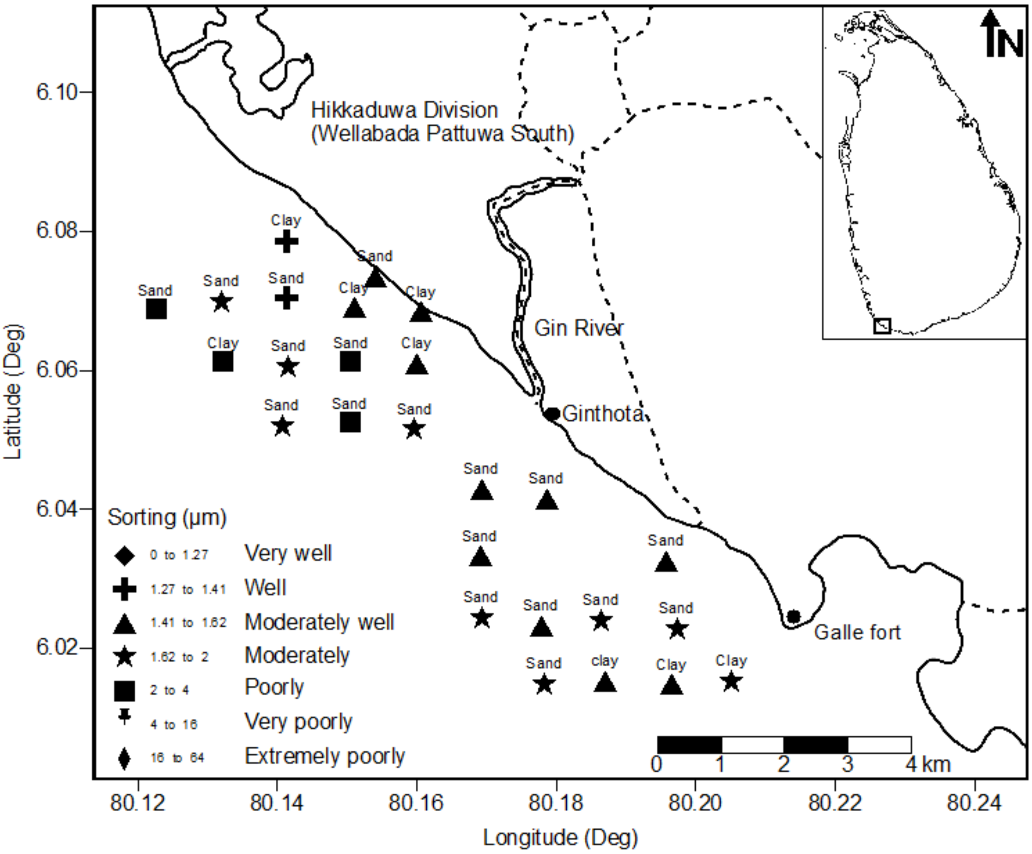


Figure 4.14: Sorting of Galle offshore samples

4.3.4 Mineral composition of the southwestern offshore region

Samples from the Galle region during the first inter-monsoon period field visit were tested for heavy mineral sands and the results were given on maps. At single location, heavy mineral content is 16 % while in all other places had below 03 % (Fig 4.15). Further, the number of Monazite grains was counted and the volumetric percent was given in Figure 4.16 and that was less than 2.0 % from the total heavies. Those are moderately well sorted coarse grains. However, total heavy mineral content is in the mix of poorly sorted and fine grain sand. No Monazite content was found in the samples collected in Benthota offshore region during the second inter-monsoon period.

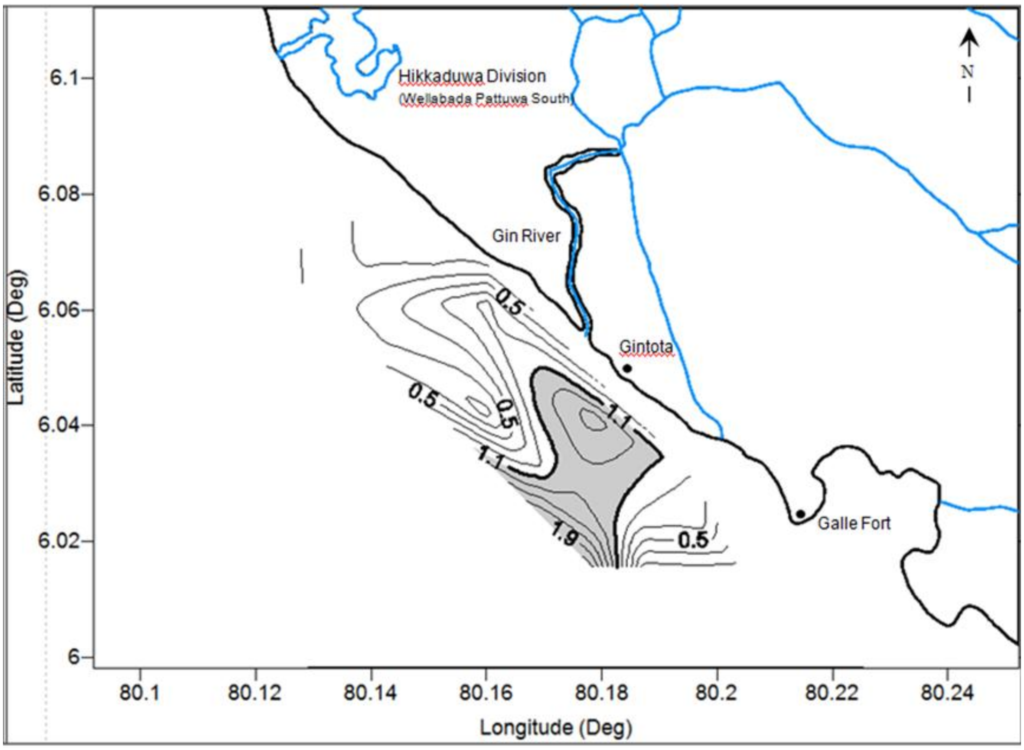


Figure 4.15: Total heavy mineral content of the Galle offshore samples

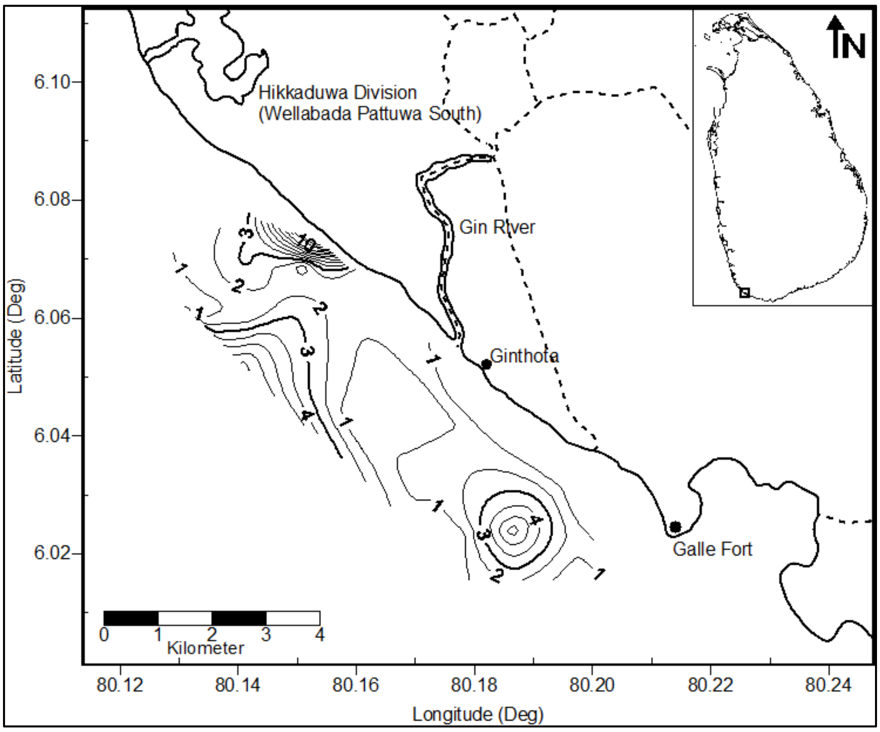


Figure 4.16: Monazite content of the Galle offshore samples

4.4 North-Eastern Region

The study on northeast region includes Verukal onshore, Pulmoddai onshore and Kokkilai offshore. Verukal onshore studies revealed potential heavy mineral sand deposit and accordingly mine plan was developed for exploitation. The area of the northeast is given in below Figure 4.17. The popular Ilmenite sand deposit is located in this region at Pulmoddai and also the longest river of the country Mahaweli River falls at Trincomalee. The Yan Oya in the north and Verukal Aru in the south are the other two important rivers for the consideration of mineral transportation from the possible sources apart from Mahaweli River at this study region. The extensive studies were done to identify the source of the Verukal deposit.

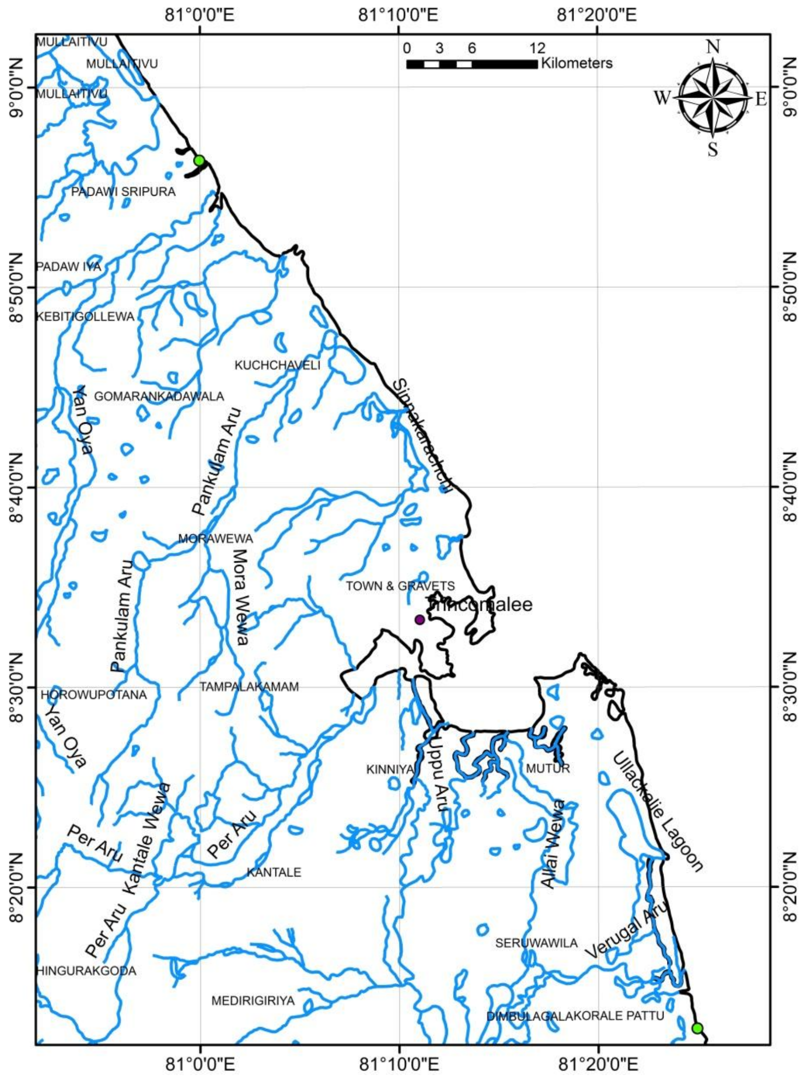


Figure 4.17: North-eastern study region

4.5 The north-eastern onshore study area of Verugal

The Verukal beach sand is rich in Garnet and pinkish in colour. The samples were collected in the area of Mahaweli River south fall called Verukal Aru covering up to 03 km distance. During the southwest monsoon period, first field visit was carried out and the samples were collected. The second field visit was carried out during the northeast monsoon period and the results were compared with the samples collected from the same sampling points. Beach survey was done at both instances and the variation of the beach profile was obtained.

4.5.1 Beach angle of the northeastern onshore region of Verugal

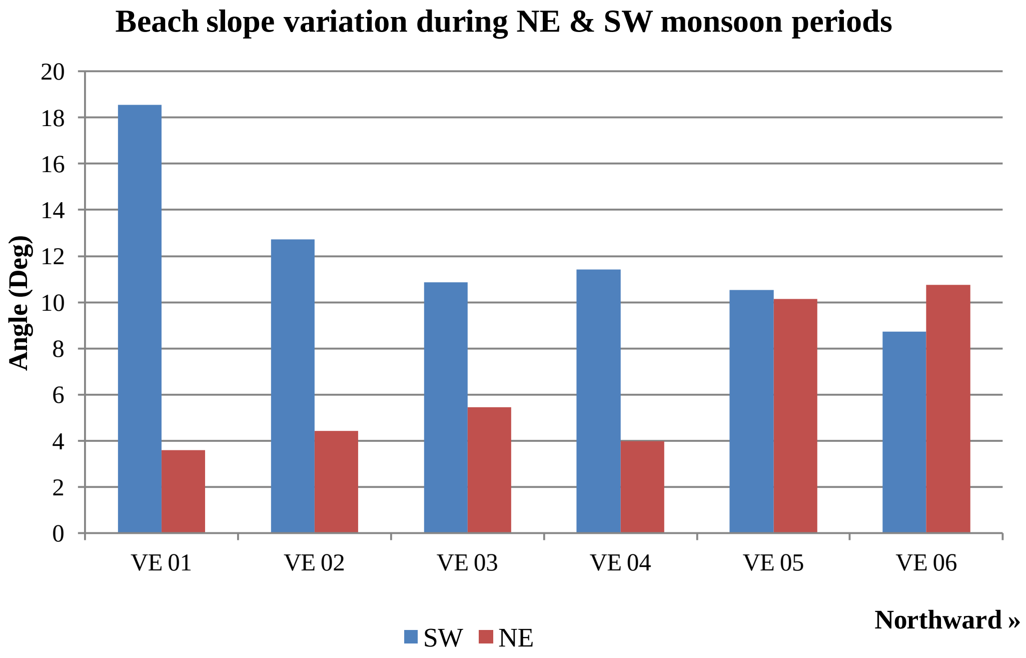


Figure 4.18: Beach slope variation during NE & SW monsoon periods

The slope of the beach along the Verukal during the northeast monsoon was gentler than slope during the southwest monsoon period. The angle is about 5 degrees in average at northeast monsoon period while it was 11 degrees in southwest monsoon. Moreover, during the southwest monsoon period, it is shown the decreasing pattern in northward but it is increasing during the northeast monsoon period (Fig 4.18).

4.5.2 Beach width of the north-eastern onshore region of Verugal

The beach profile was obtained and the beach width variation was plotted on below Figure 4.19. It was compared during both monsoons with respect to the fixed points those were demarcated at the field. It is clear that the beach was eroded during northeast monsoon and about 15 – 20 meters of the beach was eroded compared to southwest monsoon period. Beach erosion is increasing towards northward locations.

