INCORPORATION OF OFF-SHORE WIND POWER AS THE NEXT STEP OF NON-CONVENTIONAL RENEWABLE ENERGY IN SRI LANKA

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Degree of Master of Science

Department of Electrical Engineering

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DECLARATION

I declare that this thesis is my work and to the best of my knowledge and belief there is no any material incorporated therein previously submitted for a Degree or Diploma in any other University or institute of higher learning, without giving the proper acknowledgement to that effect. It also does not contain any material previously published or written by another person except where due acknowledgement is made in the text.

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N.H.M. Prabhath
2022/02/15

The above candidate has carried out the research for the Master thesis under my supervision.

Dr. Asanka Rodrigo Date: 2022/02/15
Supervisor

ABSTRACT

With the current increasing trend for the non-conventional renewable energy (NCRE) in Sri Lanka, interest has been focused on retiring of thermal/coal power plants and getting the energy via renewable sources.

Since almost all the water sources have been used, the available options will be wind, solar, biomass etc.

From them, wind energy is more promising as it is having less intermittency and more efficiency compared to other sources. Offshore winds are more consistent than on shore winds as well as they are higher in speeds. Considering the Sri Lankan Sea territory massive energy can be harvested via offshore wind power with no or minimum affections to peoples' lifestyle, existing inland natural beauty, relocation of people etc. compared to the onshore wind power. With being no/extremely little amount of effort required to relocate people and taking over lands, offshore wind power can be quickly implemented.

However, development of offshore wind farms around Sri Lanka should be carefully and seriously studied as it can also have negative impacts on some areas. It includes marine mammals & fish, coral reefs, migratory pathways of birds, fishing industry, tourism industry etc.

In this research a method is developed to locate suitable sites around a country for offshore wind power considering its technical, environmental, regulatory constraints. The method mentioned in this research is universal and validated on Sri Lanka. Initially the intended area of research (part of the Country's Sea territory) was divided into equal areas. Then for each area the technical, environmental and regulatory constraints were analyzed using digitized maps. Creation of digitized maps using GIS software is also a part of this research.

Then weightage factors are developed for each constraints using a model developed in this research and a total value for each area is calculated. Then the intended area of study is linked with the values table for that particular study area using a GIS software to visualize the suitable sites.

Keywords: Offshore wind power, constraints, GIS software, digitization of maps

DEDICATION

To my parents, my sister, and my beloved wife

ACKNOWLEDGEMENT

First and foremost, I would like to pay my sincere gratitude to my project supervisor Dr. Asanka Rodrigo for his continuous guidance and support throughout the research to develop the result into a fruitful outcome.

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Last but not the least, I would like to convey my sincere gratitude to my wife, parents and family members for their understanding, support in numerous ways to achieve my targets all the time.

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List of Abbreviations

SL	:	Sri Lanka
NCRE	:	Non-Conventional Renewable Energy
LTGEP	:	Long Term Generation Expansion Plan
CEB	:	Ceylon Electricity Board
USA	:	United States of America
NREL	:	National Renewable Energy Laboratory
OWF	:	Offshore Wind Farm
DFIG	:	Doubly Fed Induction Generator
UK	:	United Kingdom
UN	:	United Nations
EEZ	:	Exclusive Economic Zone
HSZ	:	High Security Zone
GIS	:	Geographical Information System
USD	:	United States Dollars
MW	:	Mega Watts
kV	:	Kilo Volts
GW	:	Giga Watts
FPSO	:	Floating Production Storage and Offloading

1. Introduction

1.1 Background

With the current increasing trend for the non-conventional renewable energy (NCRE) in Sri Lanka, interest has been focused on retiring of thermal/coal power plants and getting the energy via renewable sources.

Being a developing country Sri Lanka is still lagging.

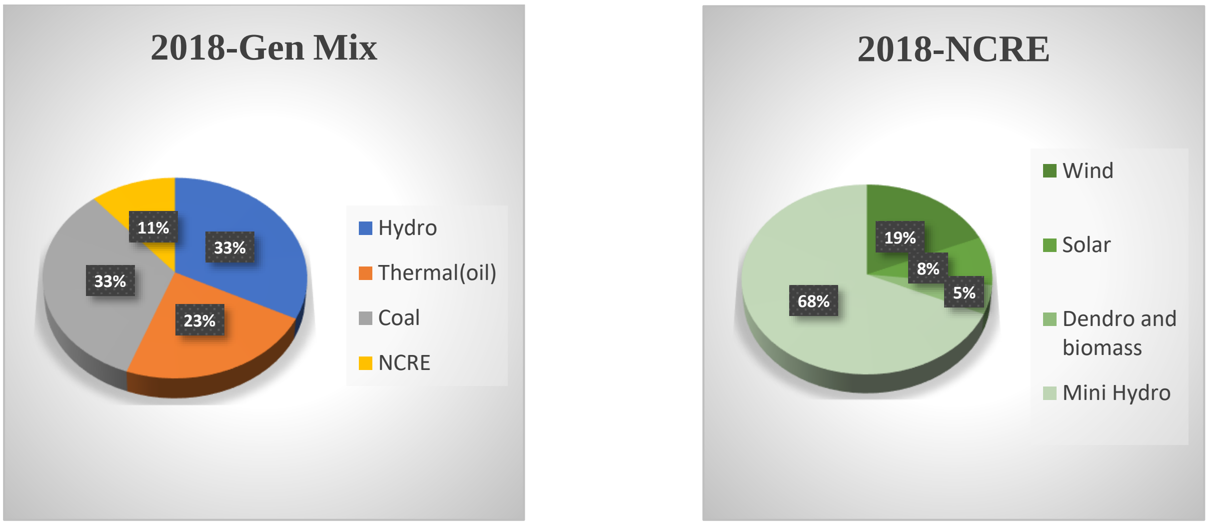


Figure 1-1 Generation Mix and NCRE contribution in Sri Lanka for 2018: Source CEB

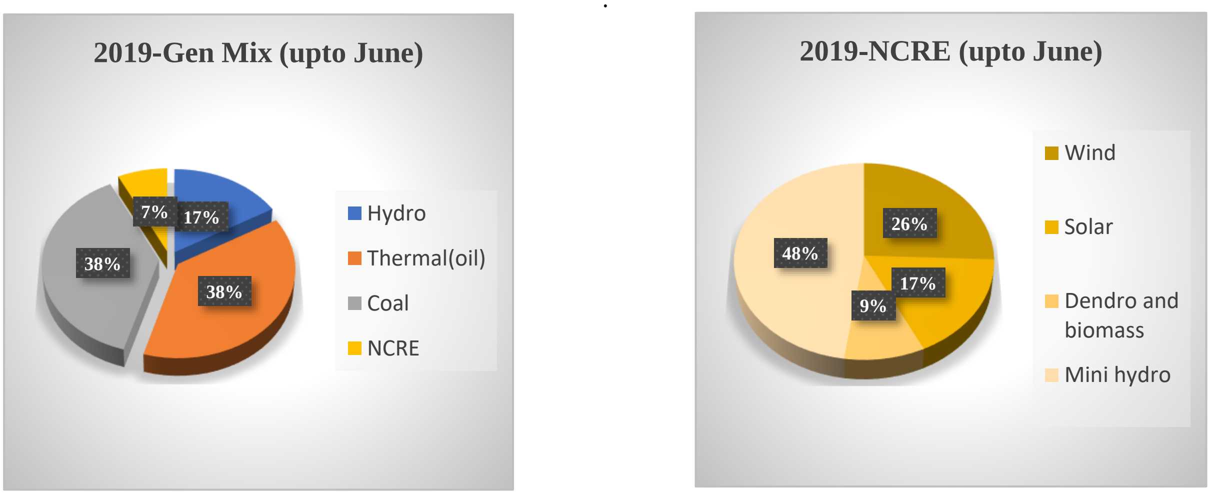


Figure 1-2 Generation Mix and NCRE contribution in Sri Lanka for 2019 (up to June): Source CEB

When considering the current non-conventional renewable energy sources in which are currently being developed in Sri Lanka, mini hydro can be categorized as most suitable source being a resource that can be used with a storage as well as a source of firm energy. But Mini hydro development consists of higher impacts to the existing natural environment as well as relocating of people sometimes. Hence development can take much time from planning stage to become a reality. Further natural beauty will be affected and there will be negative impacts from the tourism side as well when considering the monetary value to the country.

The pumped hydro is also a good option, but sites are limited and further electrical energy wise it does not generate any additional energy.

From the other available NCRE options, wind energy is more promising as it is having less intermittency and more efficiency compared to other sources. Several wind farms have already been built onshore in Sri Lanka and recent construction of Mannar Wind farm makes its contribution increased by another 100MW. However, development of onshore (inland) wind power results in sensitive issues such as taking over lands, relocation of people etc. where it is extremely difficult to solve and be agreed by everybody who are affected. So, development shall take a considerable time from planning stage to implementation.

Although onshore wind power has been taken into account while planning, there is a massive energy available at offshore which is yet to be developed/planned.