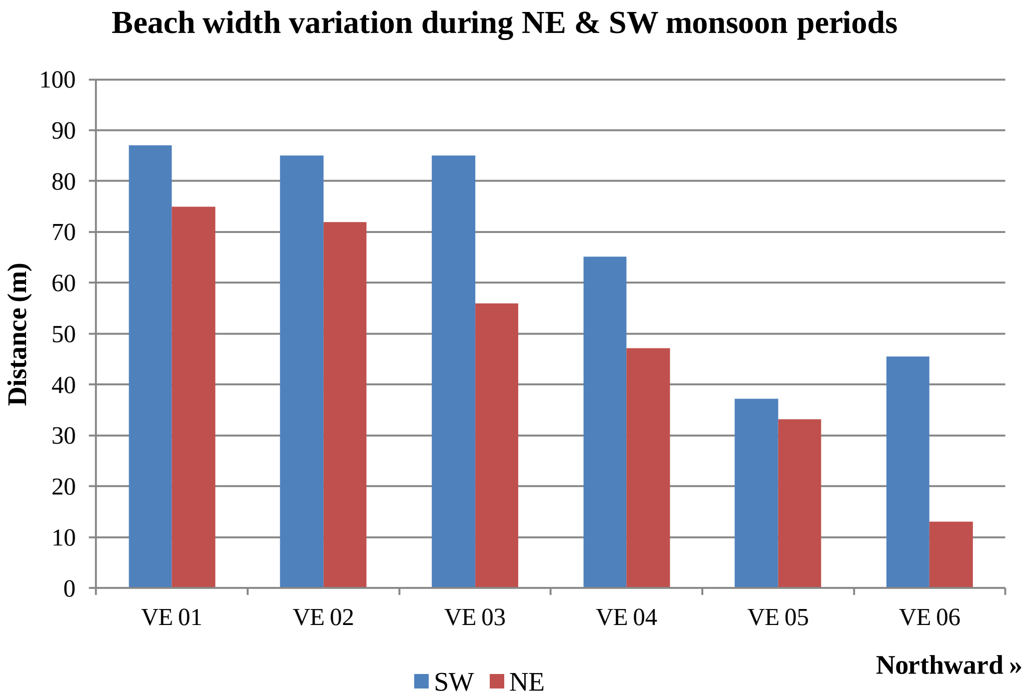


Figure 4.19: Beach width variation during NE & SW monsoon periods in Verugal

4.5.3 Mean grain size of the Verugal samples

The first sampling was done during the southwest monsoon period and the grain sizes fall in the range of 350 – 700 µm around the area of study. Therefore beach contains mostly medium grain sand and slightly coarse grain sand. Along the coastline size is not vary highly but towards landward it is slightly increasing in the north direction. Coarse grains are concentrated at the distance of more than 15 m from the MSL and it gets narrow but extended with the depth (Fig 4.20). Results obtained for grain sizes during northeast monsoon also show a similar range of 300 – 700 µm and showing a higher concentration of coarser grain sands on the surface. However, there is no any considerable variation of grain size during both monsoons. The coarser grain sedimentation distance from MSL is remained same in both periods but the area is extended from north to south that is covering the whole area of study during the northeastern monsoon period (Figure 4.21).

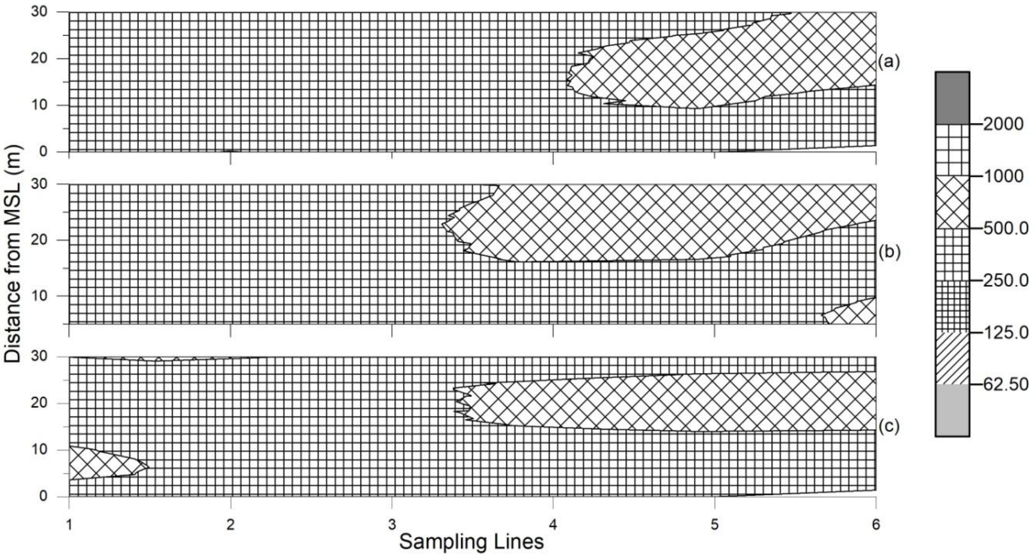


Figure 4.20: Mean grain size distributions at Verugal onshore during southwest monsoon Period
a - Samples at 0.3 m depth
b - Samples at 0.7 m depth
c - Samples at 1.0 m depth

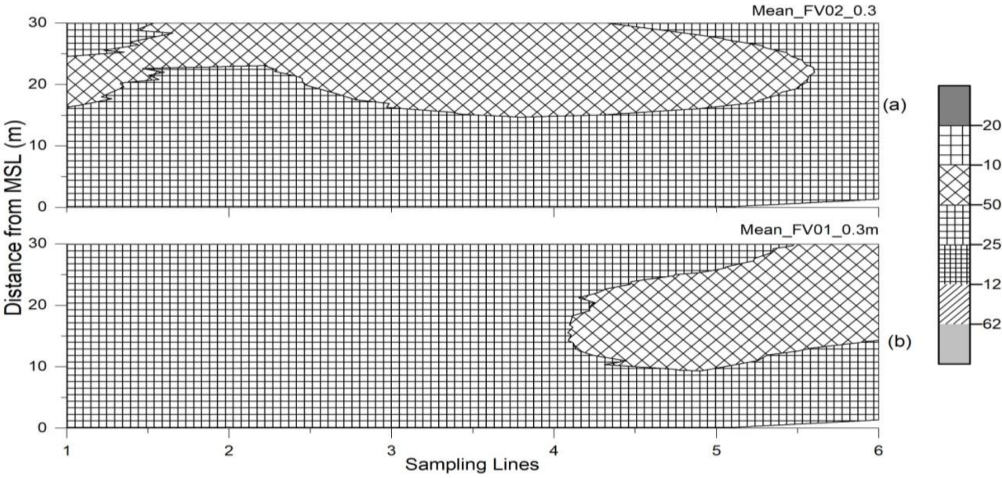


Figure 4.21: Mean grain size of surface samples during both monsoon periods

a – during northeast monsoon period field visit
b – during southwest monsoon period field visit

4.5.4 Sorting

Sorting of the Verugal during southwest monsoon was moderately well sorted, but the surface and at 1.0 m depth there is well-sorted sand were encountered at the distance of 20 – 30 m on northward locations. There was moderately sorting seen at a depth of 0.7 m (Fig 4.22).

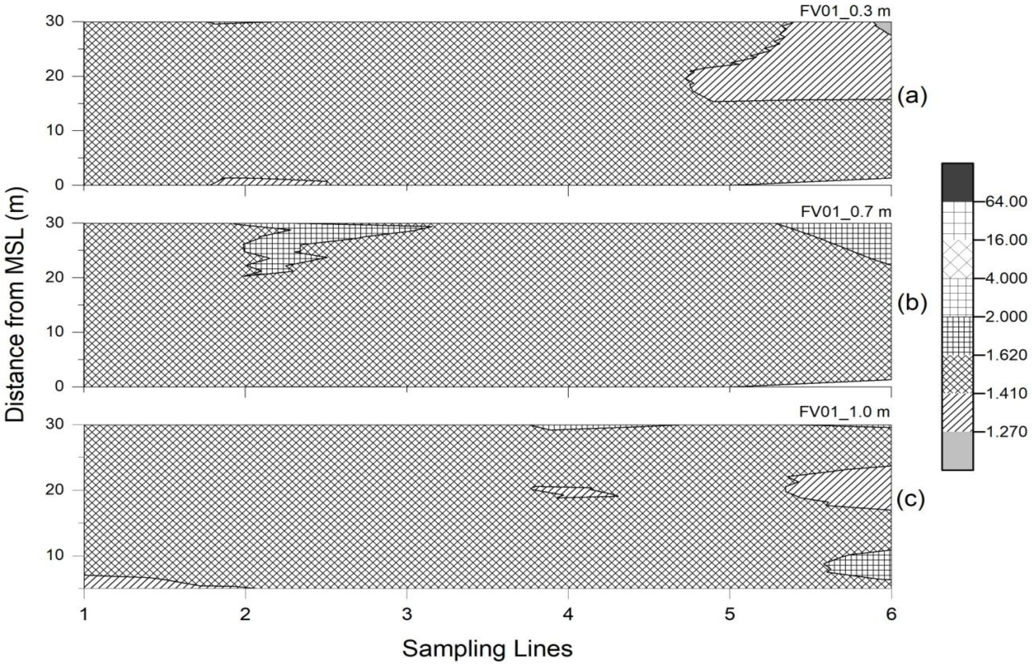


Figure 4.22: Sorting at Verugal onshore samples during the southwest monsoon period

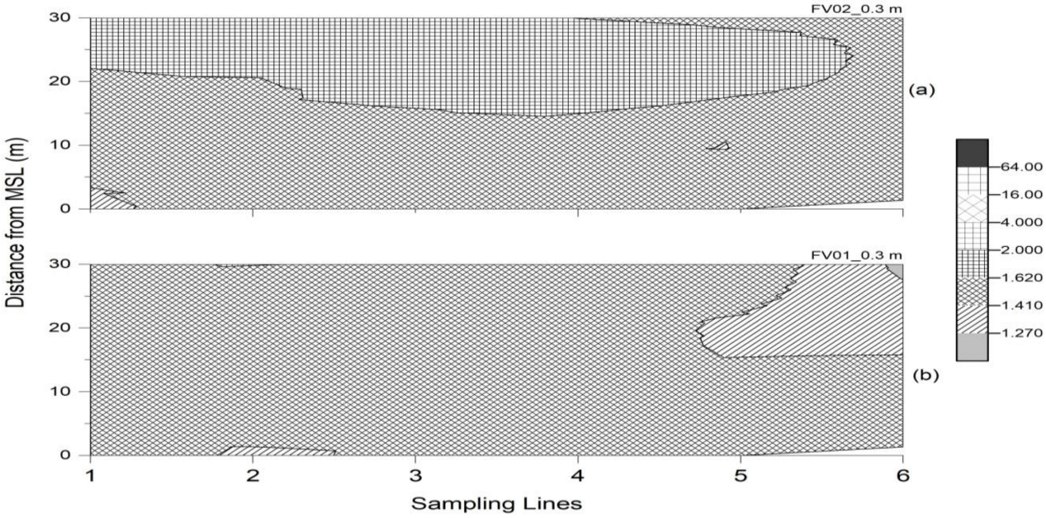


Figure 4.23: Sorting at Verugal onshore samples during both monsoon periods

Figure 4.23 illustrates the sorting of the Verugl during both monsoon periods. Sorting is mostly seen as moderately well sorted. However, during the northeast monsoon period, there are some locations encountered as moderately sorted at 20 – 30 m distance throughout the sampling area.

4.5.5 Heavy mineral composition of the Verugal onshore samples

All the samples were tested for heavy mineral sand content and the weight percent was given on the contour map of Figure 4.24 and Figure 4.25. Figure 4.24 illustrates the distribution of heavy minerals in three depths. Most of the surface samples contain about 50 – 70 % of heavies with 70 – 90 % in a few samples. Higher percent was observed near to MSL and at the south end locations (Figure 4.24 (a)).

Similarly, at 0.7 m depth samples (Figure 4.24 (b)) contains up to 70 % of heavies at the south part locations as highest. Half of the area had 50 – 80 % heavies at the 1.0 m depth. Maximum of 80 % was in the south end samples while in the north end samples had a lower percentage of 10 – 40 % heavy minerals. The contours clearly illustrate the intrusion of lower grade sand deposition from north to south end samples (Figure 4.24 (c)).

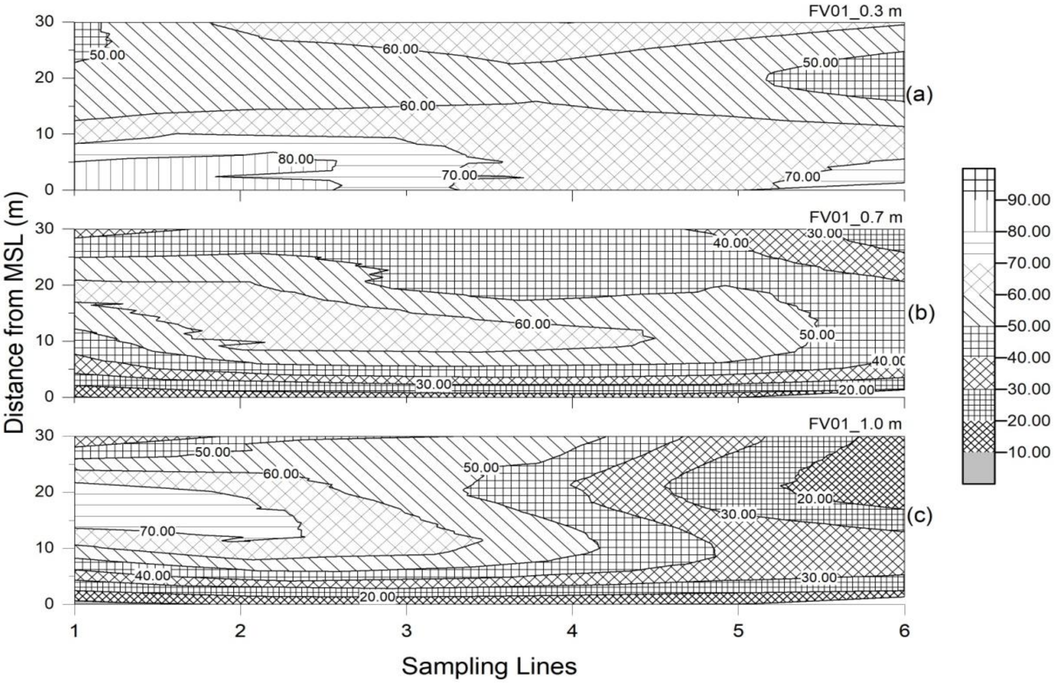


Figure 4.24: Heavy mineral content of the Verugal onshore during the SW monsoon

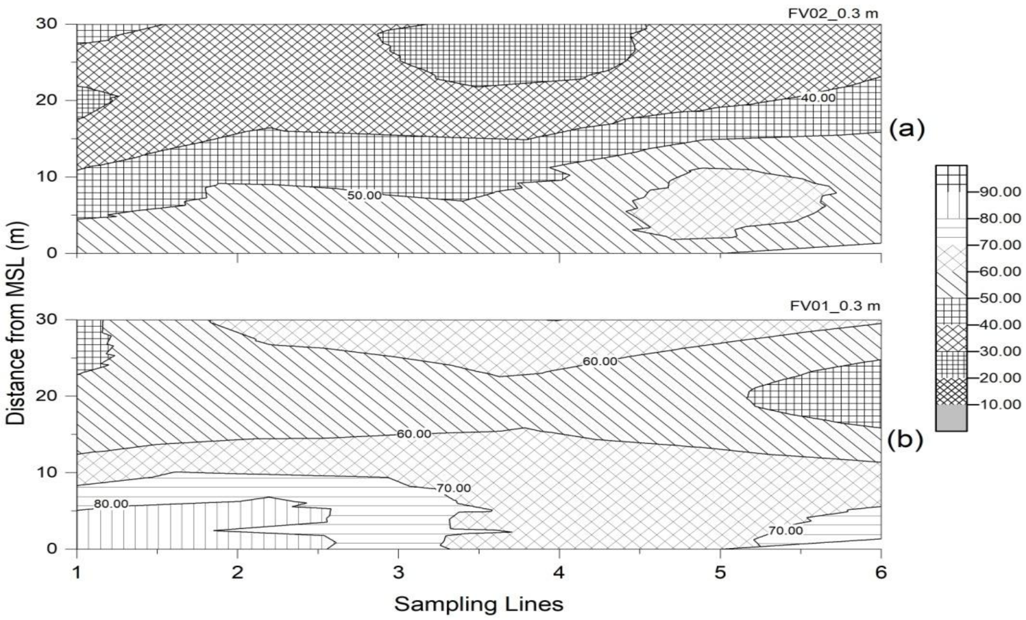


Figure 4.25: Heavy mineral content of the Verugal onshore during both monsoons

40 – 60 % was the content of heavy mineral during northeast monsoon with the very small area having 70 % which is lower than southwest content of heavies in the Verugal. Heavies are higher nearby MSL which can be a result of erosion during northeast monsoon and the eroded area is matching with the heavy mineral content during the southwest monsoon. Average heavy mineral content from the samples of southwest monsoon is 66.32 % while it is 46.49 % during the northeast monsoon. It shows the considerable reduction of heavies during the northeast monsoon period. Further, the shift of the sediment by erosion after northeast monsoon reveals the fact that far from the MSL has lesser deposition of heavy mineral in the Verugal area.

Figure 4.26 and 4.27 are illustrating the average content of each transects along the Verugal deposit. It can be seen the same composition during both seasons with the highest content of Ilmenite followed by Zircon but the least of Rutile. Total heavy mineral content in these lines has around 54 % and 46 % during southwest monsoon and northeast monsoon respectively.

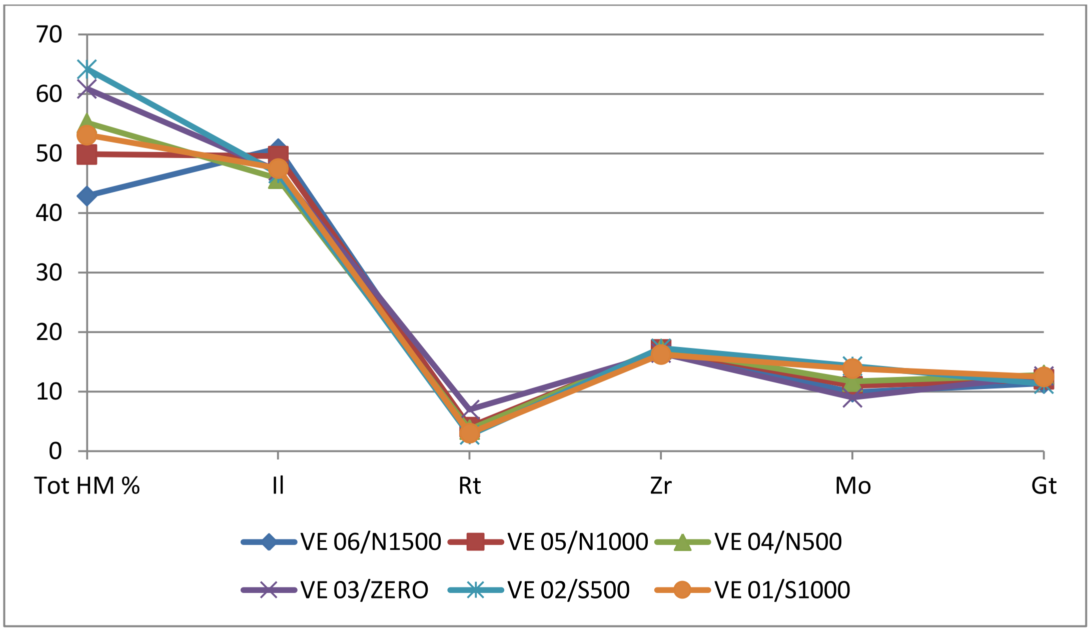


Figure 4.26: Heavy mineral content of the Verugal deposit during the southwest monsoon period

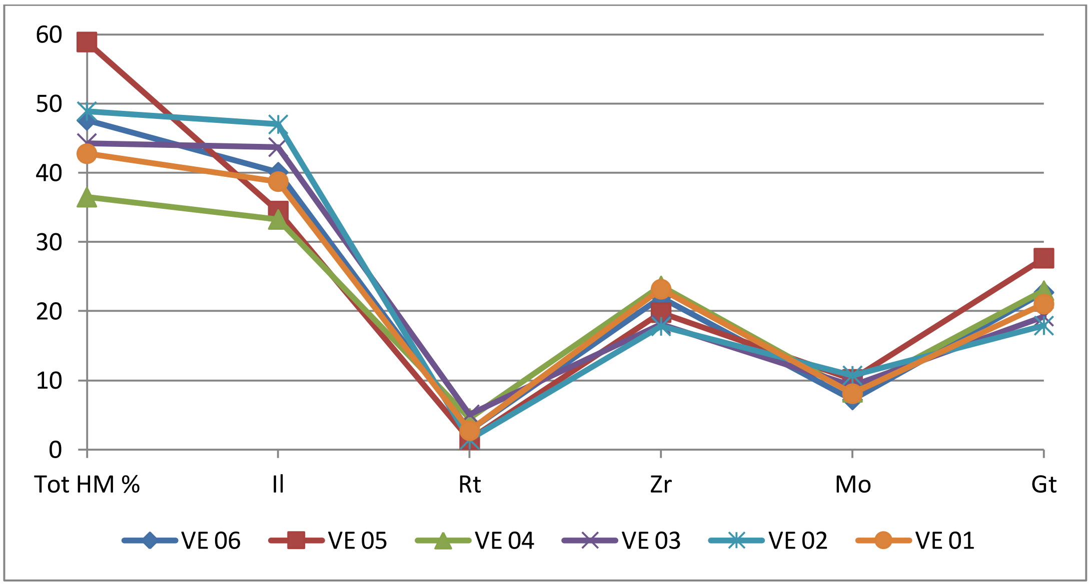


Figure 4.27: Heavy mineral content of the Verugal deposit during the northeast monsoon period

4.6 Northeastern Offshore Analysis at Kokilai

Offshore study at the northeast area covered the Kokkilai area. Samples collected around Yan Oya river mouth from Arisimalai beach to Thiriyai were tested for textural and mineral properties.

4.6.1 Mean grain size at Kokilai offshore

Results indicate that most of the samples represented by medium-grained samples and very less of coarse-grained samples (Fig 4.28). Fine grain sand is seen nearby the coast. Also, the fine grains were transported both north and south of the river mouth while medium grains are deposited close to Yan Oya mouth.

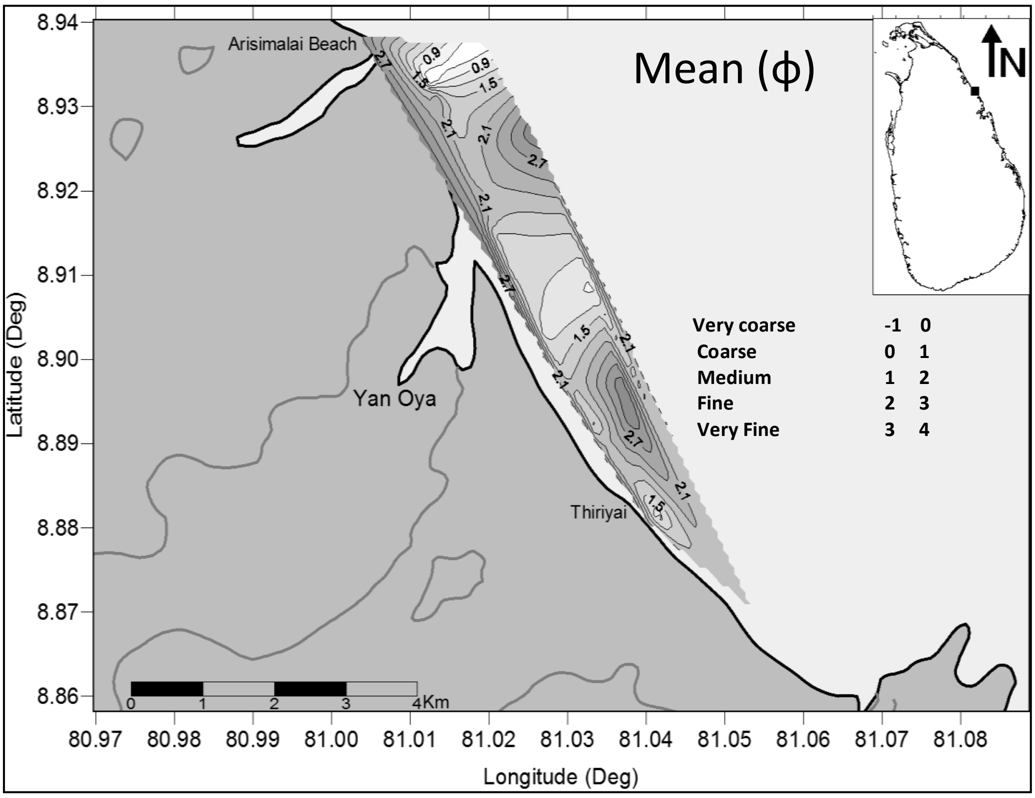


Figure 4.28: Mean grain size of the Kokilai offshore samples

4.6.2 Sorting of the Kokilai offshore samples

The sorting values given in figure 4.29 can be evidence of the mean grain size analysis of the region as it exactly matches the pattern. The coastal line has very well sorted and poorly sorted sands are associated with coarse grain samples.

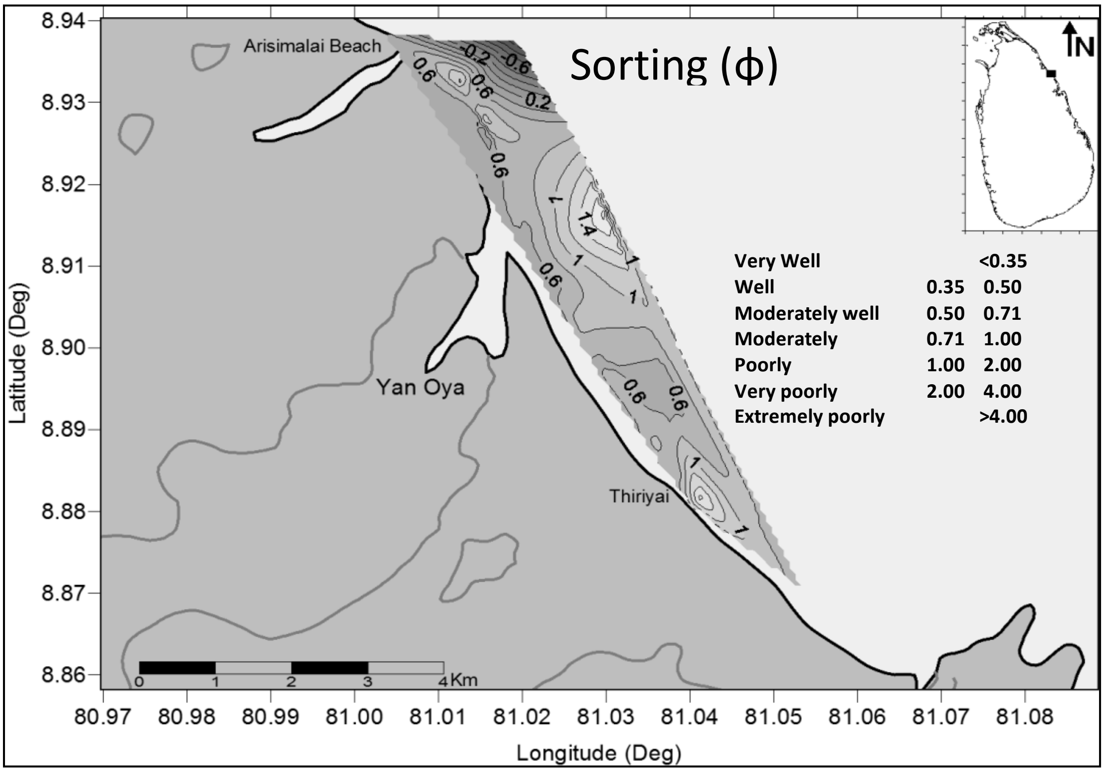


Figure 4.29: Sorting of the Kokilai offshore samples

4.6.3 Heavy Mineral Composition of the Kokilai offshore samples

The results revealed of around 5 % of heavy sands in that area. Figure 4.30 shows there are few anomalies up to 44 % of heavies which were deposited near the Yan Oya mouth and it decreases to 5 % in both south and north direction on the sea bed. Poorly sorted medium grain samples contain more heavy minerals in this area. Ilmenite is the most abundant among the heavies with around 60 % and Rutile is the second abundant with around 10 % of heavies in the Kokilai offshore.

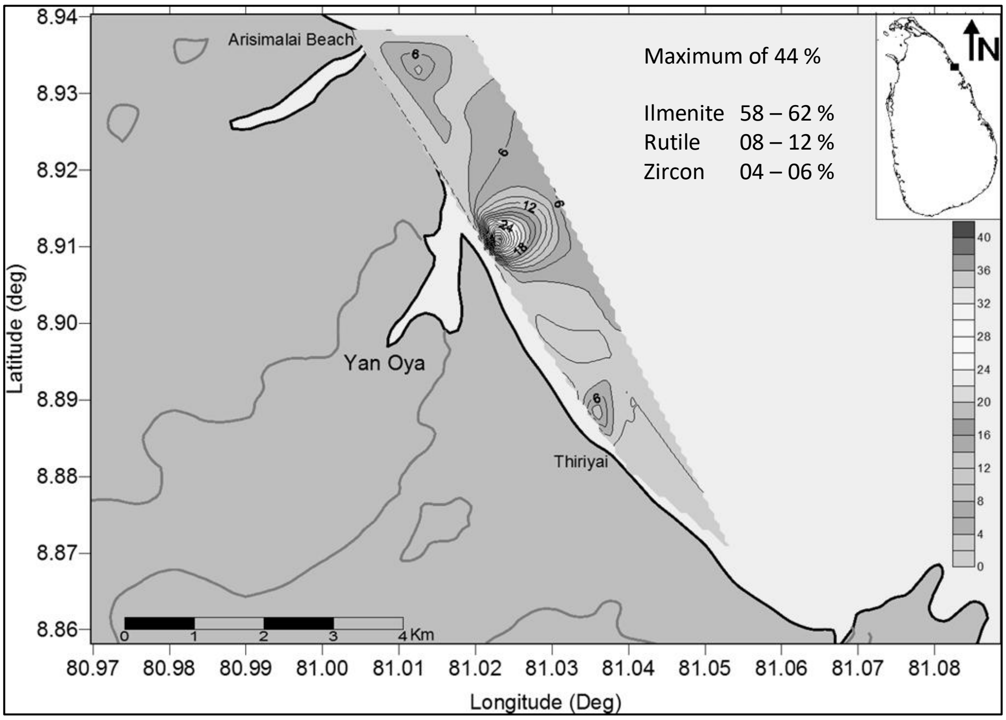


Figure 4.30 Heavy Mineral Sand at at Kokkilai Offshore

4.7 Along the Mahaweli River

The important study was done along Mahaweli River and eleven locations from Nawalapitiya to Trincomalee were subjected to sampling and analysis.

4.7.1 Mean grain size

Samples are coarse grain sand but the decreasing trend is observed towards Trincomalee (Fig 4.31). Up to Randenigala from Nawalapitiya samples are coarse grains with the range of 650 – 900 microns but at Randenigala, Minipe and Mahiyanganaya it was very coarse grains. Then from, Polonaruwa to Trincomalee decreased to medium grain.

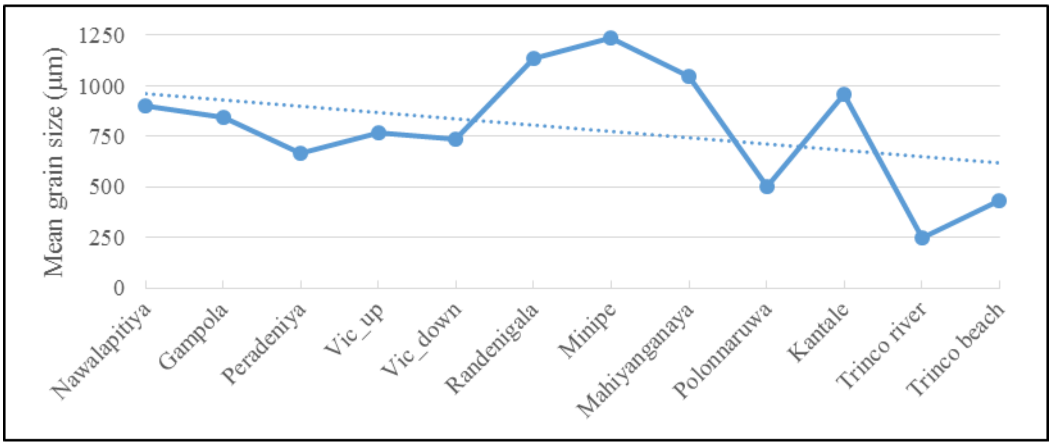


Figure 4.31: Mean Grain Size along the Mahaweli River

4.7.2 Sorting

The samples are poorly sorted along the river. However, the sorting is better towards Trincomalee (Fig 4.32). The Trincomalee river and beach samples are moderately well sorted. Higher energy stream shows the poorly sorted and finer grain sediments but low energy locations show better sorting.