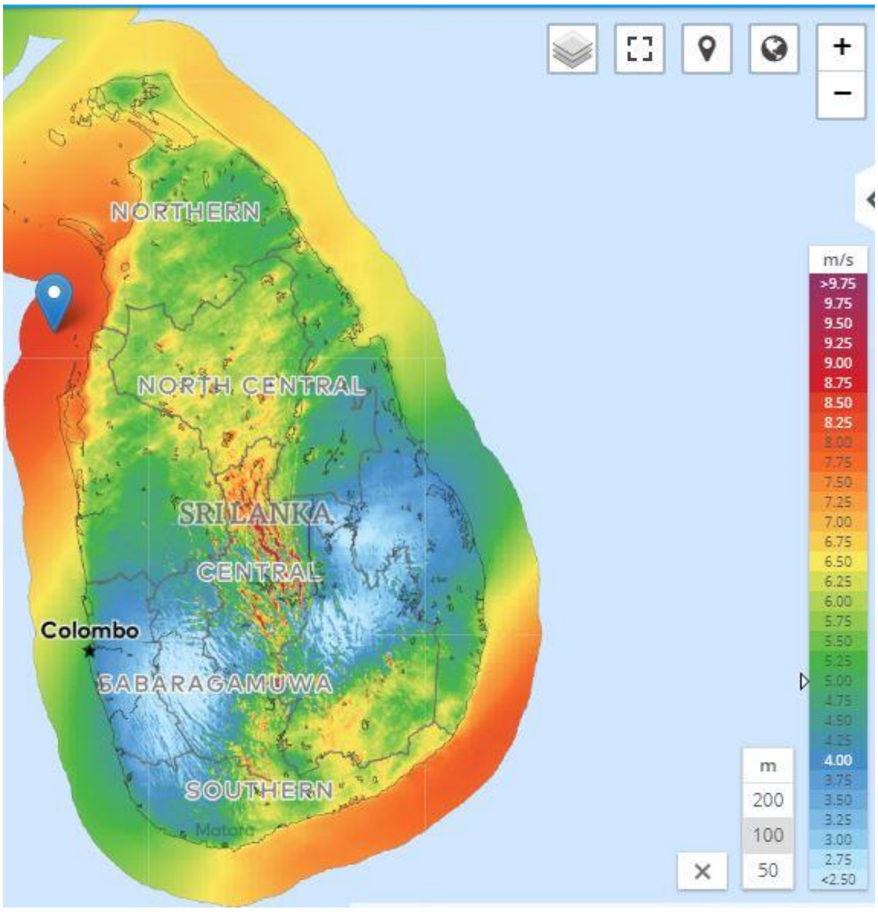


Figure 1-3 Windspeed around Sri Lanka: Source-Global Wind Atlas

Offshore winds are more consistent than on shore winds as well as they are higher in speeds. Considering the Sri Lankan Sea territory massive energy can be harvested via offshore wind power with no or minimum affections to peoples' lifestyle, existing inland natural beauty, relocation of people etc. compared to the onshore wind power.

With being no/extremely little amount of effort required to relocate people and taking over lands compared to the onshore wind power, offshore wind power can quickly be implemented. Even though some non-popular sources such as wave energy also having the same advantages when selecting the sites, most of them are not implemented/widespread around the world so those sources have drawbacks on procuring spare parts due to increased cost, expertise knowledge etc. compared to offshore wind power.

Further, being away from the shore, people will not experience flickering effects, annoying sounds from wind turbines.

Hence it will be ideal to get offshore wind power into the existing generation plan as with the developing technologies wind power farms can be operated as dispatchable plants and generators will have the possibility of supporting the system disturbances with their massive inertia. So, by default in the near future offshore wind power shall be the key to ensure a stable power system with meeting the targets of renewable energy requirements.

However, development of offshore wind farms around Sri Lanka should be carefully and seriously studied as it can have negative impacts on some areas. It includes marine mammals & fish, coral reefs, migratory pathways of birds, fishing industry, tourism industry etc.

In this research a method is developed to locate suitable sites around a country for offshore wind power considering its technical, environmental, regulatory constraints.

1.2 Research Gap

Sri Lanka Power Generation is planned by Ceylon Electricity Board for a period of 20 years called Long Term Generation Expansion Plan (LTGEP) which is renewed/revised by every 2 years. This report discusses what generating plants are to be commissioned in the future and what plants are to be retire depending on the demand forecast.

Further it also depends on the Transmission Expansion Plan which is planned for next 10 years and reviewed by every 5 years which discusses about the addition of new transmission lines, augmentation/replacement of existing lines.

Since there is a trending of increased power generation from renewable energy in the world and Sri Lanka being trying to adopting the same strategy, it is required to add more and more energy from renewable sources while keeping the stability at the power system at a manageable level.

In the sense, as mentioned in the introduction, offshore wind power is a very good option. But there are almost no any studies have been carried out to cater the power from off shore wind to the existing power system in the future although catering power from onshore wind and other forms of NCRE has been carried out.

Hence in this research, the research gap is to provide of an addon plan for absorbing the offshore wind power into the existing grid system in Sri Lanka for the LTGEP (Long Term Generation Expansion Plan)

1.3 Research Objectives

The specific objectives for achieving the research gap are

- Potential of the Offshore wind power is to be decided by the available satellite data and software.
- Determination of Security, Economic and Environmental constraints for developing offshore wind power around Sri Lanka
- Evaluation of Existing power grid’s ability to absorb the power and developments scheduled in the future.
- Creation of weightages for each selection factors and Development of a model to locate suitable sites.

2. Literature Review

2.1 Identification of intended area of study

There is an analysis that has been based in the GIS software on the potential locations around Sicily islands. There the intended area of study has been arbitrary selected, and that particular area has been broken in to 50 m grid using GIS software. [1]

2.2 Identification of potential wind power and the lying constraints

The same study talks about the constraints and selection factors for the development of wind power. The primary data is the wind speed around Sicilian coast, and it has been obtained via Italian wind atlas.[1]

Two types of constraints have been identified in the paper namely natural constraints and regulatory constraints. Natural constraints are referred to as bathymetry and seabed geology where regulatory limits are primarily applied from the viewpoint of environmental protection. [1]

Some other papers discuss the technological concepts which affect the costing & reliability of wind farms.

1. Foundation types

	Monopile	**Gravity Base**	**Tripod**	**Jacket**	**Floating**
Depth, m	0-30m	0-40m	0-50m	0-50m	>60m
Wind Farm	Thanet, UK	Rodsand, Denmark	Hooksiel, Germany	Thornton Bank Phase 2, Belgium	Hywind, Norway
	Baltic, Germany	Sprogo, Denmark	Alpha Ventus, Germany	Ormonde UK	
	Belwind, Belgium	Lillgrund, Sweden		Beatrice, UK	

Table 2-1 Foundation design and depths [2]

2. Wind turbine towers

The design of the offshore wind tower has been originated from the onshore wind turbine tower design. Design of the Offshore wind turbine tower has evolved over time to include higher strength characteristics for additional loading and incorporation of specialist coating materials in the purpose of withstanding the corrosiveness of the seawater. The assembly process of offshore wind tower is similar to that of onshore turbines. [2]

3. Blades

A report on the cost breakdown of a 5MW turbine determined the blades as the largest component cost [3].

Generally, the blades are built using the fiberglass and there is a risk of cracking under extreme weather conditions. In addressing this issue, self-healing composites and nano-fillers are being under development. Once a blade is cracked it allows to self-healing composites (nano fillers) which are sealed in small tubes in the blades and seal the cracked location. The stiffness and fatigue characteristics of blades can be increased using these nano fillers (self-healing composites) which results in extended lifetime of blades [4].

Weight and size of the blade is also important. Larger the size, more the power it can extract as well as more the difficulty of transportation. A new type of blade which consists of a metal space frame and fabrics are currently under development as a solution to this issue. This new blade is lighter and quicker to fabricate than existing fiberglass blades. This new method will allow the designing of longer blades (typically more than 120m) which ultimately results in higher power extraction. Also, this will reduce lot of problems regarding manufacturing and transportation as the blades are lighter and can be built and assembled on site. General Electric is in view of reducing cost of blades by 25% to 40% by this new design [2]

4. Drivetrain & the Generator

There are typically two types, Gear driven system and direct drive system. In gear driven system it allows the coupling of a low-speed turbine with a typical high speed generator though a gear box where direct drive system allows reducing the number of components and increased reliability. In the USA NREL views direct drive generators as more reliable than the high speed DFIG gear-driven systems [5].

5. Interconnection to the Grid (Substations)

The wind farm shall connect with the existing grid via existing substation. The grid & the substation shall be capable enough to incorporate the power generated from the offshore wind power farm. As the power output of the offshore wind farm is higher and the distance to the shore is also higher (distance to the existing substation), a separate substation in offshore is generally required to step up the generation voltage in order to reduce transmission losses. Offshore substations usually include power transformers (step up), switch gears, electrical generators, batteries and busbar systems to regulate power flows to the grid. It is estimated that a single offshore substation generally cost up to £50 million depending on the ratings of the equipment. These substations may be also equipped with fuel tanks, helipads, living quarters etc. [6].

Depending on the availability of suitable grid substations in the land, a suitable substation may be selected, or a separate dedicated onshore grid substation can be implemented (subjected to land availability).

Another paper discusses the factors used for selection of sites for offshore wind power in a broader way. There apart from the factors mentioned above which accounts for costing of the plant, some other factors/constraints are discussed. There four main criteria and sixteen sub criteria are discussed.[7]

Main Criteria

- Economic and Technical Factor
- Costs
- Social and Environmental Impacts
- Characteristics of the region

These main criteria are divided into fourteen subcategories

- Economic and Technical Factors
    - Wind speed
    - Investment incentives
    - Benefit to the local economy
- Costs
    - Cost of Investment
    - Operation and Maintenance Cost
    - Total Project payback Period
    - Cost of Cabling (Installation)
- Impact to the Environment and Society
    - Community Local Acceptance
    - Effects of Wind farm on marine life
- Characteristics of design
    - Depth of the water

- Distance to the shore
- Distance to harbor
- Distance to natural environment conservation area
- Availability of materials and technical equipment for construction
- Distance to military restrictions areas
- Ability of extension

The next paper also discusses the site selection criteria. Accordingly, the initial step is the analysis of wind speed. Since there is a lack of offshore wind speed data, the data collected from the meteorological stations which are situated onshore are used in that study. The potential offshore sites' wind speeds were estimated based on these data.[8]

When referring to the available data on wind speed, the measurements has been only on 10m heights and calculated wind speeds have been obtained using the following equation.

$$V = V_0 \times \left(\frac{h}{10}\right)^{\alpha}$$

Where, V= desired wind speed at desired height h

V_0 = Wind speed at 10 m height

h = height

α = surface roughness coefficient

Since assessment were made for sites having smooth sea surfaces α has been assumed as 0.12.[8]

The second step was to filter of the sites which were selected based on the wind speed by applying several selection criteria. These selection criteria/constraints may include areas with extractions of gas and oil, military bases/exercises, harbors, shipping routes, environmental restrictions, impacts to the fish and marine mamals, marine archaeology sites, availability of underwater cables, landscape and seascape as public heritage, already installed offshore projects in the region of interest and the relevant characteristics (depth of the water, distance to shore, geology of seabed etc.) of the area [9,10].

When going through the different literatures which are available on offshore wind farm site selection it's observed that lot of constraints need to be considered apart from technical feasibility.

Another paper discusses the particularly about the impact on marine mammals due to offshore wind farms. There the study has been carried out for assessing of impact of offshore wind farms on Swedish waters.[11]

There three main phases are identified where the marine mammals can get affected.

- construction phase
- operational phase
- decommissioning phase

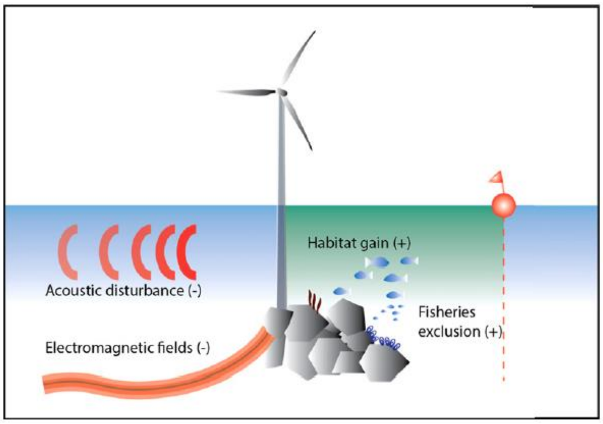


Figure 2-2 Overview of main pressures from OWF during the operational phase

Probable impact on marine species was assessed with respect to the following aspects.

(i) temporal extent

(ii) spatial extent

(iii) sensitivity of species

within each ecosystem component.

Research has been based on only considering the construction phase and the operational phase and during the research, impacts to Marine mammals, Fish (into some extent) and Benthos have been assessed

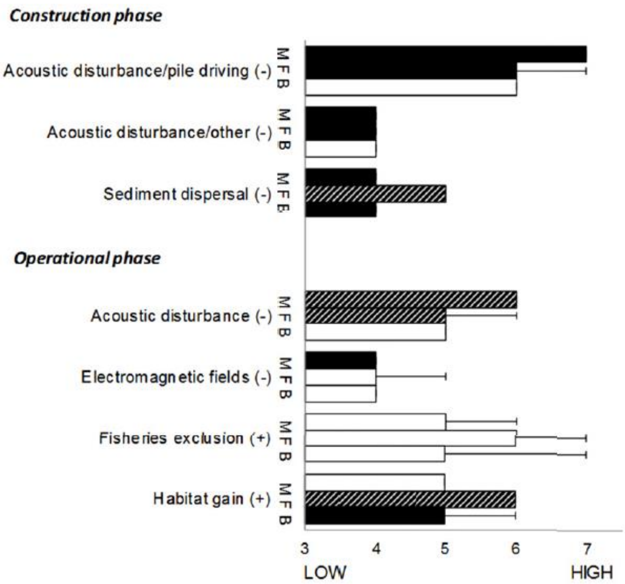


Figure 2-1 Summary of the generalized impact assessment [11]

Here a comparison of impacts on marine mammals (M), Fish (F) and Benthos (B) due to the construction and operational phases of offshore wind farms are described with negative sign indicating an adverse impact where plus sign indicating positive impact. From the color of the bar, the certainty level in the study is indicated.
black = high, striped = Moderate, grey = low.[11]
Marine animals use acoustical senses for communication, locating foods, and for their own protection underwater. They usually emit short pulses of sound, and by listening to the echoes they can identify preys or navigate around objects. This functions similar to the sonar systems on navy ships. Hence the producing and hearing sound is extremely important for the survival of marine mammals.

Similarly fishes also produce various sounds for different purposes. Ex: as a mating call as well as ward off predators [11-1]

When considering the adverse impacts of noise from the noise of offshore wind farms, the size and scale of each wind farm is vital as with the decreasing size, effects will be more localized. In addition, the type of foundation, ambient level of noise, spacing of the turbines can be different from site to site and can affect the noise generation. [12]
From the studies it is evident that the generated sound at the construction phase, especially the pile-driving, has a higher impact than that of operational noise (both physicological impact and behavioral impact). Pile-driving can generate a high intensity underwater sound which is detectable at quite a distance where operating wind turbines is emits a low intensity noise which results in lower impact.[12][18]
During the operation of wind turbine, the motion of particles due to generated sound may be detected fishes which are in very close vicinity around the turbine. It is possible that some fishes at higher distance from the turbine (10,20 m) may still detect the sound pressure. Behavioral changes and masking are the main identified impacts of the operational noise of wind turbines.[12]
Marine fishes make their communication including the very important biological signals like mating calls though low frequency sounds which is around below 1 kHz. When the generated sound from the wind turbines is in the range of such frequencies it acts as a noise to those fishes, and they will be unable to detect the sound just like being difficult to make communications in a loud party. This is called masking. This is backed by the noise level as well as the amount of time it presents.[13]

The operation of wind turbine causes the vibration in its nacelle and is transmitted to the foundation. These vibrations propagate through water and seabed and generally the frequency of the sound will be below 700 Hz with a source level of 80-150 dBre 1 µPa @ 1 m. In addition the produced noise by the rotating wind turbine blades will also enter the water through air.

The variations of the wind speed causes the variation of the sound level (ie: increased wind speed causes increased sound level) The foundation type of wind turbine will also affect the propagation of the sound in underwater.[14], [18]

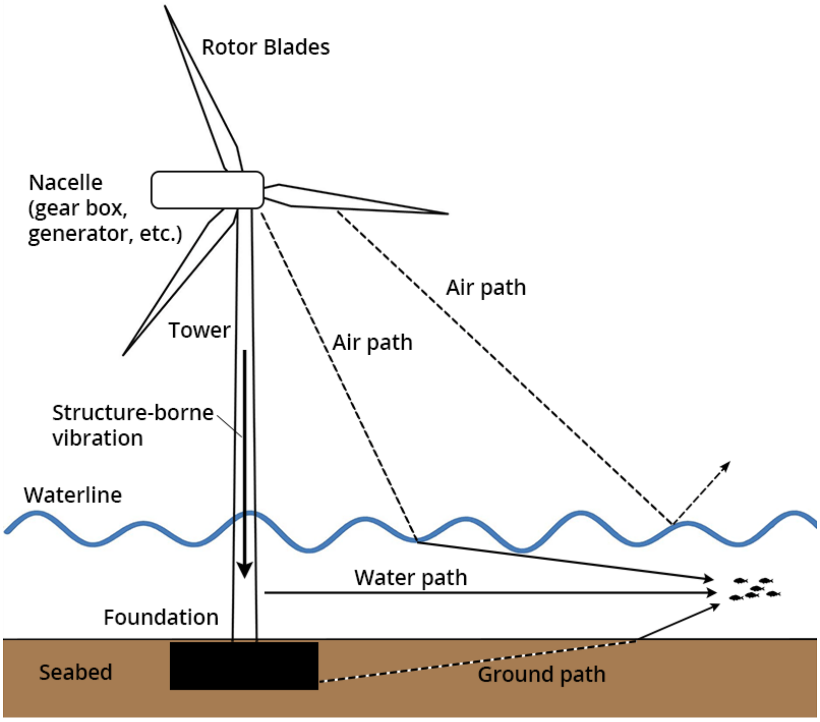


Figure 2-2 Acoustic paths for underwater noise from an offshore wind turbine under operation [15]

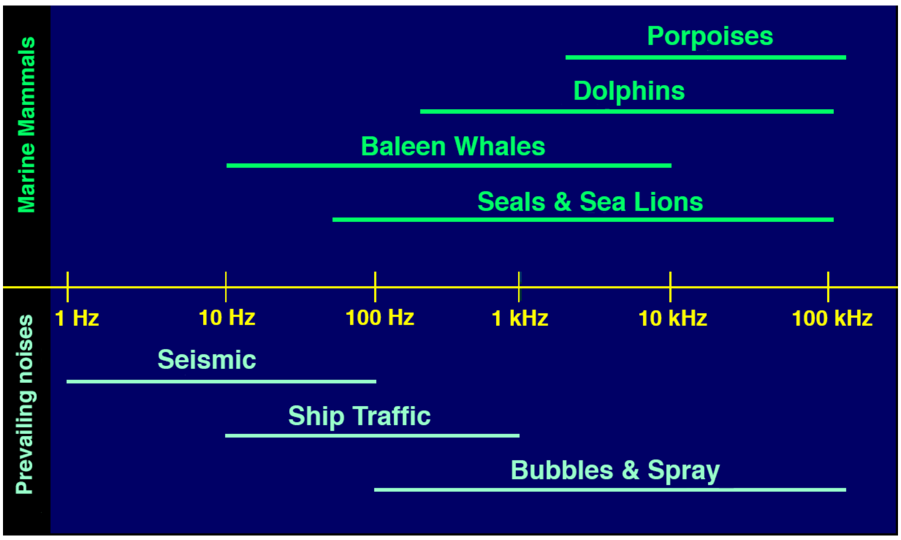


Figure 2-3 Approximate frequency ranges of marine mammals sounds and ambient noise [16]

Figure 2-4 Porpoise (sea pig)

Figure 2-5 Dolphins

Figure 2-6 Sea lion

Figure 2-7 Seal

Figure 2-8 Baleen Whale

Fishes' behavioral responses to sounds may results from exhibiting a momentary awareness, making small movements, or escaping. Small behavioral responses may be neglected since it does not have a significant impact (not affecting to change migratory paths, ceasing reproductions, moving away from breeding grounds etc.).