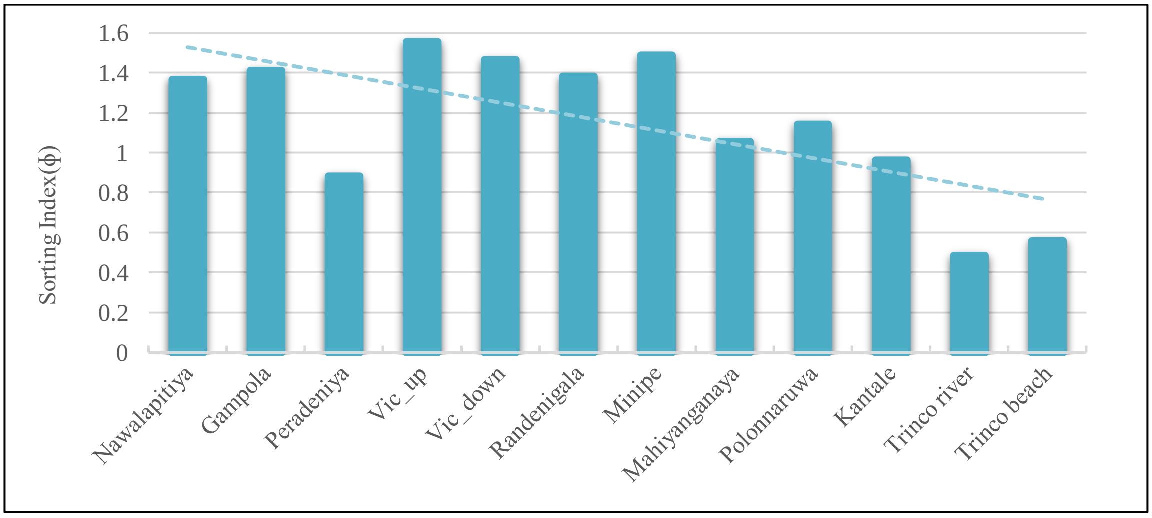


Figure 4.32 Sorting along the Mahaweli river samples

4.7.3 Heavy mineral composition along Mahaweli River

All samples were tested for heavy sand component and all are less than 7 % of the total weight of each sample (Fig 4.33). Peradeniya and Mahiynganaya samples consist of 6 and 7 % of heavies respectively. However, from Mahiyanganaya to Trincomalee it was decreased continuously to 0.78 %. Samples along the Mahaweli River reveals the content of Ilmenite is about 80 % of the composition followed by Zircon and Garnet but less than 10 % of the total heavy mineral content.

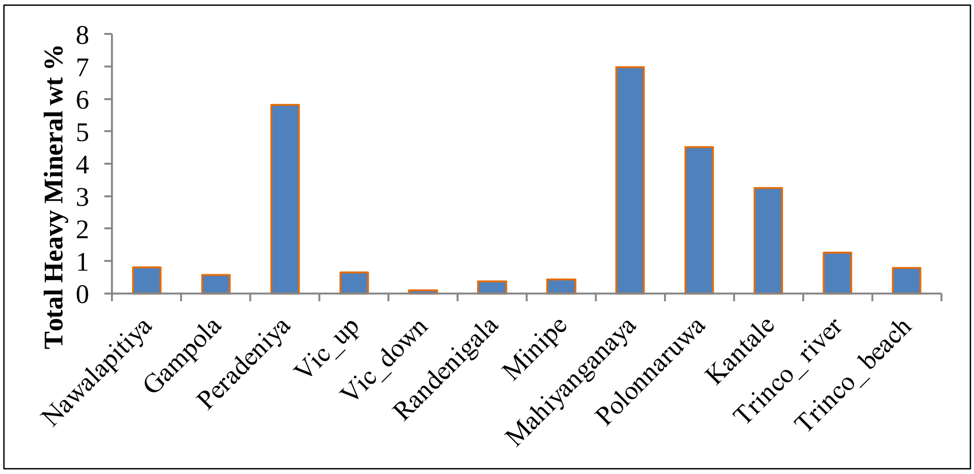


Figure 4.33: Heavy mineral sand content along the Mahaweli river samples

CHAPTER 5: DISCUSSION

The research was studied extensively about the southwest coast and the understandings were compared with the findings of the northeast region. Further, the seasonal impacts and the provenance of the deposits were analysed. Moreover, the mining plan was developed with those considerations to the identified deposits of study areas.

5.1 Beach Profile

The beach profile is essential to understand for the mine plan. The slope and the width of the coast need to be studied and predictability of their behaviour with the seasonal changes are vital in economical, technical and environmental aspects.

5.1.1 Beach slope

Mean sea level, berm and dune are the key points which are associated with the morphology of the beach. The slope of the beach is generally very gentle but varies with the coastal dynamics.

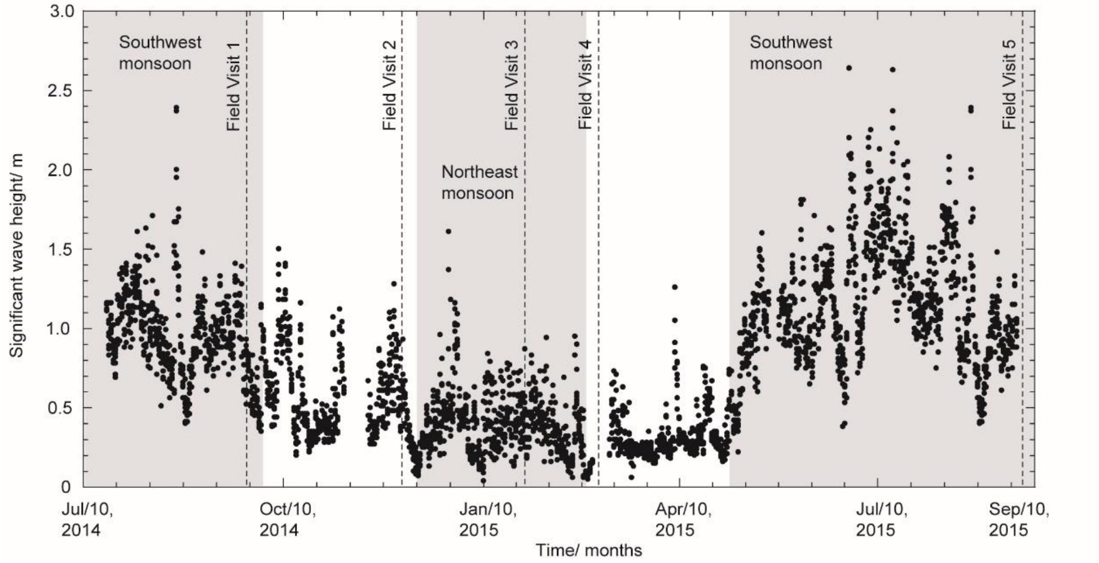


Figure 5.1: Significant wave height variations from 2014-06-01 to 2015-09-12 in the west coast of Sri Lanka

Typically wave energy is higher at the southwest coast during the southwest monsoon period (Figure 5.1) and the strong backwash erodes the coast along the southwest part of Island. Whereas southwest coast is very calm during the northeastern monsoon period and incoming low waves bring the sediments and deposits in the beach. Thus, gentle slope during the north-eastern monsoon period was observed along the southwest coast as a typical phenomenon. However, the steeper slope was observed at few locations which are northward to the Kalu Ganga mouth of the southwestern coast. The direction of the longshore current in that area is northward and the sediment from the Kalu Ganga shall be transported by the currents might have the cause of this observation. Kalu Ganga is the major river in the southwest region has significant sediment supply to the coast of the region.

Beach face slope at the northeast coast is steeper during southwest monsoon is the finding that not comply with the observation at the southwestern coast.

5.1.2 Beach slope of northeast and southwest coast

The beach angles of the coasts were comprehended with seasonal impacts (Fig:5.2).

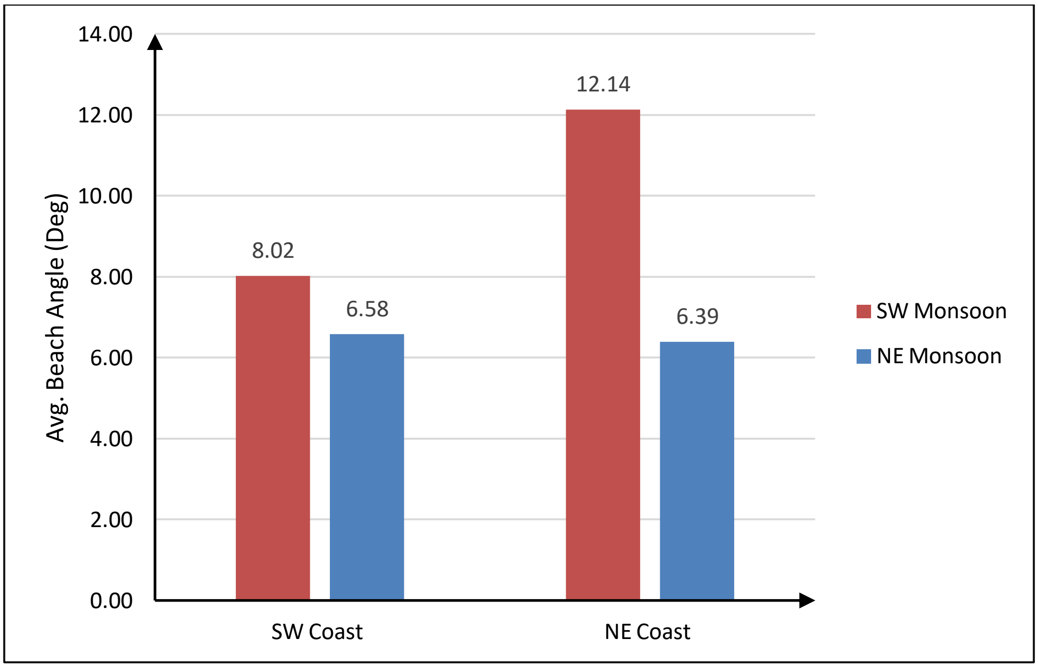


Figure 5.2: Beach slope of SW and NE coasts during both monsoons

The slope is lower during the northeast monsoon period compared to southwest monsoon for both coasts. In concern of southwest coast, during southwest monsoon period wave energy might be higher and the rough waves should erode the coast along the southwest part of Island. While, southwest coast is very calm during the north-eastern monsoon period due to no direct effects on the waves and the accretion takes place during that period. Thus, the gentle slope will be created by smooth swash and backwash action during the northeast monsoon period. The average slope of the beach during the southwest monsoon recorded as 08 degrees while it is 6.5 during the northeast monsoon period.

However, the slope of the beach along the northeast coast during the northeast monsoon was gentler than slope during the southwest monsoon period. The angle is about 6.4 degrees on average at northeast monsoon period while it was 12 degrees during southwest monsoon. This observation can be explained as; the energized waves of northeast monsoon washed back the sand to the beach face. Therefore, the beach profiling gives the gentle slope rather than steeper as found at the southwest coast. Also, the numerical values obtained for the angle is not incorporated the geomorphologic effects on beach forming process. Further, the content of the beach sand may vary in both regions and the grain size and composition of the beach may cause the opposite results in seasonal impact to the beach slope. The significant cause of the impact may vary between the beaches. It was learned that high energy beaches tend to have lower slopes for a given grain size than low energy beaches. The mean grain size of the Verugal beach in both seasons are same and the wave energy should determine the beach slope of the northeast coast of study. But, during the southwest monsoon period angle shown the decreasing pattern northward but it was increasing during the northeast monsoon period. It is due to the variation of the mean grain size at the locations within the comparison of northward and southward samples. During the southwest monsoon slope had decreasing pattern towards VE05 and VE06 locations (northward) where the mean grain sizes are smaller compared to other locations during the southwest monsoon and it was in another way during the northeast monsoon. The significant parameter of the southwest coast for the slope highly depends on the mean grain size.

5.1.3 Beach width

Beach width is one of the parameters to the decisions on mining of beach sand. The accretion and erosion taking place on the beach with the seasonal changes due to sediment transportation with the wave action and current direction. Apart from that the geomorphologic aspects of the particular location also have a key impact on regional variation from the typical observation of the beach widths. The southwest coast is highly influenced by the southwest monsoon, geological set up of the beaches and rivers from the southwest mountain range of the country. Beach width of the southwest coast is subjected to the erosion towards the south coast during the northeast monsoon period which is not a normal scenario. The difference of the geomorphology at the coastal region lower to the Beruwala area compared to the straight beaches from the Beruwala to Egoda Uyana might cause such differences. Moreover, the direction of longshore current plays a vital role in sediment transportation which might enhance the accumulation of sand along the west coast. The sediment supply from the Kalu Ganga is significant and it shall be transported at the direction of northward by the current.

Northeast coast of Verugal beach is heavily eroded during northeast monsoon as expected due to the northeast monsoon wind power that creates rough sea and high wave energy at the northeast coast. However, the width of the beach is less at north points also the erosion is high towards north direction locations. The longshore current direction is southward and the sediment transportation by the current might had an effect on this local variation.

5.1.4 Beach width variation of northeast and southwest coast

The below graphs show the beach width variation on southwest (Fig 5.3) and northeast (Fig 5.4) coast compared to southwest monsoon period. The cumulative bar reflects the erosion or accretion of both regions. Hypothetically during the southwest monsoon southwest coast should undergo erosion while northeast coast should accrete. The results obtained for both southwest and northeast regions shows the cumulative accumulation and erosion respectively during northeast monsoon compared to the southwest monsoon period, comply with the expected outcomes.

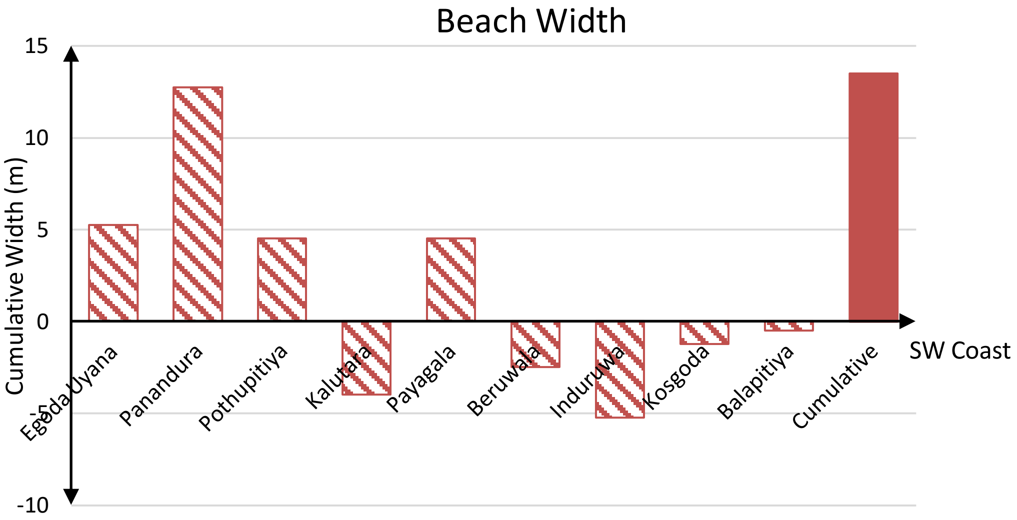


Figure 5.3: Beach width of the southwest coast during northeast monsoon with respect to the southwest monsoon

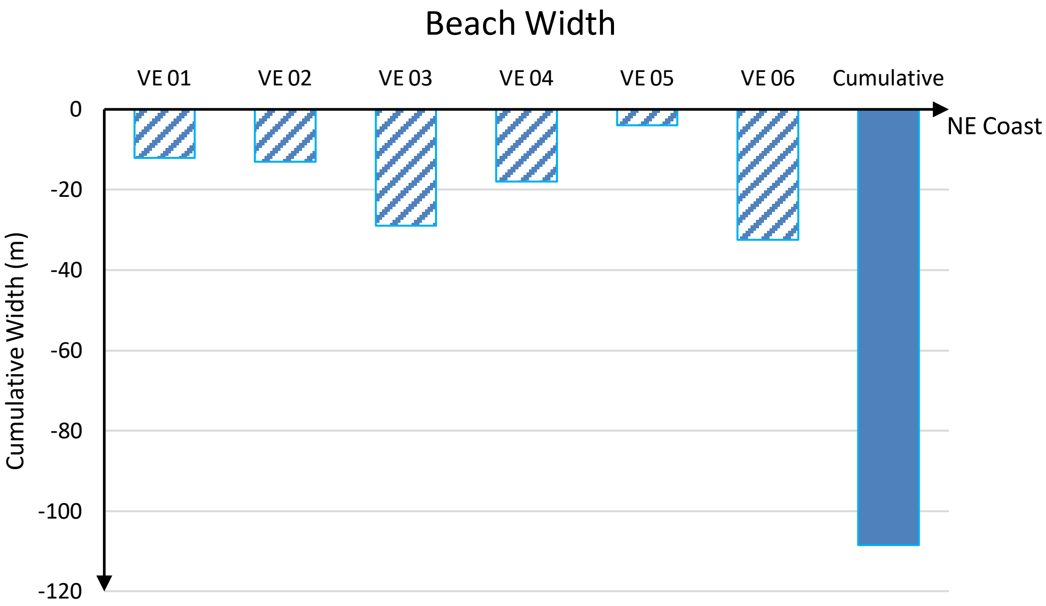


Figure 5.4: Beach width of the northeast coast during northeast monsoon with respect to the southwest monsoon

However, the beach width of the shore is favourable for mining during the calm season of the site. Southwest monsoon period of May to September and 2nd inter-monsoon period of October to November are suitable for mining at the northeast coast and it should be other two periods for the southwest coast. Replenishment process will take place during the next cycle of the season and it will reset the beach.