Furthermore the factors such as individual animal's hearing sensitivity, behavioral stage at the time of exposure, tolerance to noise, the history of exposure to the same noises, sex, group composition, age etc. affect the degree of the behavioral response to a particular noise.[17]

There is no direct impact on pile driving near the coral reefs but installed turbine will act as an artificial reef increasing the fish population of the nearby area.

Wind turbines are generally colonized by high densities of suspension feeders. A large portion of the biofouling community feeds on food particles suspended in the water column that include phytoplankton, zooplankton, and detritus. The predominant blue mussel *Mytilus edulis*, for example, actively filters water and ingests particles from it.[20]

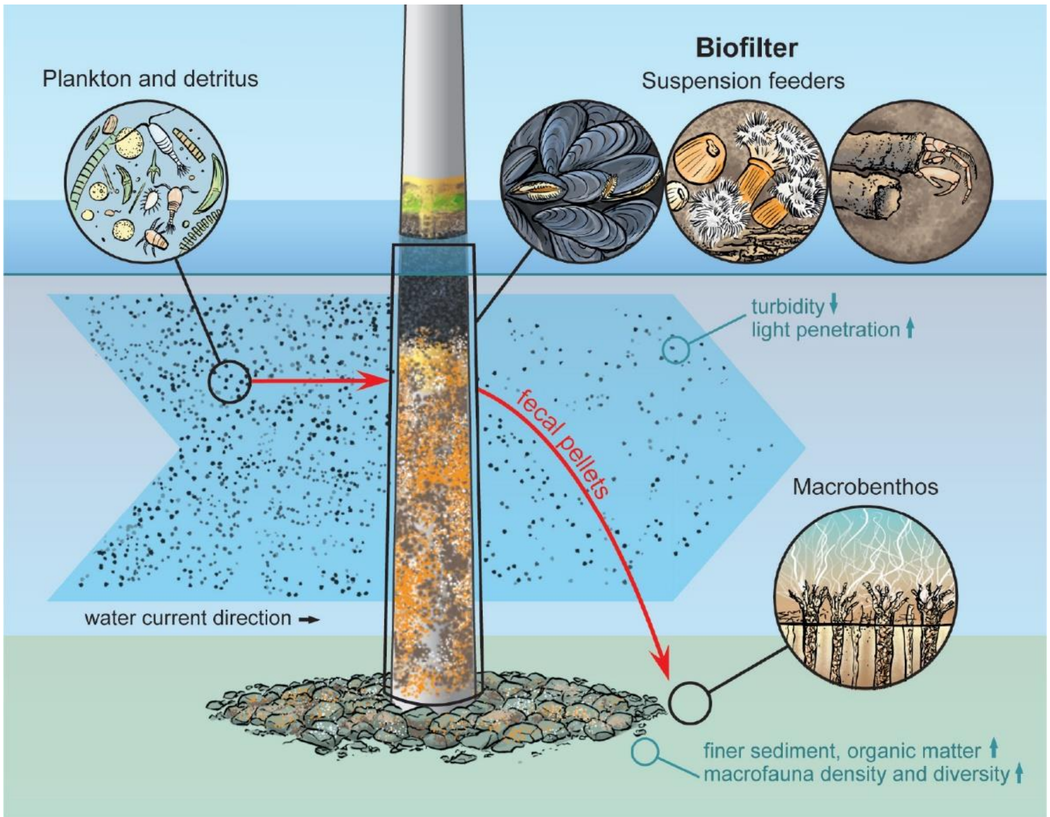


Figure 2-9 Offshore wind farm artificial reefs acting as "biofilters [20]

There are few studies which discuss the tourists' attitudes regarding the wind farms among the lot of studies looking at attitudes of the public regarding the offshore wind farms.

The tourists' attitudes towards wind farms were examined by an independent survey in 2011carried out on Visit Scotland. It included a sample of both British and Scottish people and participants were given a number of questions to get their feedback on their views on wind farms. The summery of findings are mentioned below.

• Majority of the participants (British - 80%, Scottish - 83%) has given the conclusion that presence of a wind farm **would not** affect the visit/stay

• Over the half of participants (52%) **disagreed** that wind farms negatively affect the natural beauty (scenery), where nearly one third of participants (29%) neither agreed nor disagreed for the same question

• Nearly half the participants (British - 40%, Scottish - 46%), were keen on visiting a wind farm.

• Most importantly, over half of the participants (55%) agreed that even if they knew there was a wind farm, they **wouldn't avoid** visiting such area

• Participants **agreed** that wind farms play a necessary role in upcoming energy generations projects in the future

• Participants **disagreed** that wind farms add a disgrace to the landscape and destroy the attraction of tourists (mean score 4.63) [21]

In waters of Rhode Island, which is a state of the United States, a separate study has been carried out where a total of 75 persons (fishermen) have participated for the survey [22]. Out of the total more than 2/3 are recreational fishermen while rest is commercial fishermen. Most of the respondents (>85%) have been participated online for this survey regarding offshore wind farms.

Majority of the participants for that survey (81.3%) of respondents were supporting for the wind turbines installation in waters of Rhode Island where 12% were opposing. Around 6.67% of the participants haven't indicate a proper answer for the survey (neither opposing nor supporting). [22]

Below table shows the results of the responses for the survey.

Fishermen	Opposing	Supporting	Neutral	Total
Commercial	5	16	2	23
Recreational	4	45	3	52
Total	9	61	5	75

Table 2-2 Responses for the survey questions [22]

A comparison of results of different surveys carried out on different places regarding the public opinion on offshore wind power is presented in below table.

Survey / Result	**Rhode Island's Fishermen**	**New Jersey**	**Town of Bristol**	**Cape Cod**	**Delaware**	**Nysted - Denmark**
Opposing	12%	41%	23.4%	42.4%	19.5%	<20%
Supporting	81.3%	27%	76.6%	24.6%	65%	>80%
Not sure	6.7%	32%	?	32.3%	15.5%	?

Table 2-3 Comparison of results of different surveys on public opinion on offshore wind energy [22]

When considering the effects of offshore wind turbines on migratory birds, death of migratory birds due to collisions has attracted the highest attention. It is possible that they may collide with stationary structures or stationery/rotating blades causing them mortal injuries. Furthermore, vortices occurred in the wake of the blades can also cause deadly injuries to the birds.

It has been observed that when the turbines are illuminated it attracts the birds at night and increase the probability of collisions. Considering that, there have been some initiatives for introduction of navigation lights for the turbines avoiding the requirement of the illumination as well as reducing the attractions of the birds.

Furthermore, when studying the behavior of the birds, it has been observed that they tend to avoid the turbines at three scales.

1. Macro (within the area of three kilometers from the wind turbine)
2. Meso (Between the turbines)
3. Micro (in the proximity of blades and the structure)

At different scales different strategies of avoidance may be used by birds and hence the rate of collisions are found to be low. [23]

Earlier it has been thought as offshore wind turbines might cause large amount of migrating bird collisions. For example, in the Anholt OWF of Denmark, consists of 111 Nos of turbines, located at Kattegat, it has been expected initially that it will cause higher rate of collisions of birds and subsequently the fatalities after the construction of the project. But post observations has confirmed a larger amount of birds have avoided the wind turbine. However, the wind turbines will act as a barrier to their original migratory paths.[23]

Another aspect of the offshore wind farms is the visual impact. It tends to affect the visual quality of the scenery negatively.

Figure 2-10 Visual impact from Offshore wind farms – Ormonde (9.5 km) – Thanet (12.3 km)

The above 2 images were taken from the internet and shows how it visually affect the quality of the scenery. The first image shows “Ormonde” wind farm of United Kingdom which is situated at 9.5 km from the shore where the quality of the scenery is very much affected, and it is not anymore, a calm scene. The next figure shows “Thanet” wind farm of United Kingdom which is situated at 12.3 km from the shore. Its affection is very much reduced being further far away from the shore, but it is still visible.

The visibility of the wind turbines affects the beauty of the seascape. Hence an assessment of distances which the wind turbines should be constructed has been carried out as a part of a study on visual sensitivity. This assessment has been carried out for the Scotland and when going through the existing documents it has been noted that distance and the visual sensitivity were made related as below. These values were found on the document, Strategic Environmental Assessment for Offshore Wind Power - UK Department of Trade & Industry. [25]

Distance range from the shore (km)	Visual impact on the seascape
0 - 8	High
8 - 13	Moderate
13 - 24	Low
>24	Insignificant

Table 2-4 Visual Impacts of Offshore Wind Turbines with the increasing distances from the shore [25]

3. Methodology

Using the aid of the literature review a draft methodology mentioned below was adopted for the project.

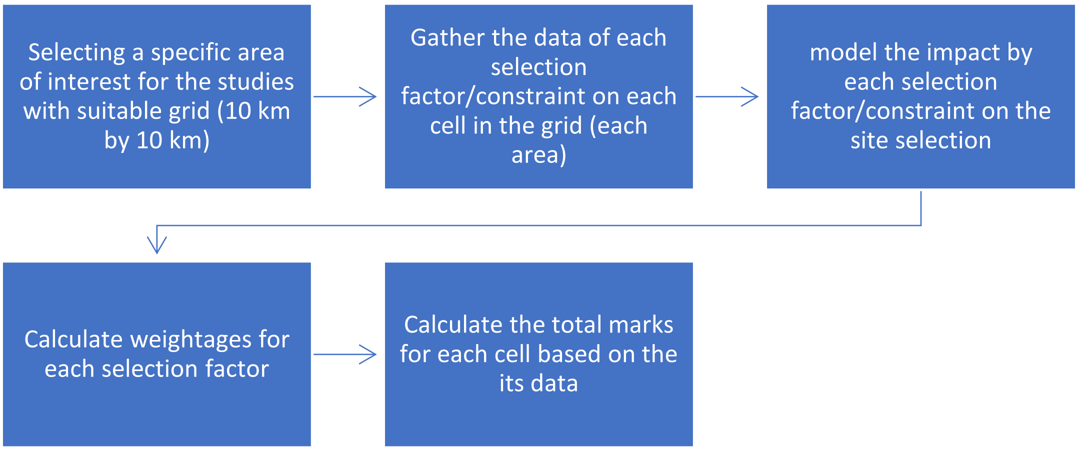


Figure 3-1 draft methodology for selection of sites

3.1 Declaration of Area of Study

Sri Lanka sea territory is having a much larger sea area than its land area. The boundary of the Sea territory is known as the limit up to the boundary of exclusive economic zone which is around 200 nautical miles from the shore.

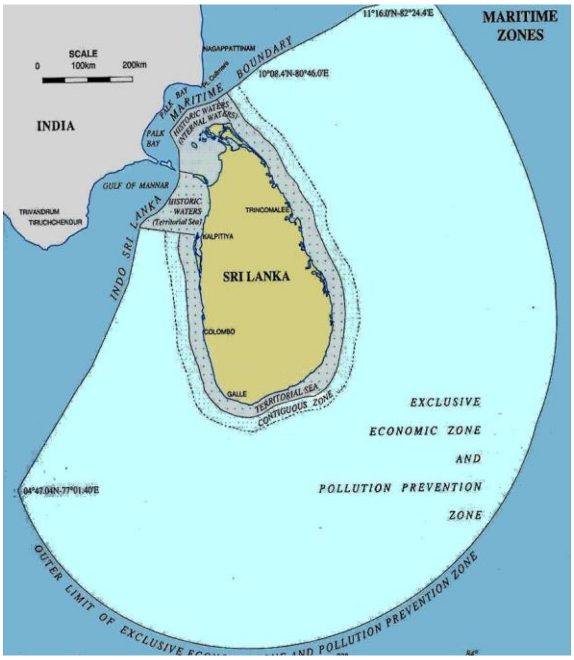


Figure 3-2 Sri Lanka Sea area

Source : https://maps-sri-lanka.com/sri-lanka-sea-map

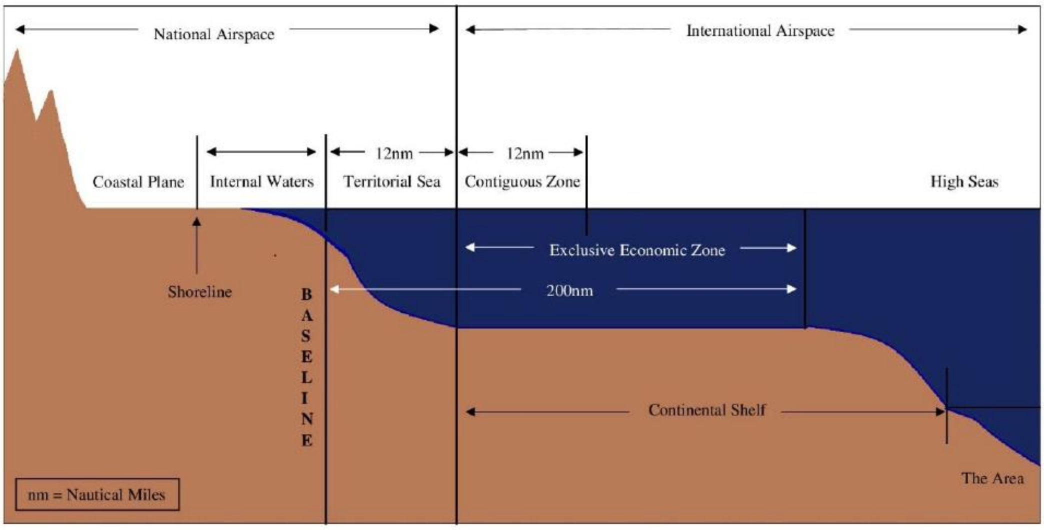


Figure 3-3 Sri Lanka Sea area description

Source: Emerging Issues under the UN Convention on the Law of the Sea for the Indian Ocean, Natalie Klein*, Natalie Klein*

Here the area of intended study was selected such that it will be within the legal sea boundary of Sri Lanka. The selected area was then broken apart into 10 km by 10 km squares where each square (cell) will represent a fraction of the selected area. This is done for the purpose of modelling the intended area of study and having a visual final outcome at the end of the research.

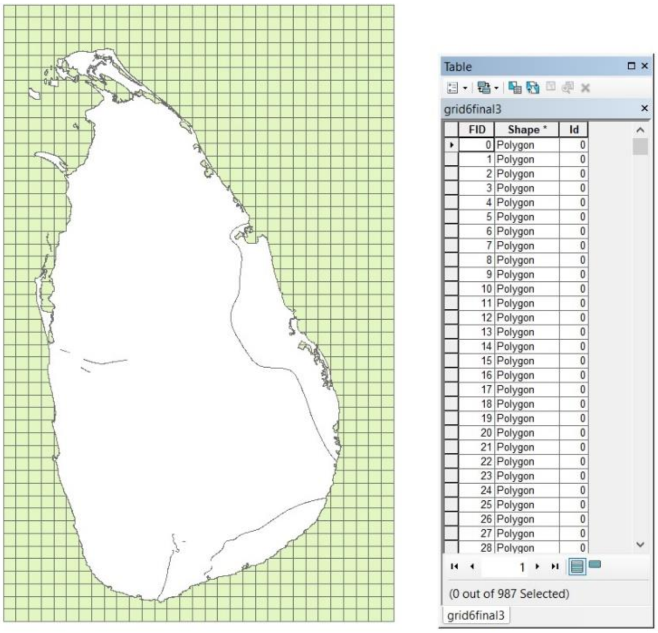


Figure 3-4 selected area for intended study - ArcGIS

For this purpose, a GIS software was used. The above is an image of the selected area with 10 km by 10 km squares which was created with ArcGIS.

3.2 Identification of Selection Factors/Constraints

First the selection factors/constraints that were relevant for the study (Sri Lanka) were identified. They are

1. Wind Speed
2. Bathymetry
3. Distance to the onshore grid substation
4. Visual impact (distance to the shore)
5. Regulatory constraints
    a. Oil & gas explorations
    b. Oil well locations
    c. Shipping lines
    d. Coastal restricted zones
    e. High security zones
6. Environmental Constraints
    a. Impacts for the marine mammals
    b. Impacts for the coral reefs
    c. Impacts for the birds' migratory paths etc.
7. Tourism related constraints
    a. Whale & dolphin watching routes
    b. Surfing areas
    c. Most tourist attracted beaches etc.
8. Technical related constraints
    a. Existing nearshore windfarms

The selection factors were identified using the above-mentioned literature review. Accordingly, the following main selection factors have been identified

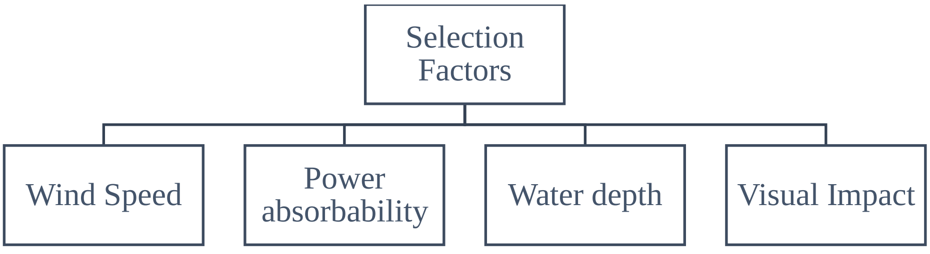


Figure 3-5 Main Selection Factors for Sri Lanka Offshore wind power site selection

Then weightages for each selection factor/constraint was obtained using a self-developed model and finally the total marks for each sub area.

3.2.1 Wind speed and Water depth

For the wind speed values and bathymetry data was obtained using the global wind atlas was used. It was possible to download a raster of a wind velocity as well as bathymetry and open in the ArcGIS software to extract the values of wind speed and water depth of each and every cells

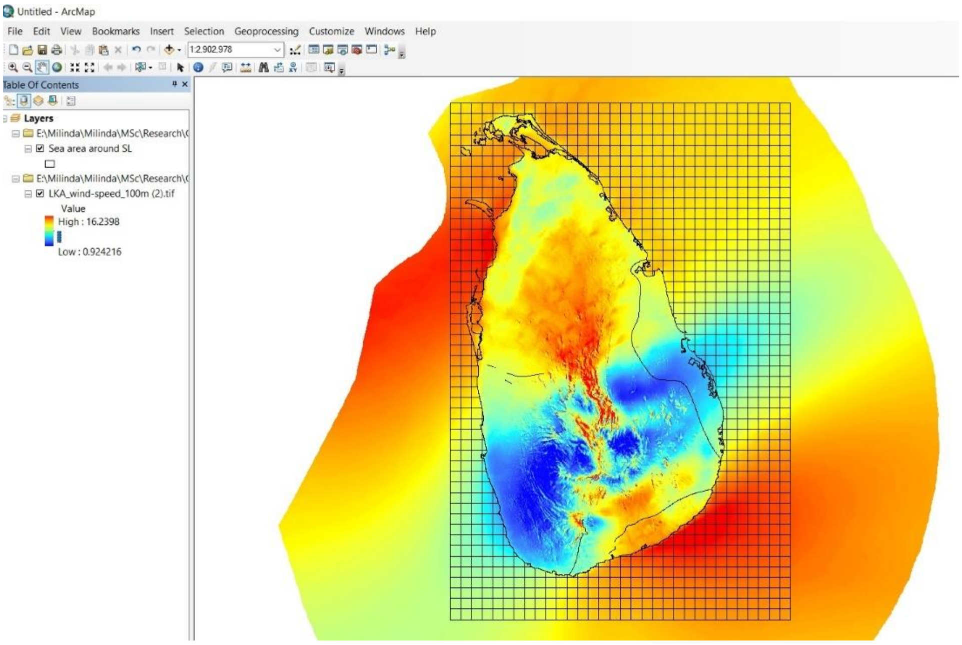


Figure 3-6 Raster image of wind speed over 100m above the sea level intended area of study is shown overlapped