5.2 Textural Properties

The mean grain size and the sorting were calculated for all the samples to study the textural understanding of sedimentation and seasonal variation.

5.2.1 Mean grain size

Beach sand mean grain size will give the idea of the energy of the wave action; the distance of transportation from the source hence will show the source of the sediments. Conform to general phenomenon southwest coast beaches should have bigger grains during the southwest monsoon period. That due to the southwest monsoon wave energy at southwest coast is higher and causes strong backwash, high waves flow and erosion will be at the coast. The smaller and lighter particles will be backwashed and heavier will remain at the beaches.

In the southwest coast from Pothupitiya to Aluthgama mean grain sizes are smaller during southwest monsoon. But it is bigger from PodiInduruwa to Telwatta except for Akurala. The supply of the sediments from the rivers of the southwest mountain range is always significant in the analysis of the beach and nearshore of the southwest region. The west coast is supported by the sediments from rivers but normal impacts can be seen along the southwest coastal region.

The mean grain sizes of the offshore samples from the south-western region are found as coarse to very coarse grain sands. Meanwhile, the result obtained at the onshore was medium size sand. Thus, the size wise correlation of both on and offshore samples is not seen.

Most of the northeast onshore samples shown medium grain sizes irrespective of the seasonal changes. However, Verugal result shows that the difference between monsoons in the coarse grain deposition. During the northeast monsoon coarse grains deposited at the 20 – 30 m distance from MSL at all the locations. This is evidence for the high energy and hindered deposition during the northeast monsoon. At the offshore samples from the Kokilai are found fine grain samples which result is also not supporting the possibility of sediment accumulation from the ocean basin in the northeast coast.

The understandings of the Robert L. Weigel, (Wiegel, 1964) from his study matches with the findings of the Verugal northeast coast for the relationship between mean grain size, beach face slope and energy of the beach. However, it does not completely comply to the southwest coast but it is true to the straight beach are off the west coast at the southwest region.

Along the Mahaweli River mean grain size has decreased with the distance from the Nawalapitiya to Trincomalee that is where the river starts and falls. Sediment transportation is along the streamline and the heavier and coarse grains will not be transported far away since the energy of the stream generally decreases towards the sea. Hence, smaller or lighter grains travel long distances and get deposited in between or at the ocean basin. However, in the locations of Randenigala, Minipe and Mahiyanganaya grain sizes are bigger than the trend and those three locations showed very coarse grains. Uma Oya, Badulu Oya and Loggal Oya are the three channels joints with Mahaweli at those sampled locations respectively. Therefore Mahaweli River accumulates sediment from many tributaries and contain mixed debris constituents. A feature of this river is that it has relatively few tributaries in its lower reaches, whereas many tributaries are found in its upper reaches. (Young, 2013). Hence those rivers input might cause the grain size difference in those samples. The medium grain size of the Mahaweli River samples near the coast has a match with the samples of Verugal onshore, suggest the possibility of the source as the Mahaweli River to the Verugal beach deposits.

5.2.2 Sorting

Sorting and mean grain size has a direct relationship. Finer grains have well sorting and will explain about the sedimentation process on the beaches. Sorting mainly depends on the grain size of the particles. Finer grains get well sorted by panning process. The result of the southwest coast during northeast monsoon has to be better sorted than southwest monsoon period. However, mean grain sizes of west coast samples are finer than south coast samples during the southwest monsoon period. Accordingly, an outcome of sorting matches with the results obtained for the mean grain size. Akurala and Payagala samples are kind of mixed and sediments and had exhibit different properties.

Considering the offshore samples of the south-western region near Beruwala area samples are moderately sorted. However, samples from Galle near shore has moderately well sorted and the north of the Gin river fall area is poor in sorting compared to the south side and the sorting is mixed up with wider range of the sorting indexes.

Sorting at the Verugal has no any anomalies and are moderately well sorted which are mostly medium grain sizes. Kokilai offshore at northeast region got very well sorted for medium grains and poorly sorted for medium and coarse grains.

The textural relationships between offshore and onshore samples could not found for the southwest region but it has the link to the some extent at the northeast region. Meanwhile, along the Mahaweli River sediments are poorly sorted in general.

5.3 Heavy Minerals distribution of all study areas

Figure 5.5, clearly illustrates the study areas all over the Island and the sampling points. Results show the heavy mineral potential of the northeastern coast was high (average about 45-55% in the Verugal and 70-85% in the Pulmoddai deposits and

3.5-5.0% in the offshore samples from Nilaveli to Kokkilai), compared to the southwestern sediments (average about 10% in onshore and 2% in offshore Gin River mouth). Therefore, no large economic-grade heavy mineral placers have been discovered by offshore investigations. However, it may be possible to occur concentrated heavy minerals in paleo-river channels that were developed due to glacioeustatic sea-level changes. Observed high concentrated heavy minerals in beach and low concentrated offshore sediments suggest the panning system in the surf zone to form enriched placer deposits.

Microscopic observations of the heavy mineral fractions show that Ilmenite, Zircon, Garnet, Monazite and Rutile were the most abundant heavy minerals in the shelf and beach sediments of the northeast and southwest coasts of Sri Lanka (Fig. 5.6). The total heavy mineral distribution is remarkably high in the surface (average = 66.3 %) and bottom sediments (i.e., depth > 0.3 m, average = 46.8 %) in the onshore Verugal deposit of the northeast coast (Fig. 5.6). The lightweight constituents such as Quartz grains might wash back to the ocean during the panning process led to a higher amount of heavies in the surface samples. The total heavy mineral content of surface samples after northeast monsoon revealed the 46.49 % which is very closer value to the deep sediment samples of previous field study. In the course of the northeast monsoon, the coast is eroded and the surface sediments washed back to sea. Therefore, the second field surface samples are identical to the previous field deep samples. The beach slope is also validating the above result by indicating gentle slope after the northeast monsoon. The results show that the Verugal deposit is mainly composed of Ilmenite (average = 48.0% in bottom sediments and average = 47.6% in surface sediments). The average compositions of Zircon and Garnet vary between 17.71-15.43% and 11.77-12.55% in the bottom (depth > 0.3 m) and surface (depth < 0.3 m) sediments of the onshore Verugal deposit, respectively.

The Pulmoddai beach in the northeast coast (Fig. 5.5) has been well-known as the high purity and economically important placer deposit as far back as the early 19th century. This deposit has been exploited economically since 1957 (Herath, 1980; Lanka Mineral Sand Ltd., 1999). The total heavy mineral percentages reached the maximum value of 95% in the southern part of the Pulmoddai deposit with an average of about 70-85%. The approximate compositions of Ilmenite, Rutile and

Zircon in the Pulmoddai deposit are 70-80%, 8-12% and 8-10%, respectively (Herath, 1980; Ismail et al., 1983).

The total heavy mineral percentages are relatively low in the southwest onshore (average = 10.7%) and offshore (average = 2.2% in the Gin River and absent in the Bentota River mouth) sediments compared to the Verugal deposit (Fig. 5.6). Similarly, Ilmenite can be recognized as the dominant heavy mineral in the southwest onshore (average = 62.2%) and offshore Gin River mouth (average = 60.7%) sediments. Figure 5.6 shows that Zircon is the second abundant mineral in these samples (average = 17.3% in the southwest onshore and average = 20.2% in offshore Gin River mouth sediments). In contrast, Wickremeratne (1986) reported about 4-13% of heavy minerals in the Bentota River offshore area. However, the present offshore investigation in the Bentota River mouth area showed that no considerable amount of heavy minerals was recorded for economically feasible exploration.

The accumulation of total heavy mineral percentages are noticeably low (average = <2%) along the Mahaweli River (Fig. 5.6). However, the total heavy mineral percentages are remarkably enhanced (average = 16.1%) in the Mahaweli River sediments closed to the northeast shore (Fig. 5.6). The results show that the upper watershed of the Mahaweli River produces flushing of heavy minerals, and thus deposited in the downstream close to the shore. This trend can probably suggest maturation of sediments during transportation along the Mahaweli River. However, the tides can also bring some amount of concentrated beach pan heavy minerals along the estuarine part of the river.

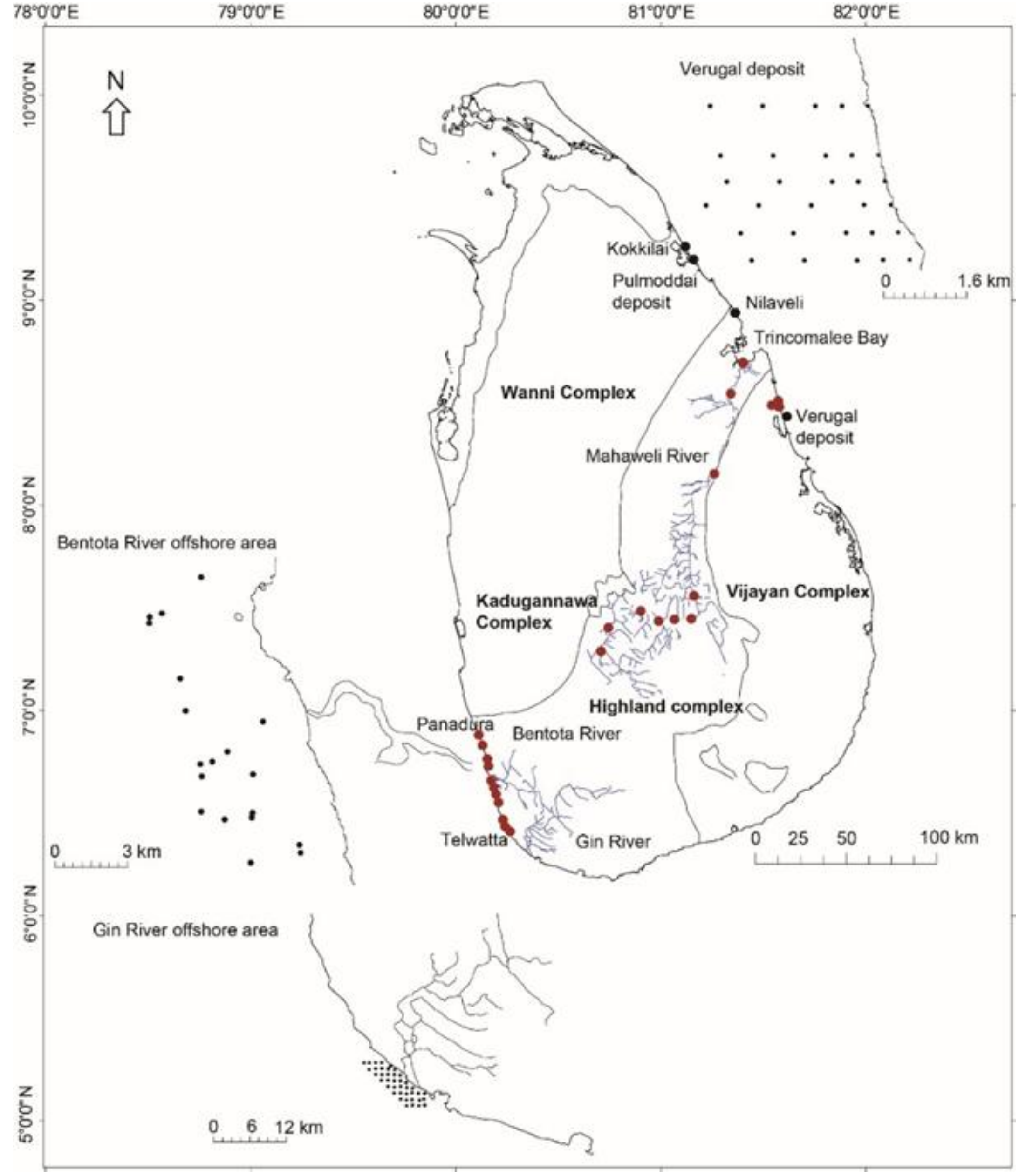


Figure 5.5: Sampling points of all the regions of the research study of Sri Lanka

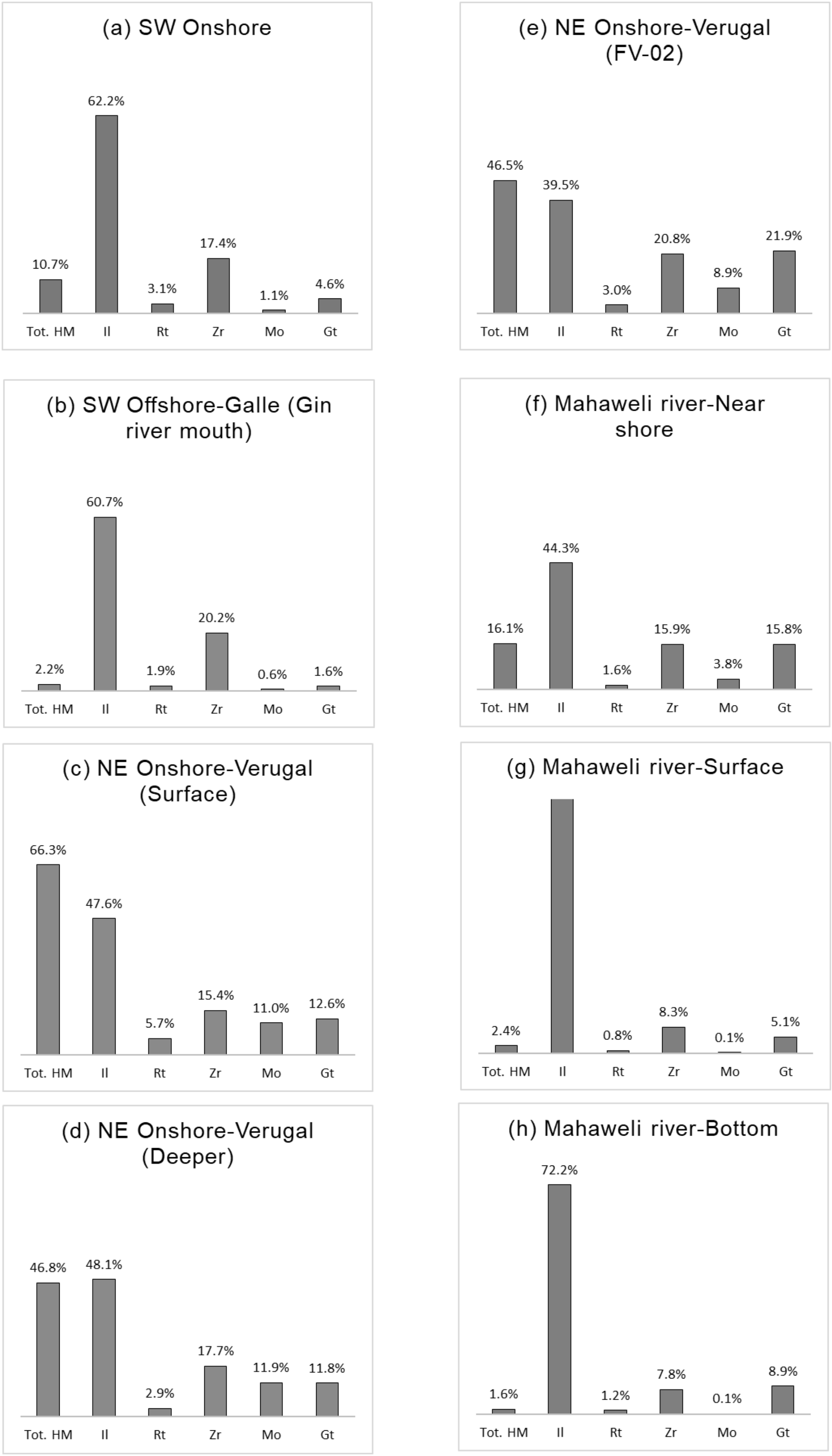


Figure 5.6: Heavy mineral composition of all study regions

5.4 Analysis to find the possible source of northeast deposits

The economically important deposit discovered in Verugal area and the source of the deposit became important to identify for enhancing the exploitation of the deposit. Therefore, the possible sources of northeast coast deposits are identified as follows;

Potential sources for the North East region deposit;

- from the country's mountain ranges via rivers (Yan oya/ Mahaweli river/ Verugal aru)
- from the ocean basin or
- from India through the continental shelf by the currents

A total of 35 sediment samples were collected along Mahaweli River (Fig 5.7) and Verugal Aru (Fig 5.9) (last branch of Mahaweli River) and from the Verugal (Fig 5.9) and Pulmoddai deposits (Fig 5.8). Among them, 12 samples along the Mahaweli River, 11 samples along the Verugal River, nine samples from the Verugal deposit and three samples from the Pulmoddai deposit were taken. All samples are subjected to textural and mineralogical properties in the way to find any correlation among them.