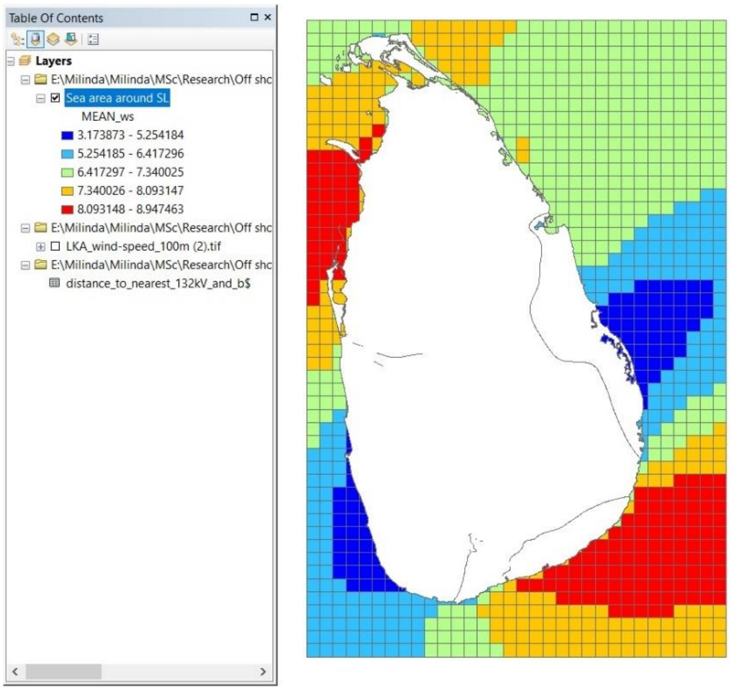


Figure 3-7 digitized wind speed (based on the extracted values for the each cell from the above raster image)

3.2.2 Distance to the nearest grid substation

Here this parameter has been selected reflect the impact of the power absorbability of the existing network. Depending on the distance to the nearest grid substation the length of export cable length increases. It results in increased cost for the cable and the installation.

Further the voltage level available at the grid substation also matters. It will be the voltage of coupling of the offshore wind farm to the existing grid. With the increased voltage of the point of common coupling the generally the stability is higher. Hence the offshore wind farm gets a lower impact from system disturbance. Hence when calculating the impact from the distance from the nearest grid substation the distances and available highest voltage of the grid substation was evaluated.

For the purpose of above, the first step was chosen as collecting of the data of the existing grid substations near the shore. For that a map of the existing power transmission network of Sri Lanka by the Ceylon Electricity Board was referred.

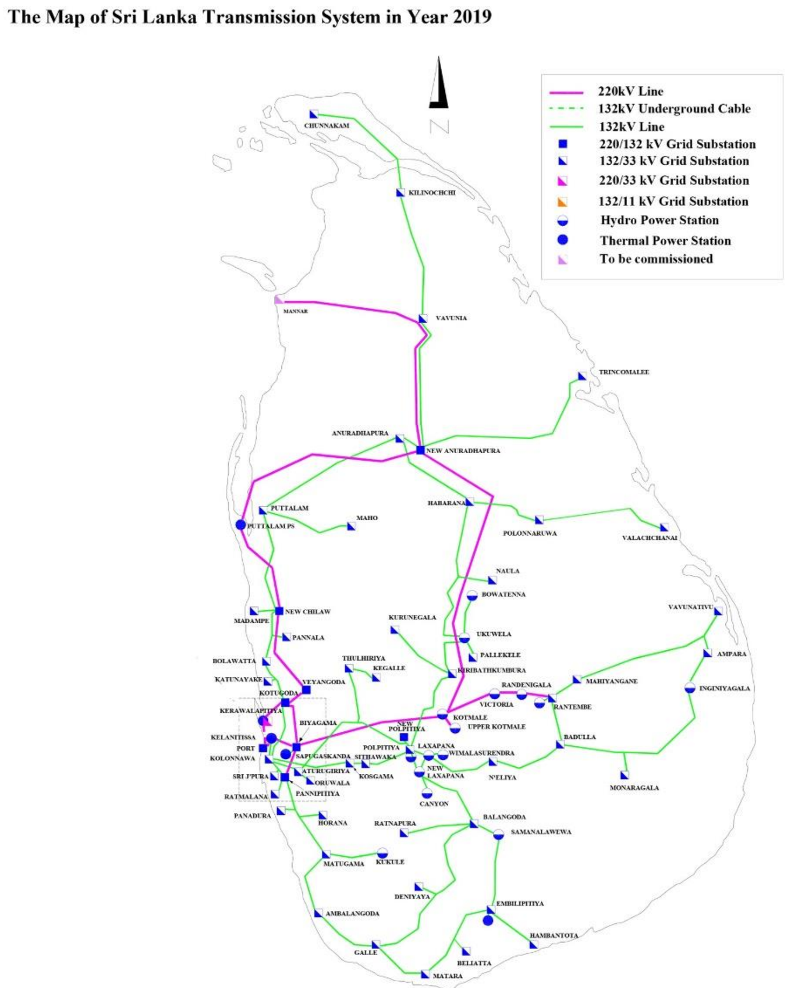


Figure 3-8 Map of Sri Lankan Transmission System 2019: Source-CEB

This data consists of the grid sub stations in Sri Lanka and voltage level of each. For extracting this data, this map was digitized using the ArcGIS software and then distance of the nearest grid substation was extracted for each and every cell. There it was sub divided as nearest 132 kV grid substation and nearest 220 kV grid substation because it was learnt that both the distance and the voltage level affect the selection factor in different ways and hence the resultant impact shall be a combination.

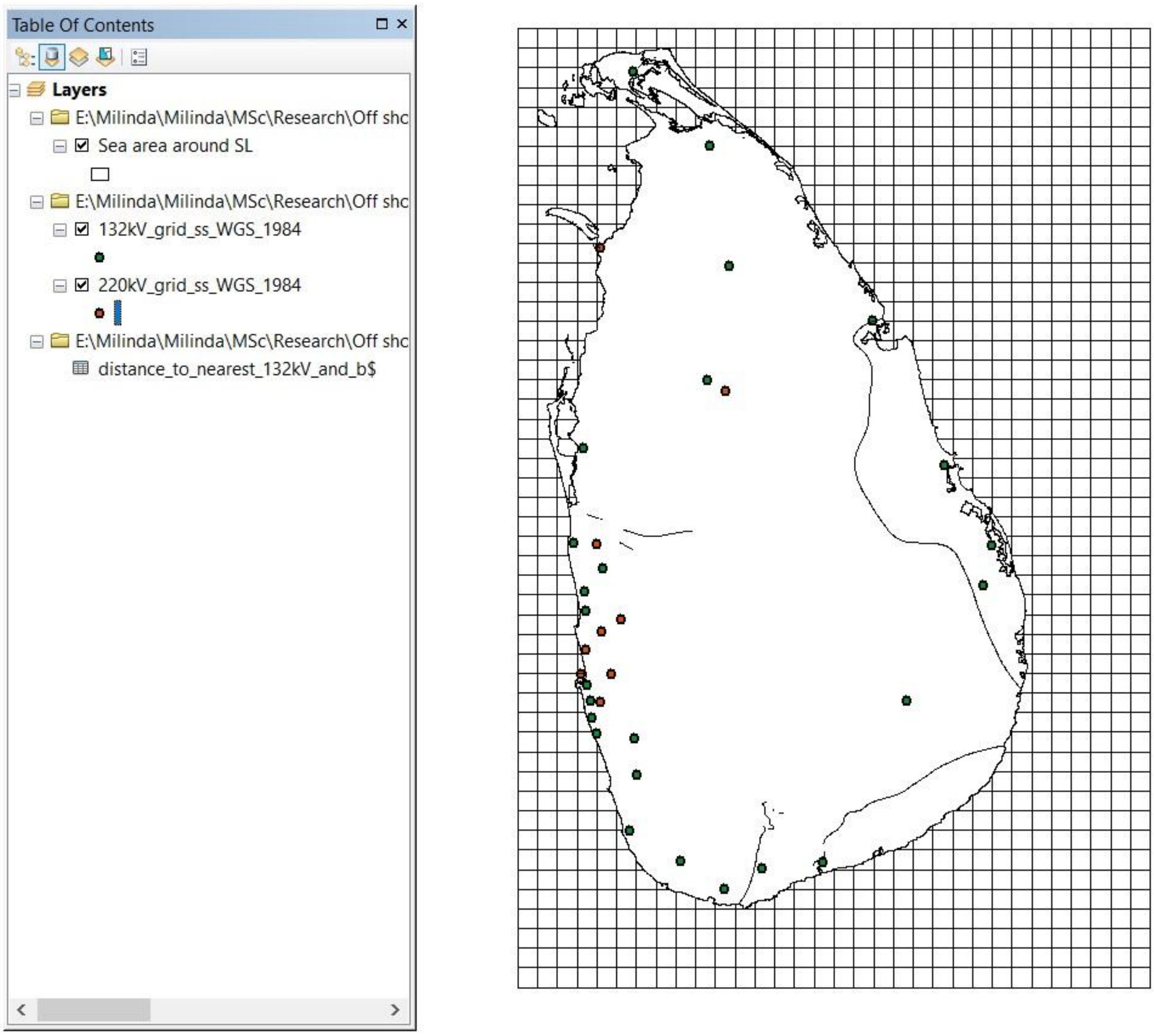


Figure 3-9 locations of grid substations near the shore, Sri Lanka and the highest voltage levels

Table

Sea area around SL

FID	Shape	OBJECTID	Id	Shape_Leng	Shape_Area	NEAR_FID	NEAR_DIST
0	Polygon	1	0	0.358467	0.008031	15	0.746354
1	Polygon	2	0	0.358467	0.008031	15	0.700181
2	Polygon	3	0	0.358467	0.008031	15	0.663024
3	Polygon	4	0	0.358467	0.008031	16	0.615312
4	Polygon	5	0	0.358467	0.008031	16	0.563818
5	Polygon	6	0	0.358467	0.008031	16	0.522792
6	Polygon	7	0	0.358467	0.008031	17	0.472038
7	Polygon	8	0	0.358467	0.008031	17	0.417903
8	Polygon	9	0	0.358467	0.008031	17	0.377633
9	Polygon	10	0	0.358467	0.008031	17	0.355963
10	Polygon	11	0	0.358467	0.008031	17	0.353286
11	Polygon	12	0	0.358467	0.008031	17	0.356302
12	Polygon	13	0	0.358467	0.008031	17	0.378593
13	Polygon	14	0	0.358467	0.008031	17	0.419349
14	Polygon	15	0	0.358467	0.008031	17	0.473829
15	Polygon	16	0	0.358467	0.008031	19	0.477684
16	Polygon	17	0	0.358467	0.008031	19	0.480243
17	Polygon	18	0	0.358467	0.008031	19	0.497593
18	Polygon	19	0	0.358467	0.008031	19	0.529814
19	Polygon	20	0	0.358467	0.008031	19	0.57441
20	Polygon	21	0	0.358467	0.008031	19	0.628752
21	Polygon	22	0	0.358467	0.008031	19	0.690545
22	Polygon	23	0	0.358467	0.008031	19	0.757967
23	Polygon	24	0	0.358467	0.008031	19	0.829648
24	Polygon	25	0	0.358467	0.008031	19	0.904575
25	Polygon	26	0	0.358467	0.008031	19	0.982006
26	Polygon	27	0	0.358467	0.008031	19	1.061393
27	Polygon	28	0	0.358467	0.008031	19	1.142328
28	Polygon	29	0	0.358467	0.008031	19	1.224505
29	Polygon	30	0	0.358467	0.008031	19	1.307689
30	Polygon	31	0	0.358467	0.008031	19	1.391699
31	Polygon	32	0	0.358467	0.008031	19	1.476396
32	Polygon	33	0	0.358439	0.00803	15	0.674043
33	Polygon	34	0	0.358439	0.00803	15	0.622529
34	Polygon	35	0	0.358439	0.00803	15	0.580423
35	Polygon	36	0	0.358439	0.00803	16	0.548166
36	Polygon	37	0	0.358439	0.00803	16	0.489661
37	Polygon	38	0	0.358439	0.00803	16	0.441802
38	Polygon	39	0	0.358439	0.00803	16	0.408349
39	Polygon	40	0	0.358439	0.00803	17	0.345651
40	Polygon	41	0	0.358439	0.00803	17	0.295699
41	Polygon	42	0	0.358439	0.00803	17	0.26747
42	Polygon	43	0	0.358439	0.00803	17	0.263898
43	Polygon	44	0	0.358439	0.00803	17	0.267923
44	Polygon	45	0	0.358439	0.00803	17	0.296924
45	Polygon	46	0	0.358439	0.00803	17	0.347397
46	Polygon	47	0	0.358439	0.00803	18	0.390042
47	Polygon	48	0	0.358439	0.00803	19	0.388296
48	Polygon	49	0	0.358439	0.00803	19	0.39144
49	Polygon	50	0	0.358439	0.00803	19	0.412541
50	Polygon	51	0	0.358439	0.00803	19	0.450882

1 (0 out of 1047 Selected)

Sea area around SL

Figure 3-10 distances to the nearest grid substation (132 kV) for each cell

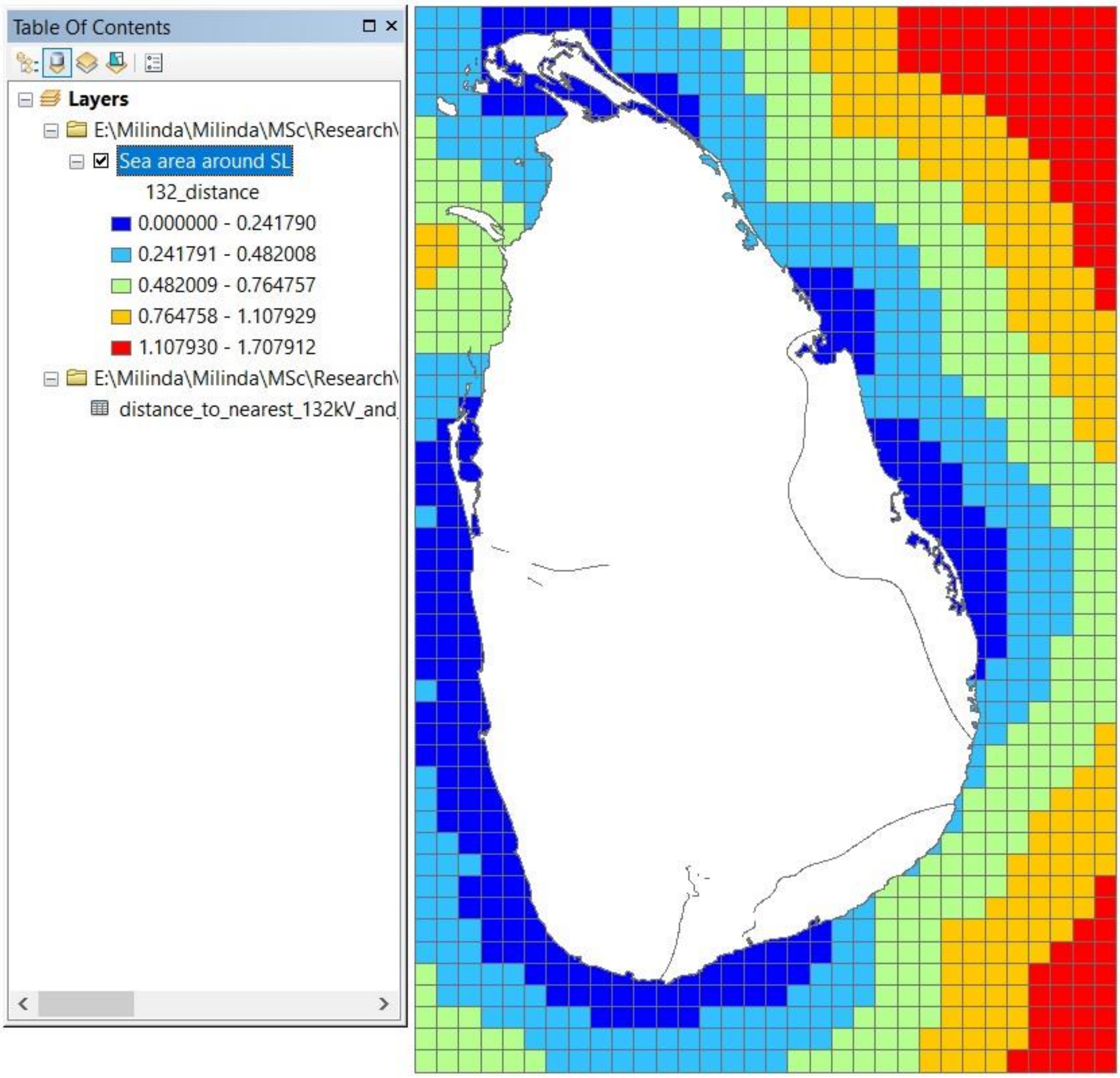


Figure 3-11 visualization of the distances for nearest 132 kV grid substations near the shore

Table

Sea area around SL

FID	Shape	OBJECTID	Id	Shape_Leng	Shape_Area	NEAR_FID	NEAR_DIST
0	Polygon	1	0	0.358467	0.008031	8	1.238886
1	Polygon	2	0	0.358467	0.008031	8	1.221194
2	Polygon	3	0	0.358467	0.008031	8	1.209931
3	Polygon	4	0	0.358467	0.008031	8	1.205275
4	Polygon	5	0	0.358467	0.008031	8	1.205145
5	Polygon	6	0	0.358467	0.008031	8	1.207304
6	Polygon	7	0	0.358467	0.008031	8	1.215984
7	Polygon	8	0	0.358467	0.008031	8	1.231175
8	Polygon	9	0	0.358467	0.008031	8	1.252639
9	Polygon	10	0	0.358467	0.008031	8	1.280061
10	Polygon	11	0	0.358467	0.008031	8	1.313068
11	Polygon	12	0	0.358467	0.008031	8	1.351251
12	Polygon	13	0	0.358467	0.008031	8	1.394185
13	Polygon	14	0	0.358467	0.008031	8	1.441444
14	Polygon	15	0	0.358467	0.008031	8	1.492619
15	Polygon	16	0	0.358467	0.008031	8	1.54732
16	Polygon	17	0	0.358467	0.008031	8	1.605188
17	Polygon	18	0	0.358467	0.008031	8	1.665892
18	Polygon	19	0	0.358467	0.008031	8	1.729134
19	Polygon	20	0	0.358467	0.008031	8	1.794645
20	Polygon	21	0	0.358467	0.008031	8	1.862186
21	Polygon	22	0	0.358467	0.008031	8	1.931544
22	Polygon	23	0	0.358467	0.008031	8	2.00253
23	Polygon	24	0	0.358467	0.008031	8	2.074977
24	Polygon	25	0	0.358467	0.008031	8	2.148738
25	Polygon	26	0	0.358467	0.008031	8	2.223681
26	Polygon	27	0	0.358467	0.008031	8	2.299691
27	Polygon	28	0	0.358467	0.008031	8	2.376666
28	Polygon	29	0	0.358467	0.008031	8	2.454515
29	Polygon	30	0	0.358467	0.008031	8	2.533157
30	Polygon	31	0	0.358467	0.008031	8	2.612521
31	Polygon	32	0	0.358467	0.008031	8	2.692542
32	Polygon	33	0	0.358439	0.00803	8	1.152119
33	Polygon	34	0	0.358439	0.00803	8	1.133073
34	Polygon	35	0	0.358439	0.00803	8	1.120924
35	Polygon	36	0	0.358439	0.00803	8	1.115897
36	Polygon	37	0	0.358439	0.00803	8	1.115757
37	Polygon	38	0	0.358439	0.00803	8	1.118088
38	Polygon	39	0	0.358439	0.00803	8	1.127456
39	Polygon	40	0	0.358439	0.00803	8	1.143822
40	Polygon	41	0	0.358439	0.00803	8	1.166895
41	Polygon	42	0	0.358439	0.00803	8	1.196284
42	Polygon	43	0	0.358439	0.00803	8	1.231539
43	Polygon	44	0	0.358439	0.00803	8	1.272171
44	Polygon	45	0	0.358439	0.00803	8	1.317684
45	Polygon	46	0	0.358439	0.00803	8	1.367589
46	Polygon	47	0	0.358439	0.00803	8	1.421425
47	Polygon	48	0	0.358439	0.00803	8	1.478763
48	Polygon	49	0	0.358439	0.00803	8	1.53921
49	Polygon	50	0	0.358439	0.00803	8	1.602415
50	Polygon	51	0	0.358439	0.00803	8	1.668066