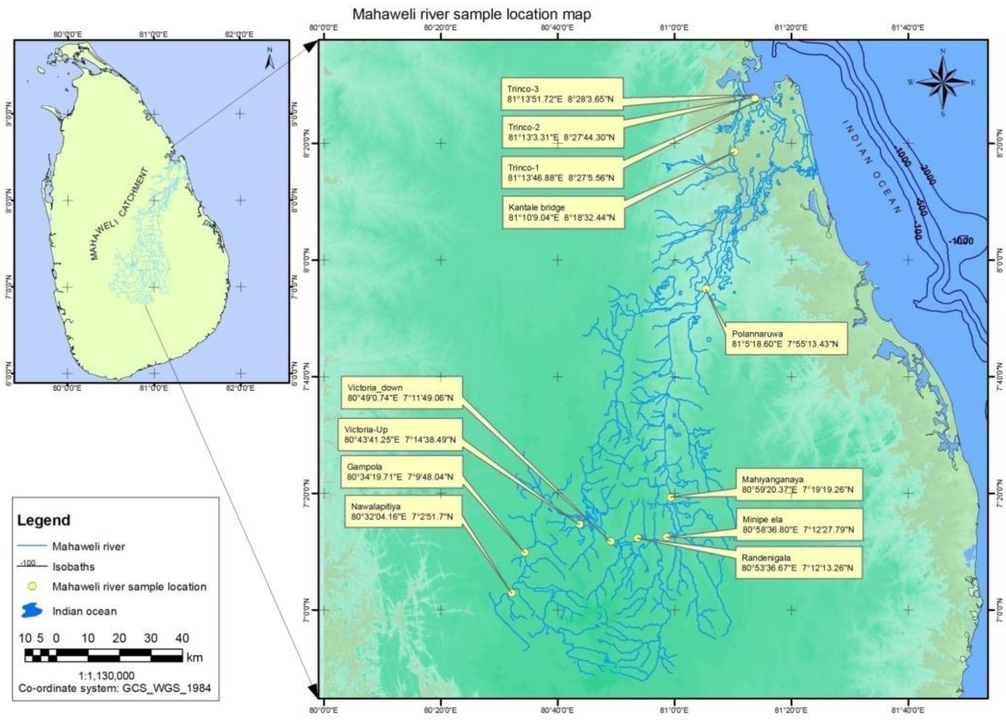


Figure 5.7: Sampling locations along Mahaweli River

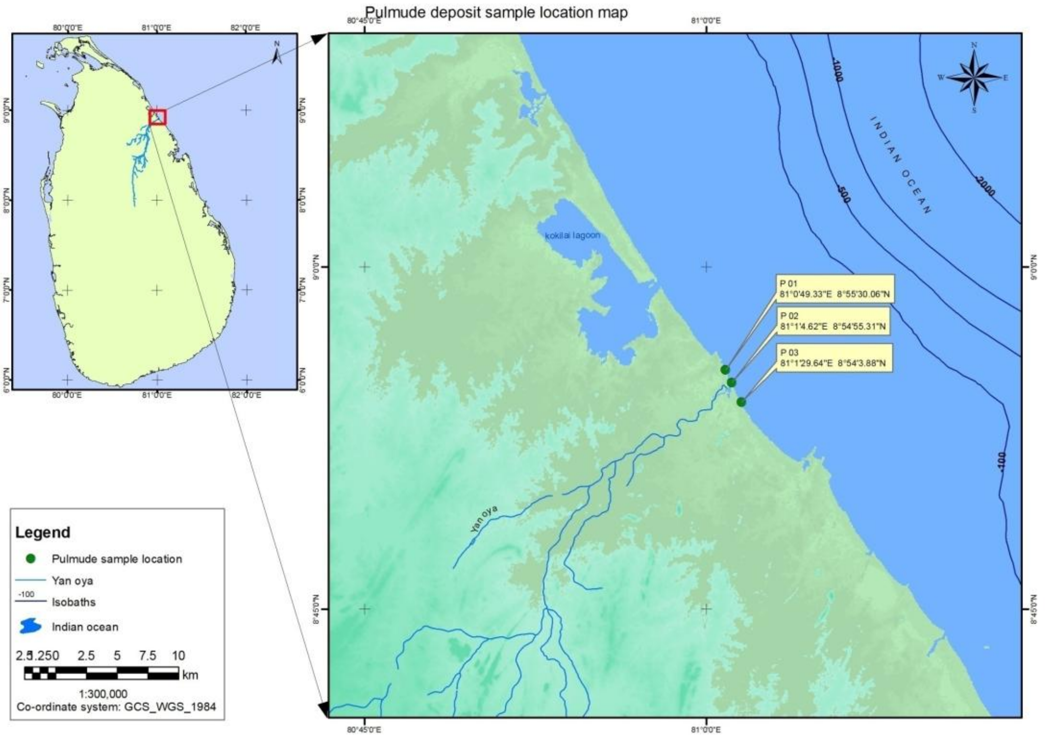


Figure 5.8: Sampled locations at Pulmoddai

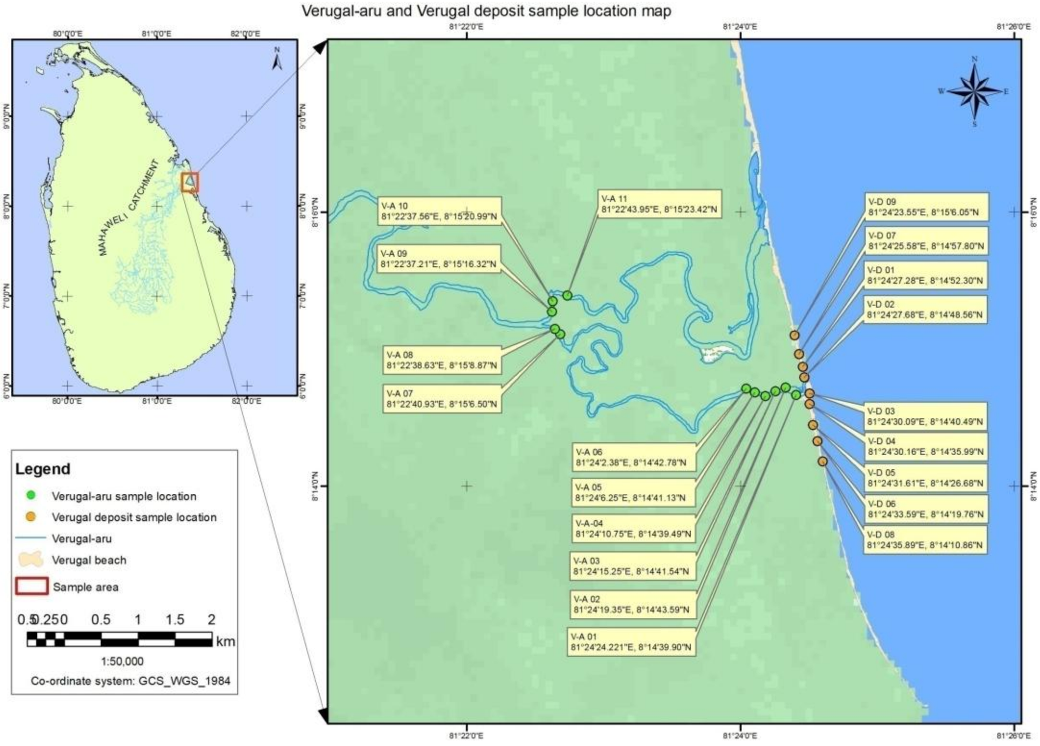


Figure 5.9: Sampled locations of Verugal Aru and Verugal deposit

The well known Pulmoddai deposit is the richest in the world and largest of the Island located 54 km north to the Trincomalee. Recently identified Verugal deposit at Verugal river mouth located 50 km south of the Trincomlee. Those deposits are looking different in their appearance of colour. It is observed that Pulmoddai is very black while it is pink at Verugal deposit; suggest the Ilmenite and Garnet predominant occurrence in those beaches respectively (Fig 5.10).

Figure 5.10: Beaches of Verugal and Pulmoddai

Textural analysis of both deposits is given below. Verugal deposits are a medium grain (Fig 5.11) and Pulmoddai (Fig 5.12) are fine grain samples. Meanwhile, moderately well sorted Pulmoddai samples are not like Verugal moderately sorted samples. Both properties are not matching to both deposits.

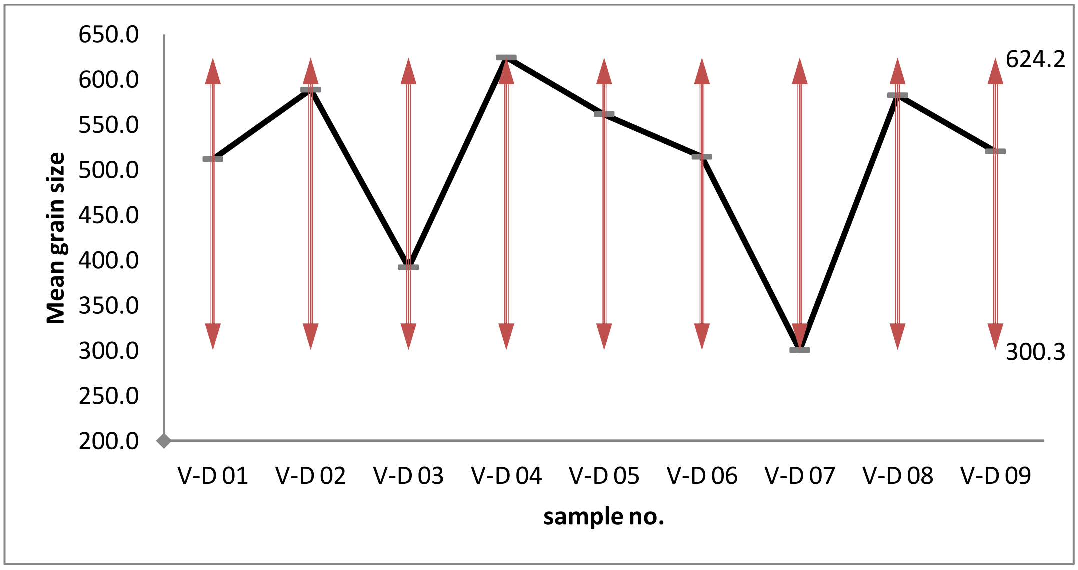


Figure 5.11: Mean grain size of the Verugal deposit

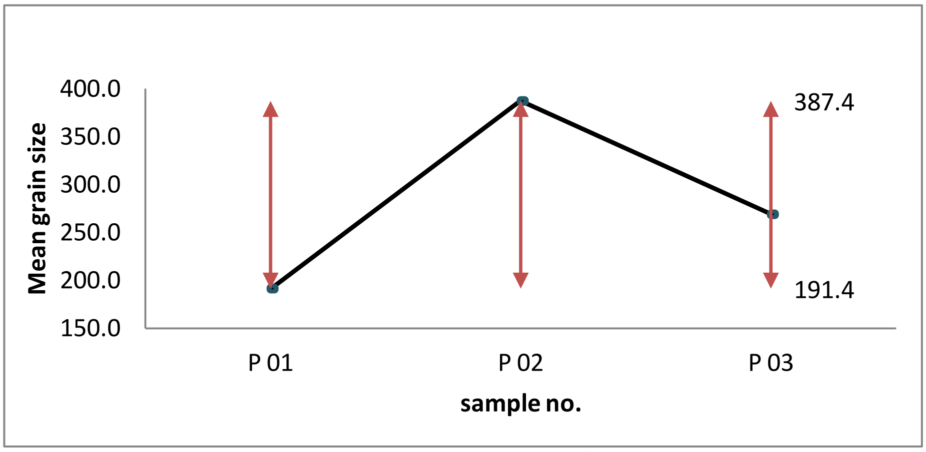
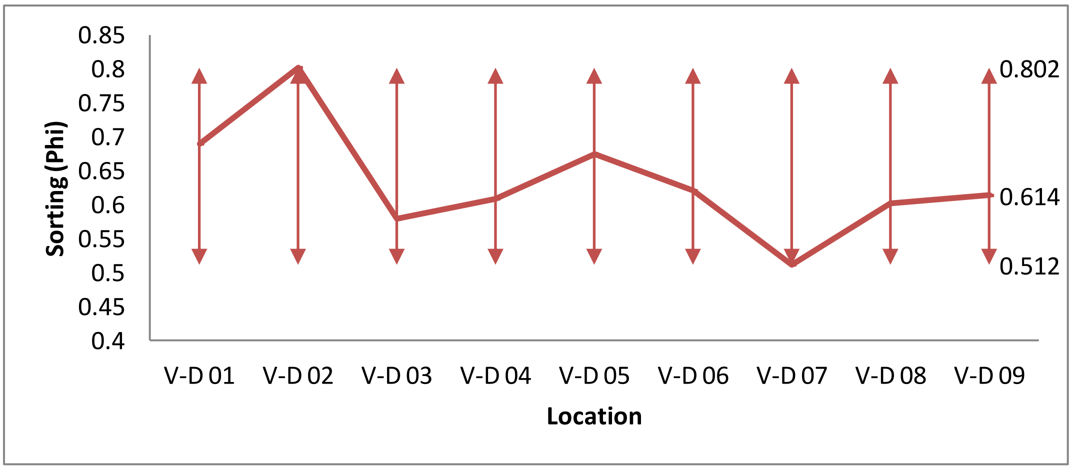


Figure 5.12: Mean grain size of the Pulomoddai deposit

Mean grain sizes of the Verugal and Pulmoddai are much different from each other is given in the figures 5.11 and Figure 5.12, respectively. Sorting indexes are showing similar variations to both deposits clearly illustrated in Figure 5.13 and Figure 5.14.

Figure 5.13: Sorting of Verugal deposit



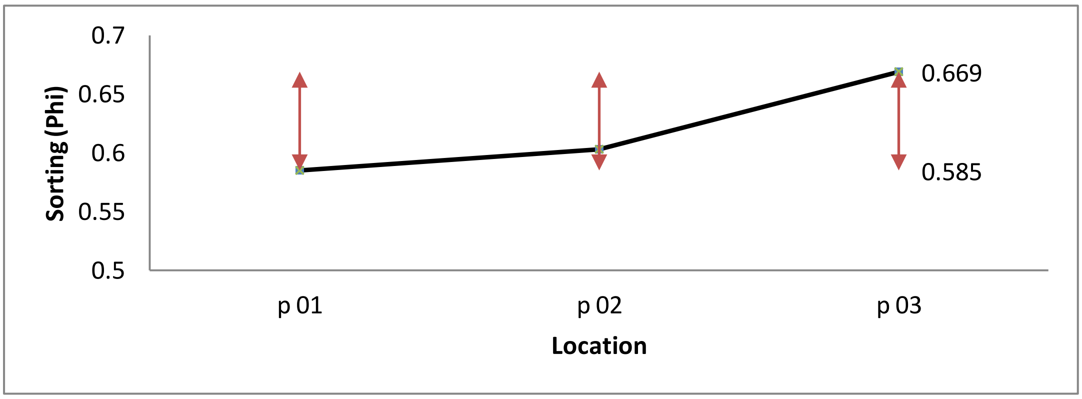


Figure 5.14: Sorting of Pulmoddai deposit

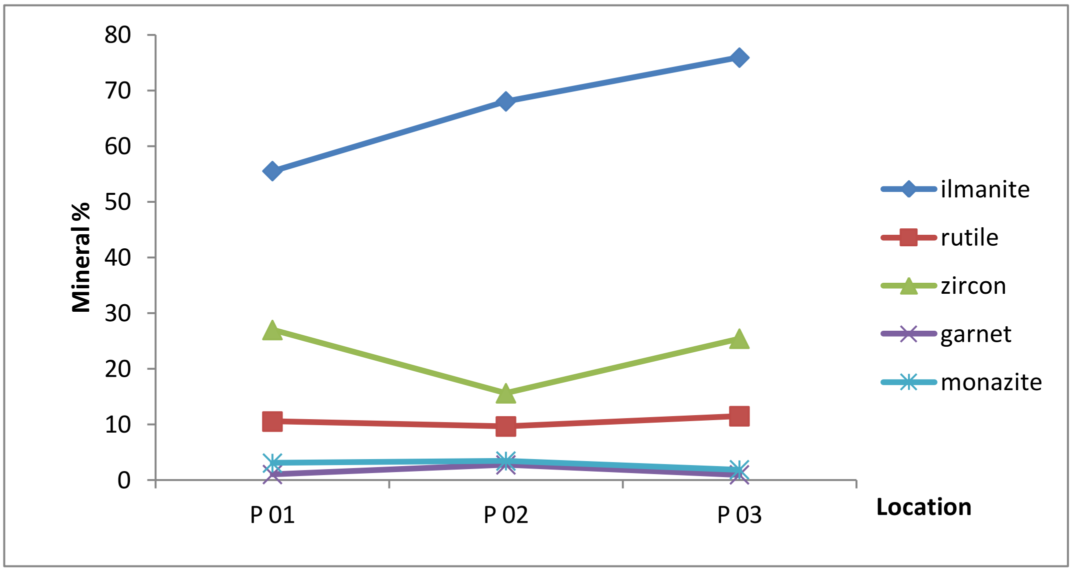


Figure 5.15: Heavy mineral composition at Pulmoddai deposit

Further to the textural analysis, mineral compositions of those two deposits are analysed and given on Figure 5.15. Pulmoddai deposit contains Ilmenite as the highest component with 60 – 80 % and Zircon as a second abundance with 20 – 30 % of total heavies. But, the Verugal deposit also has Ilmenite abundantly but contains of 40 – 50 % and Garnet as the second most composition with 10 – 20 % of total heavy minerals. The comparison of this result is given in figure 5.16. It clearly illustrates the difference between those two deposits in the northeast coast by the mineralogical data.

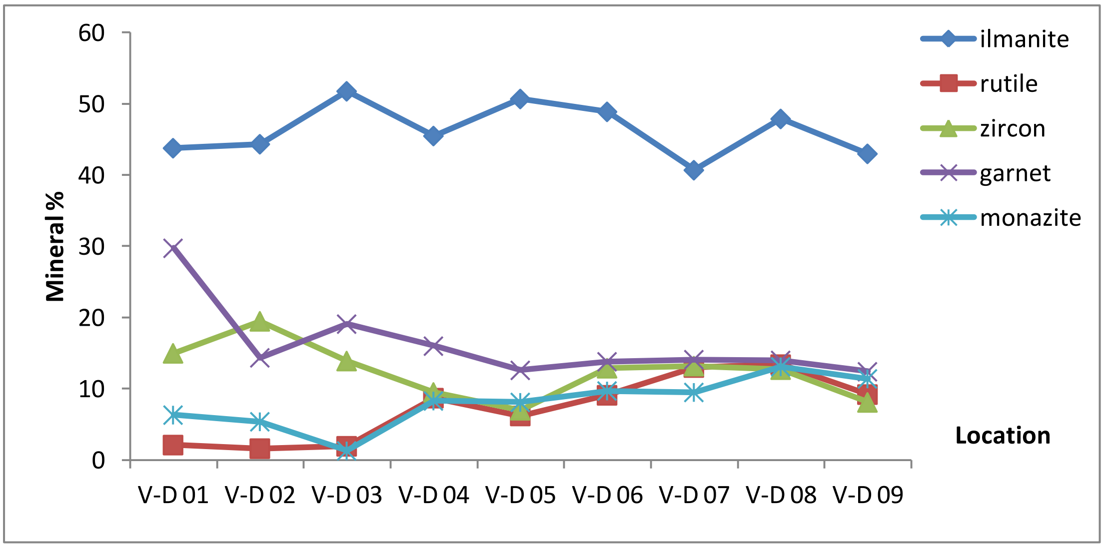


Figure 5.16: Heavy mineral composition at Verugal deposit

Comparison of average mineralogical data of source with deposit is important to understand the provenance of the deposit, because they have similar mineralogical assemblages (Ravindra Kumar and Sreejith, 2010). The below figures are showing the comparison of the samples to understand the provenance of the identified deposits. Figure 5.17, illustrates the comparison of the Mahaweli River, Verugal River and Verugal deposit samples for the mineral compositions. It is clear that those three collections of samples contain the exactly the same composition of analysed heavy minerals. The Verugal Aru is the last branch of Mahaweli River and it contains the same sediments of the Mahaweli River and the deposit on the coast of the Verugal demonstrates the same composition. However, the comparison given on the figure 5.18, for the Pulmoddai deposit and Mahaweli River (can be considered for Verugal deposit and Verugal Aru) prove the mismatch of both deposits by varying in the mineral composition dominantly by the change of concentration of Zircon and Garnet as the second abundant in the respective deposits. Therefore, it can be explained that the Verugal deposit has the source as the mountain range of the country and the sediments are being transported by the Mahaweli River but further to that, Pulmoddai deposit is not only by the Mahaweli River and subjected to any other sources as well. The finer grains of Pulmoddai deposit suggest that those grains should traveled far away from the source compared to transportation by Mahaweli River hence, the sediment supply from Indian mountain ranges and transported by the longshore current over the continental shelf. According to (Jayawardena, 2014) and our results the Pulmoddai sedimentation is not only replenished by the Mahaweli but also with the sediment transportation from the Indian continent.

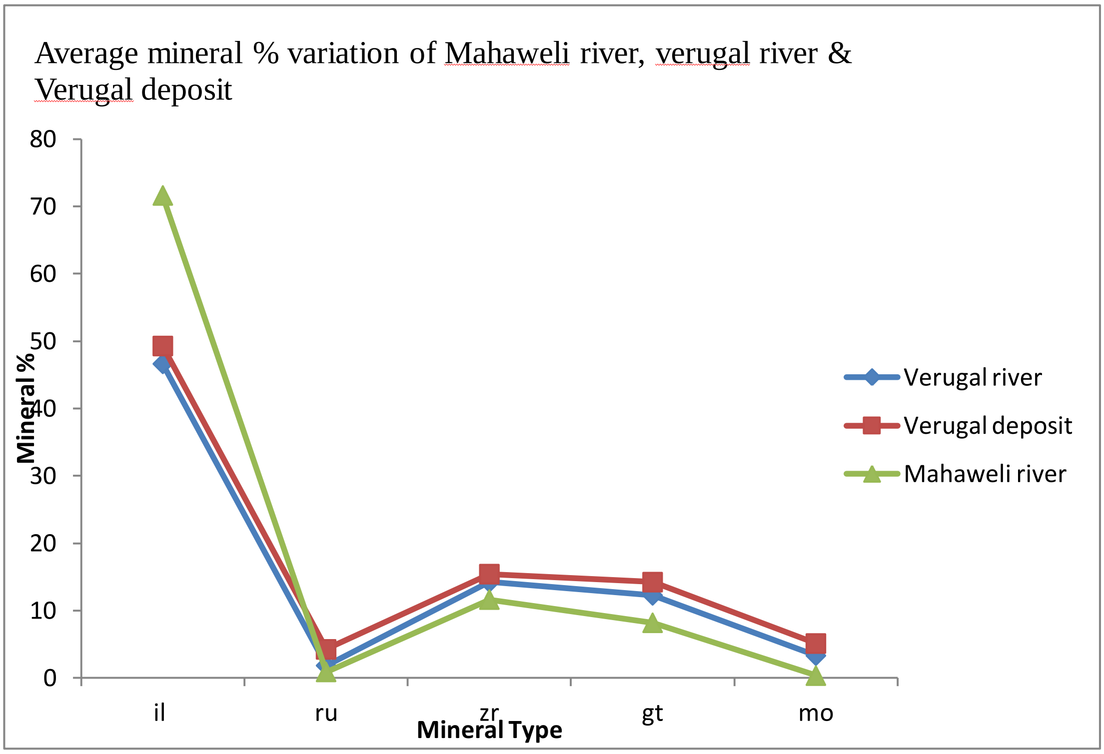


Figure 5.17: Heavy mineral composition of the Verugal Aru, Verugal deposit and Mahaweli River

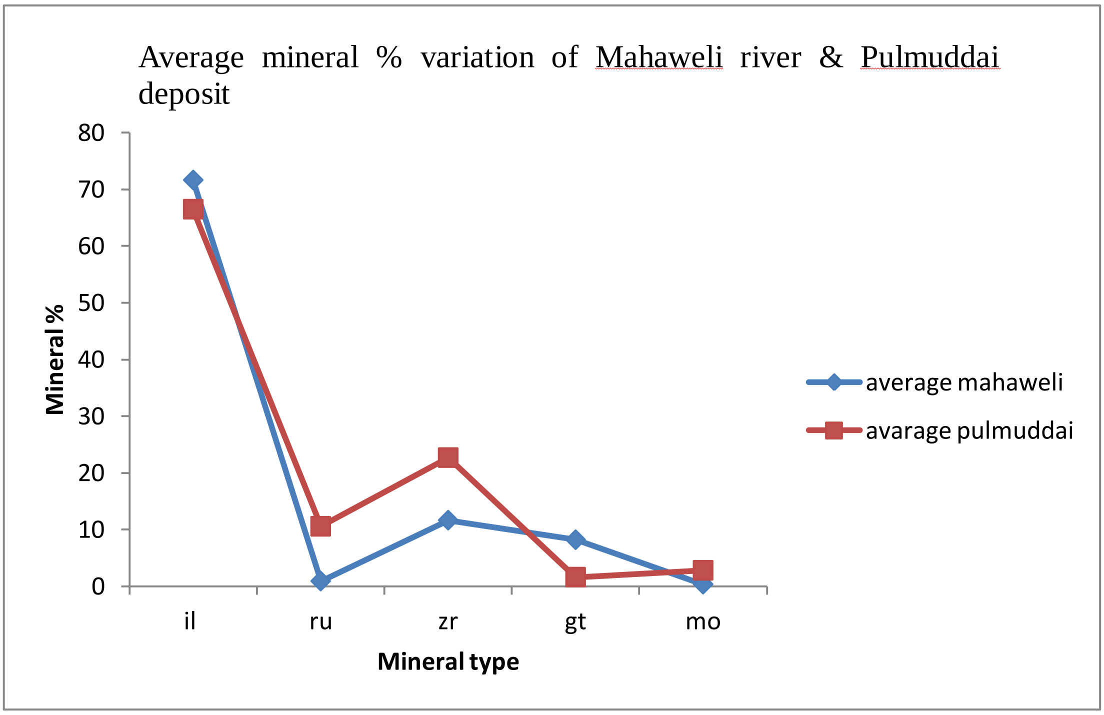


Figure 5.18: Comparison of heavy mineral composition of the Mahaweli River and Pulmoddai deposit

5.5 Exploitation of Deposits

The potential deposits estimated and developed the mine plan with studied results such as beach width, beach slope, seasonal replenishment pattern and heavy mineral association textural properties.

5.5.1 Ore reserve estimation

The mineral quantification of Verukal deposition was carried out with the results obtained at laboratory analysis. The weight of total heavy mineral sand and volumes of dominant mineral sands are considered in the calculation. Triangle method was used for the estimation. Figure 5.19 shows the method used to quantify the resource.

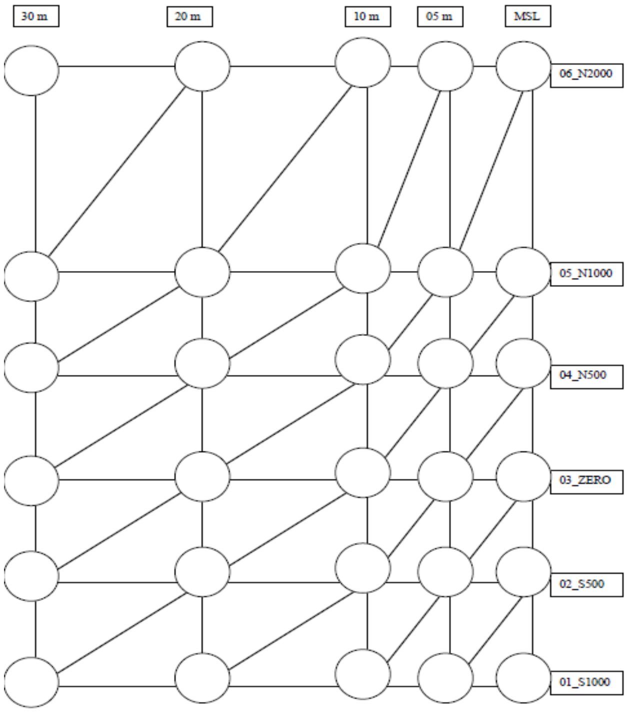


Figure 5.19: Triangle method for reserve estimation

The below-given table 5.1 shows the quantities of interested heavy minerals and their percentage changes with seasons.

Table 5.1: Mineral sand estimation of Verugal deposit

Estimated Reserve in m^3				
	After NE monsoon (FV 01)			**During NE monsoon (FV 02)**
	0.3 m depth	**0.7 m depth**	**1.0 m depth**	
Ilmenite	13,051	14,426	10,935	10,207
Garnet	3,265	3,281	2,714	6,525
Monazite	2,976	4,042	2,225	2,245
Zircon	4,397	5,286	4,017	5,705
Rutile	1,263	952	643	1,005
Total HM	16,909	15,142	9,736	12,385
Estimated Reserve in percent				
	After NE monsoon (FV 01)			**During NE monsoon (FV 02)**
	0.3 m depth	**0.7 m depth**	**1.0 m depth**	
Ilmenite	48	48	49	38
Garnet	12	11	12	24
Monazite	11	13	10	8
Zircon	16	18	18	21
Rutile	5	3	3	4
Total HM	63	50	43	46

Cut-off grade

The cut-off grade is the breakeven point, where gain not profit nor loss. However, this grade will be changed over time during the project as the fluctuation of cost of operation and the cost of the mineral vary in the local and world market. The cutoff grade used for any reserve calculation should always be stated and for the Verugal deposit, the concentration is well above such grade.

5.5.2 Mine plan

Mining process should consider the seasonal impacts and beach profile. The period at which the mining process shall do is determined with the understanding of seasonal replenishment pattern of the studied area of Verugal. It was learned during the northeast monsoon period beach is subjected to heavy erosion and the mineral content also decreased hence, it should not be mined during that period. During the southwest monsoon period from May to September is ideal for mining. This period is after the first inter-monsoon when river flow is high and should after beach is set to a dynamic equilibrium. The beach can be mined up to 45 m shoreward from MSL. Beach erosion of 15 m was observed during northeast monsoon and the samples collected at 30 m distance are equal to 45 m distance during the calm period of the beach. With the understanding of mineral concentration pattern, it is possible to mine to 60 m distance (Fig 5.20).

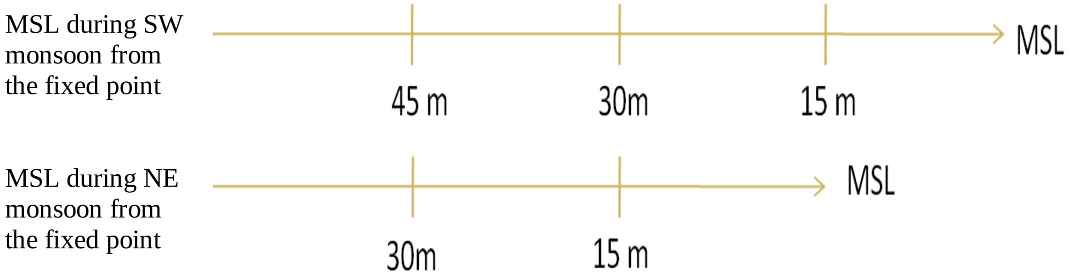


Figure 5.20: Beach width variation during the monsoon changes for mining

However, angle to be maintained and relevant depth we may mine are interdependent. Keeping the beach without destroying it and prevent vigorous erosion soon after mining the area, is vital to facilitate the natural accretion. Therefore, the slope during the southwest monsoon is in natural equilibrium and it was recorded the slope is 5 degrees during the northeast monsoon. Hence, scrapping the beach by keeping the same slope of 5 degrees is recommended (Fig 5.21).

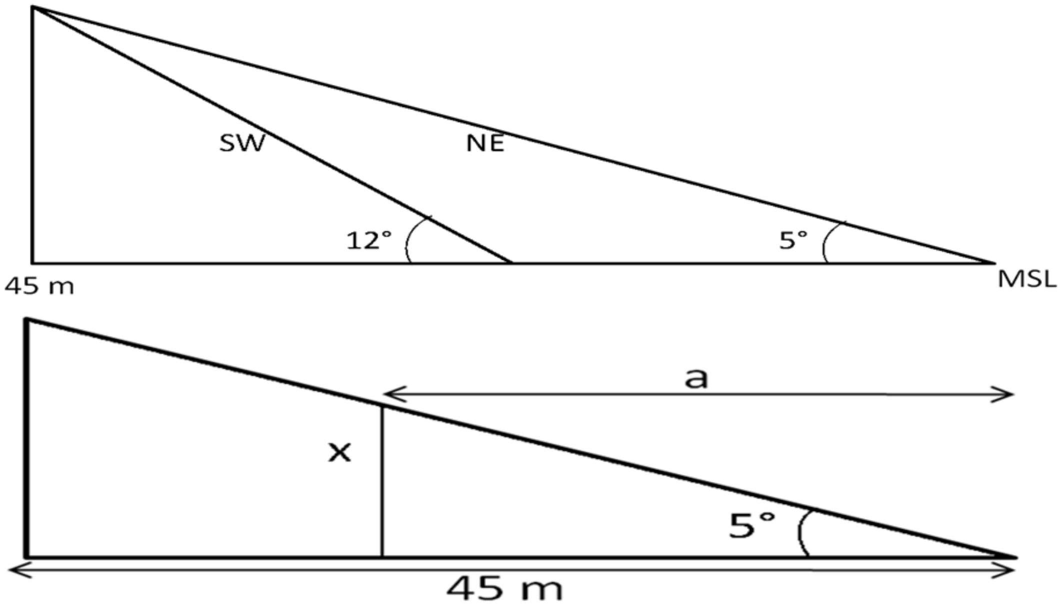


Figure 5.21: Beach slope during monsoon periods and diagram for calculation of mining depths with the distance

Table 5.2: Mining depth with the distance from the MSL

Distance from MSL	Depth for mining [x = a tan(5º)] in meters
45 m	3.94
30 m	2.62
20 m	1.75
10 m	0.87
05 m	0.44

The calculation of mining depths with the distance from MSL is given in Table 5.2. Now it is decided at what extent in distance and depth to be mined, but this deposit is 3 km in length. Beginning the mining from the north end and finish it at the south end is recommended while doing the same seaward direction. This movement will facilitate beach development for 60-meter distance naturally. Thus, sediment coming from the Verugal River flow down to the south and get deposited continuously at the north end of deposit while mining the south side. Further, seaward direction help to prevent seawater intrusion to shoreward until breakthrough closest sand to be mined and also will allow the panning process to happen up to 45-meter distance deposit the heavy minerals.

This deposit can be mined either by stripping or slurry mining method. Stripping can be done by the large machineries such as excavators to mine seam of mineral. Bucket wheel excavators can scrap up to 12,000 m^3 of material in an hour and can be opearated to the depth of 400 feet deeper. But this method is used where the depth of the deposit is relatively shallow. Area stripping can be used where the deposit on the flat terrain and for large area to be mined. The possibility to dump the vegetation to the previous strip will enhance the resettlement of the mine site as early as possible.

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

This research focused on identification of the distribution of the heavy mineral sand in the southwest and northeast onshore and offshore regions of Sri Lanka. Accordingly, it was found that the existence of the heavy minerals in the south-western is lesser than north-eastern, but both regions are subjected to the monsoon changes for the occurrences and replenishment. Comparison with the demand in the world market for heavy minerals suggests the economic feasibility of the southwest onshore region and north-eastern deposits and this research focused to the Verugal deposit as it was found higher concentration among the study areas. Research outcome of the Mahaweli River given the constructive identification of the provenance to the Verugal deposit and was used for the mine plan at the Verugal deposit. Finally, research outcomes are very effective and the objectives of the research were reached successfully.

6.2 Recommendations

This research can be expanded by collecting data for more duration and analysing with more parameters therefore to, more precisely find and quantify the reserves or potential of the resources. Further, comprising oceanography and economical aspects along with high tech instrumentation for the analysis is highly recommended.

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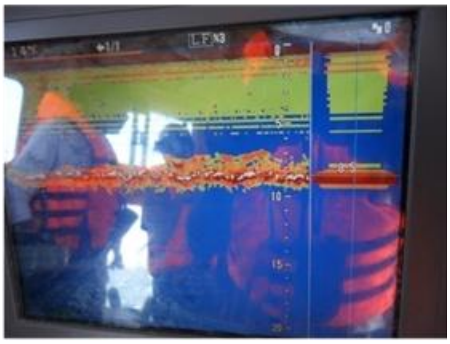
Annexure 1 Sampling at Offshore



Annexure 2 Geographical Coordinates of Sampled Locations- Galle

No. of Samples	Name	N / Y / Latitude	E / X / Longitude
1	A1	6º 00.910'	80º 12.306'
2	A2	6º 00.885'	80º 11.788'
3	A3	6º 00.917'	80º 11.222'
4	A4	6º 00.887'	80º 10.696'
5	B1	6º 01.462'	80º 12.239'
6	B2	6º 01.369'	80º 11.837'
7	B3	6º 01.435'	80º 12.184'
8	B4	6º 01.388'	80º 10.669'
9	B5	6º 01.460'	80º 10.155'
10	C1	6º 01.969'	80º 12.304'
11	C2	6º 01.954'	80º 11.746'
12	C3	6º 02.041'	80º 11.184'
13	C4	6º 01.947'	80º 10.680'
14	C5	6º 01.993'	80º 10.145'
15	C6	6º 01.984'	80º 09.577'
16	D1	6º 02.416'	80º 11.223'
17	D2	6º 02.486'	80º 10.716'
18	D3	6º 02.572'	80º 10.155'
19	D4	6º 02.526'	80º 09.594'
20	D5	6º 02.592'	80º 09.032'
21	E1	6º 02.934'	80º 10.648'
22	E2	6º 03.100'	80º 10.136'
23	E3	6º 03.088'	80º 09.581'
24	E4	6º 03.149'	80º 09.023'
25	E5	6º 03.120'	80º 08.438'
26	F1	6º 03.602'	80º 10.122'
27	F2	6º 03.656'	80º 09.598'
28	F3	6º 03.681'	80º 09.033'
29	F4	6º 03.630'	80º 08.497'
30	F5	6º 03.673'	80º 07.933'
31	G1	6º 04.103'	80º 09.634'
32	G2	6º 04.137'	80º 09.061'
33	G3	6º 04.220'	80º 08.481'
34	G4	6º 04.193'	80º 07.921'
35	G5	6º 04.129'	80º 07.354'
36	H1	6º 04.405'	80º 09.242'
37	H2	6º 04.713'	80º 08.474'
38	H3	6º 04.720'	80º 07.924'
39	H4	6º 04.708'	80º 07.375'
40	H5	6º 04.709'	80º 06.891'

Annexure 3 Geographical Coordinates of Sampled *Locations- Beruwala*

No. of Samples	Name	N / Y / Latitude (Decimal degrees)	E / X / Longitude (Decimal degrees)
1	A1	6.4765	79.9572
2	A2	6.4769	79.9518
3	A3	6.47617	79.9462
4	A4	6.47767	79.9372
5	A5	6.47617	79.9285
6	B2	6.467	79.9277
7	B3	6.46683	79.9368
8	B4	6.4665	79.9463
9	B5	6.467	79.955
10	B6	6.4665	79.9637
11	C1	6.45817	79.964
12	C2	6.45817	79.9557
13	C3	6.4585	79.9472
14	C4	6.45867	79.9375
15	C5	6.45783	79.9282
16	D1	6.44983	79.928
17	D2	6.44967	79.9377
18	D3	6.4495	79.9479
19	D4	6.44967	79.9553
20	D5	6.4495	79.9645
21	E1	6.44133	79.9728
22	E2	6.4405	79.9607
23	E3	6.44033	79.9553
24	E4	6.44067	79.9472
25	F2	6.432	79.9468
26	F3	6.43183	79.9555
27	F4	6.43133	79.9642
28	F5	6.43217	79.9737
29	G1	6.423	79.9815
30	G2	6.42317	79.9728
31	G3	6.42433	79.9628
32	G4	6.42483	79.9542
33	G5	6.424	79.9428
34	H1	6.4145	79.946
35	H2	6.41483	79.9548
36	H3	6.414	79.9648
37	H4	6.415	79.9735

38	H5	6.41383	79.9823
39	I2	6.40733	79.9827
40	I3	6.40817	79.9717
41	I4	6.406	79.9643
42	I5	6.40617	79.9555
43	I6	6.40567	79.9462
44	J1	6.39633	79.9465
45	J2	6.396	79.9553
46	J3	6.39683	79.9647
47	J4	6.39683	79.9733
48	J5	6.3965	79.9825
49	K2	6.38833	79.9822
50	K3	6.38783	79.9735
51	K4	6.38833	79.9645
52	K5	6.38783	79.9555
53	K6	6.38867	79.9463
54	L1	6.38083	79.9563
55	L2	6.38067	79.9643
56	L3	6.38067	79.9737
57	L4	6.38083	79.9823
58	L5	6.38	79.9918
59	M1	6.3715	80
60	M2	6.37233	79.9915
61	M3	6.373	79.982
62	M4	6.3735	79.9735
63	M5	6.37393	79.9638

Annexure 4 Geographical Coordinates of Sampled Locations- Kokkilai

No of Samples	**N / Y / Latitude**	**E / X / Longitude**
	(Decimal degrees)	**(Decimal degrees)**
1	8.9390	80.9995
2	8.8802	81.0365
3	8.8891	81.0305
4	8.8833	81.0348
5	8.9153	81.0159
6	8.9085	81.0189
7	8.8973	81.0250
8	8.8936	81.0349
9	8.8971	81.0340
10	8.9086	81.0303
11	8.9162	81.0270
12	8.9272	81.0232
13	8.9384	81.0167
14	8.9148	81.0178
15	8.9108	81.0198
16	8.9069	81.0219
17	8.9030	81.0238
18	8.8993	81.0257
19	8.8954	81.0281
20	8.8917	81.0304
21	8.8883	81.0328
22	8.8846	81.0356
23	8.8814	81.0383
24	8.8680	81.0525
25	8.9234	81.0143
26	8.9262	81.0127
27	8.9275	81.0126
28	8.9297	81.0111
29	8.9313	81.0102
30	8.9328	81.0095

Annexure 5: On-shore Sampling

Annexure 6 Sampled Locations Northeastern Onshore –Verukal

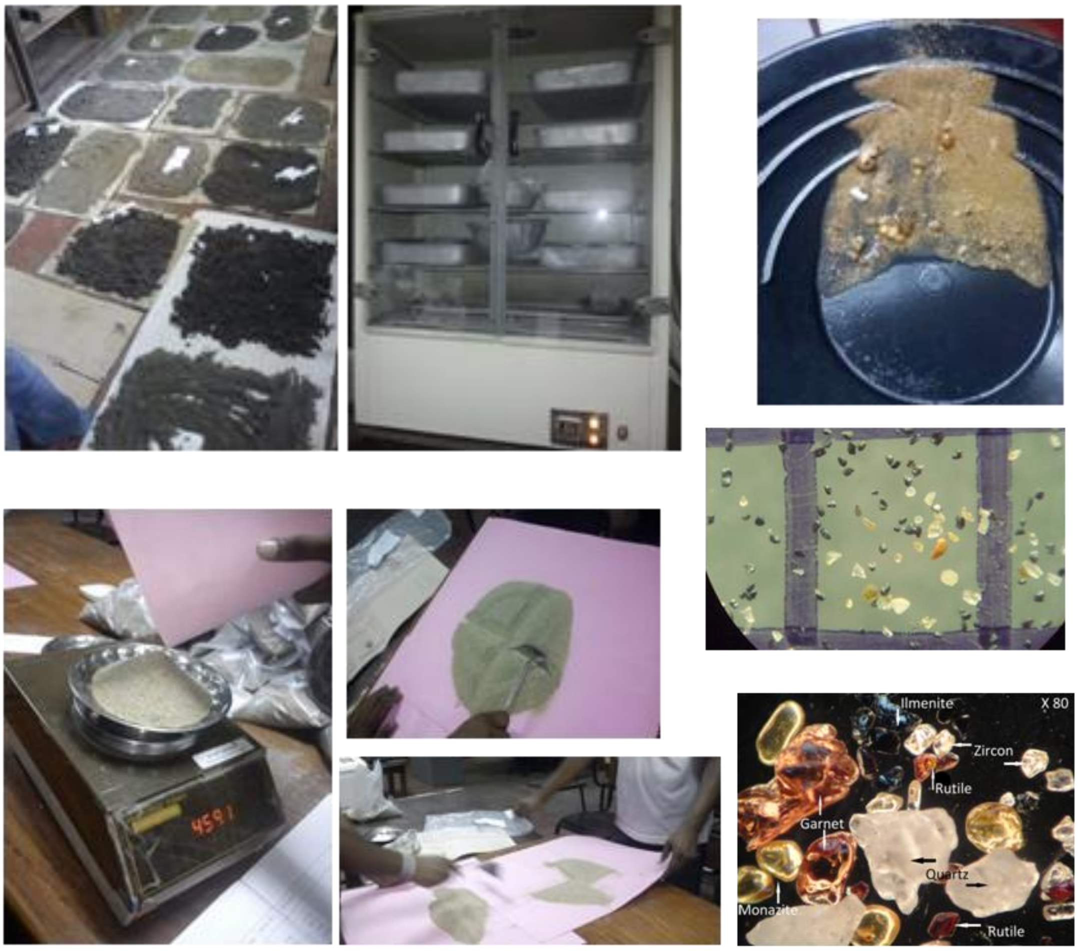
No of Samples	Name	E / X / Longitude (Decimal degrees)	N / Y / Latitude (Decimal degrees)
	VE 03	81.4128	8.2249
	5 m	81.4082	8.2249
	10 m	81.3991	8.2248
	20 m	81.3900	8.2248
	30 m	81.3809	8.2248
	VE 04	81.4118	8.2290
	5 m	81.4072	8.2289
	10 m	81.4027	8.2289
	20 m	81.3936	8.2289
	30 m	81.3845	8.2289
	VE 05	81.4107	8.2335
	5 m	81.4061	8.2335
	10 m	81.4016	8.2334
	20 m	81.3925	8.2334
	30 m	81.3834	8.2334
	VE 06	81.4089	8.2420
	5 m	81.4044	8.2420
	10 m	81.3998	8.2420
	20 m	81.3907	8.2420
	30 m	81.3816	8.2420
	VE 02	81.4141	8.2201
	5 m	81.4096	8.2201
	10 m	81.4051	8.2201
	20 m	81.3960	8.2200
	30 m	81.3869	8.2200
	VE 01	81.4161	8.2154
	5 m	81.4115	8.2154
	10 m	81.4070	8.2153
	20 m	81.3979	8.2153
	30 m	81.3888	8.2153

Annexure 7 Sampled Locations Southwestern Onshore – Panandura to Telwatte

No of Samples	**Name**	**E / X / Longitude**	**N / Y / Latitude**
		(Decimal degrees)	**(Decimal degrees)**
1	Telwatta	80.0897	6.1656
2	Kahawa	80.0736	6.1819
3	Akurala	80.0736	6.1819
4	Madampagama	80.0589	6.2139
5	Randombe	80.0586	6.2139
6	Ahungalla	80.0331	6.3081
7	Duwemodara	80.0203	6.3489
8	Maha induruwa	80.0203	6.3489
9	Podi Induruwa	80.0092	6.3811
10	Alutgama	79.9289	6.4214
11	Polkotuwa	79.9831	6.4853
12	Payagala	79.9761	6.5200
13	Kalutara	79.9789	6.5203
14	Panadura	79.9550	6.5864

Annexure 8 Beach survey

Annexure 9 Grain counting of heavy mineral sand



Annexure 10 Textural Study