1 (0 out of 1047 Selected)

Figure 3-12 distances to the nearest grid substation (220 kV) for each cell

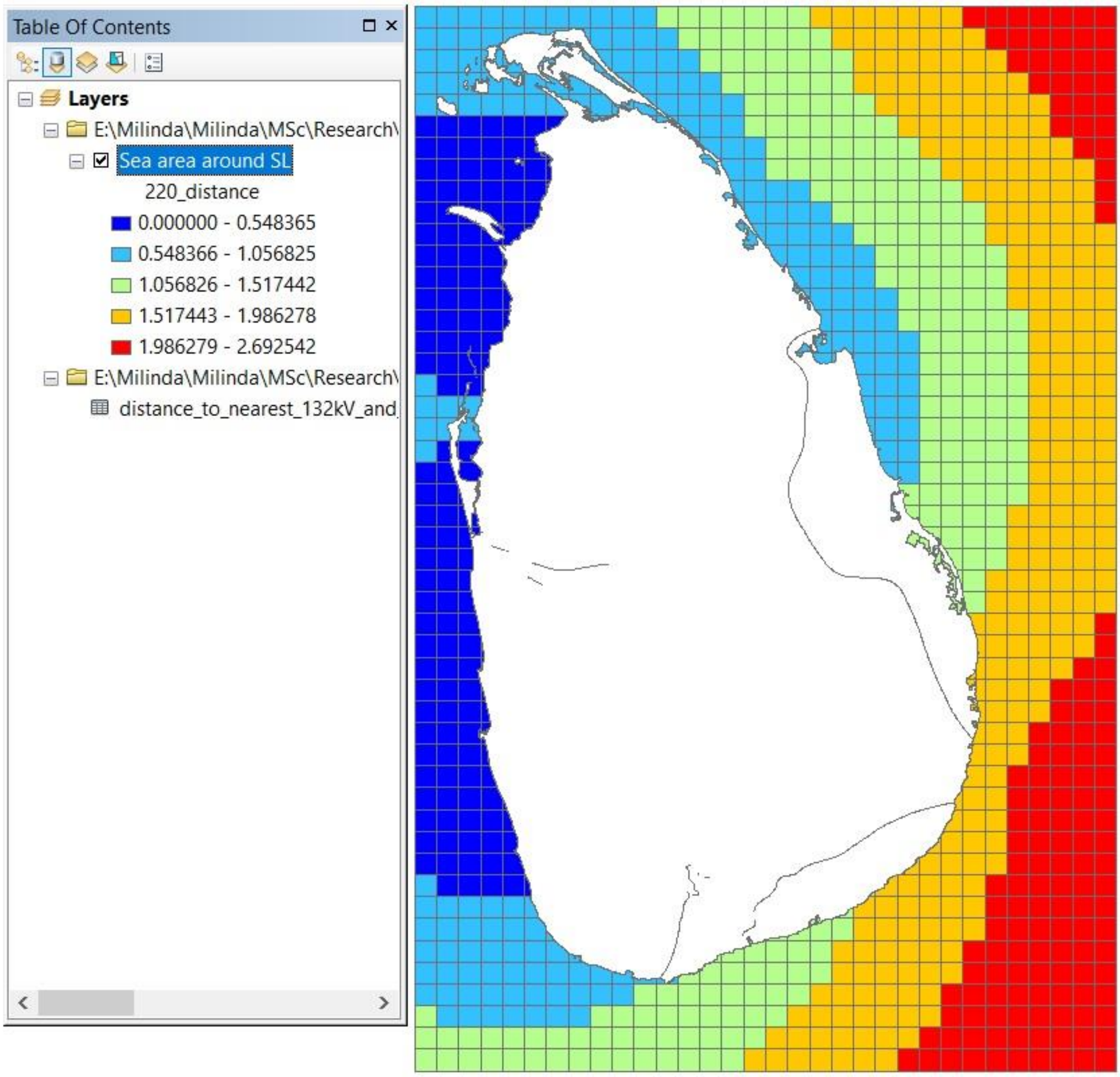


Figure 3-13 visualization of the distances for nearest 220 kV grid substations near the shore

This transmission plan is defined for a period of 10 years and will be reviewed every 5 years. When it is reviewed, some of the grid substations will be planned to be upgraded to higher voltage levels and sometimes new grid substations of different voltages will be introduced. Hence when the transmission plan gets reviewed it is necessary to re-digitize the updated map of locations of grid substations with voltage levels and re-extract the values for distance for the nearest grid substations will different voltage levels for each and every cells.

3.2.3 Visual impact

In general, as learnt in the literature review there is no criteria mentioned to determine the visual impacts of offshore wind farms. Most of the time it depends on the distance to the shore. When the distance is higher, lower the visual impact and noise & flickering effects.

In Sri Lanka although this is not a big issue in most of the areas, this is a big issue for the tourist attracted areas. So, in assessing the visual impact, tourist attracted areas were treated as a separate constraint and only the distance to the shore was only extracted for all the cells.

Table

Sea area around SL

FID	Shape	OBJECTID	Id	Shape_Leng	Shape_Area	NEAR_FID	NEAR_DIST
0	Polygon	1	0	0.358467	0.008031	12	0.653568
1	Polygon	2	0	0.358467	0.008031	12	0.591727
2	Polygon	3	0	0.358467	0.008031	12	0.532276
3	Polygon	4	0	0.358467	0.008031	12	0.477005
4	Polygon	5	0	0.358467	0.008031	12	0.424649
5	Polygon	6	0	0.358467	0.008031	12	0.382719
6	Polygon	7	0	0.358467	0.008031	12	0.356372
7	Polygon	8	0	0.358467	0.008031	12	0.329178
8	Polygon	9	0	0.358467	0.008031	12	0.302272
9	Polygon	10	0	0.358467	0.008031	12	0.286533
10	Polygon	11	0	0.358467	0.008031	47	0.271254
11	Polygon	12	0	0.358467	0.008031	47	0.268122
12	Polygon	13	0	0.358467	0.008031	47	0.272224
13	Polygon	14	0	0.358467	0.008031	47	0.301054
14	Polygon	15	0	0.358467	0.008031	47	0.325452
15	Polygon	16	0	0.358467	0.008031	47	0.363356
16	Polygon	17	0	0.358467	0.008031	47	0.413331
17	Polygon	18	0	0.358467	0.008031	43	0.45006
18	Polygon	19	0	0.358467	0.008031	43	0.471321
19	Polygon	20	0	0.358467	0.008031	43	0.490026
20	Polygon	21	0	0.358467	0.008031	43	0.522551
21	Polygon	22	0	0.358467	0.008031	43	0.55964
22	Polygon	23	0	0.358467	0.008031	43	0.587997
23	Polygon	24	0	0.358467	0.008031	43	0.626131
24	Polygon	25	0	0.358467	0.008031	43	0.674151
25	Polygon	26	0	0.358467	0.008031	43	0.723882
26	Polygon	27	0	0.358467	0.008031	43	0.777747
27	Polygon	28	0	0.358467	0.008031	43	0.831191
28	Polygon	29	0	0.358467	0.008031	43	0.883488
29	Polygon	30	0	0.358467	0.008031	43	0.938201
30	Polygon	31	0	0.358467	0.008031	43	0.995992
31	Polygon	32	0	0.358467	0.008031	43	1.05598
32	Polygon	33	0	0.358439	0.00803	12	0.595493
33	Polygon	34	0	0.358439	0.00803	12	0.52688
34	Polygon	35	0	0.358439	0.00803	12	0.465545
35	Polygon	36	0	0.358439	0.00803	12	0.405956
36	Polygon	37	0	0.358439	0.00803	12	0.351402
37	Polygon	38	0	0.358439	0.00803	12	0.301731
38	Polygon	39	0	0.358439	0.00803	12	0.269562
39	Polygon	40	0	0.358439	0.00803	12	0.244541
40	Polygon	41	0	0.358439	0.00803	12	0.217901
41	Polygon	42	0	0.358439	0.00803	12	0.197436
42	Polygon	43	0	0.358439	0.00803	47	0.183023
43	Polygon	44	0	0.358439	0.00803	47	0.178734
44	Polygon	45	0	0.358439	0.00803	47	0.18483
45	Polygon	46	0	0.358439	0.00803	47	0.220063
46	Polygon	47	0	0.358439	0.00803	47	0.242034
47	Polygon	48	0	0.358439	0.00803	47	0.287624
48	Polygon	49	0	0.358439	0.00803	35	0.331965
49	Polygon	50	0	0.358439	0.00803	43	0.364075
50	Polygon	51	0	0.358439	0.00803	43	0.383426

1 (0 out of 1047 Selected)

Sea area around SL

Figure 3-14 distances to the shore for each cell

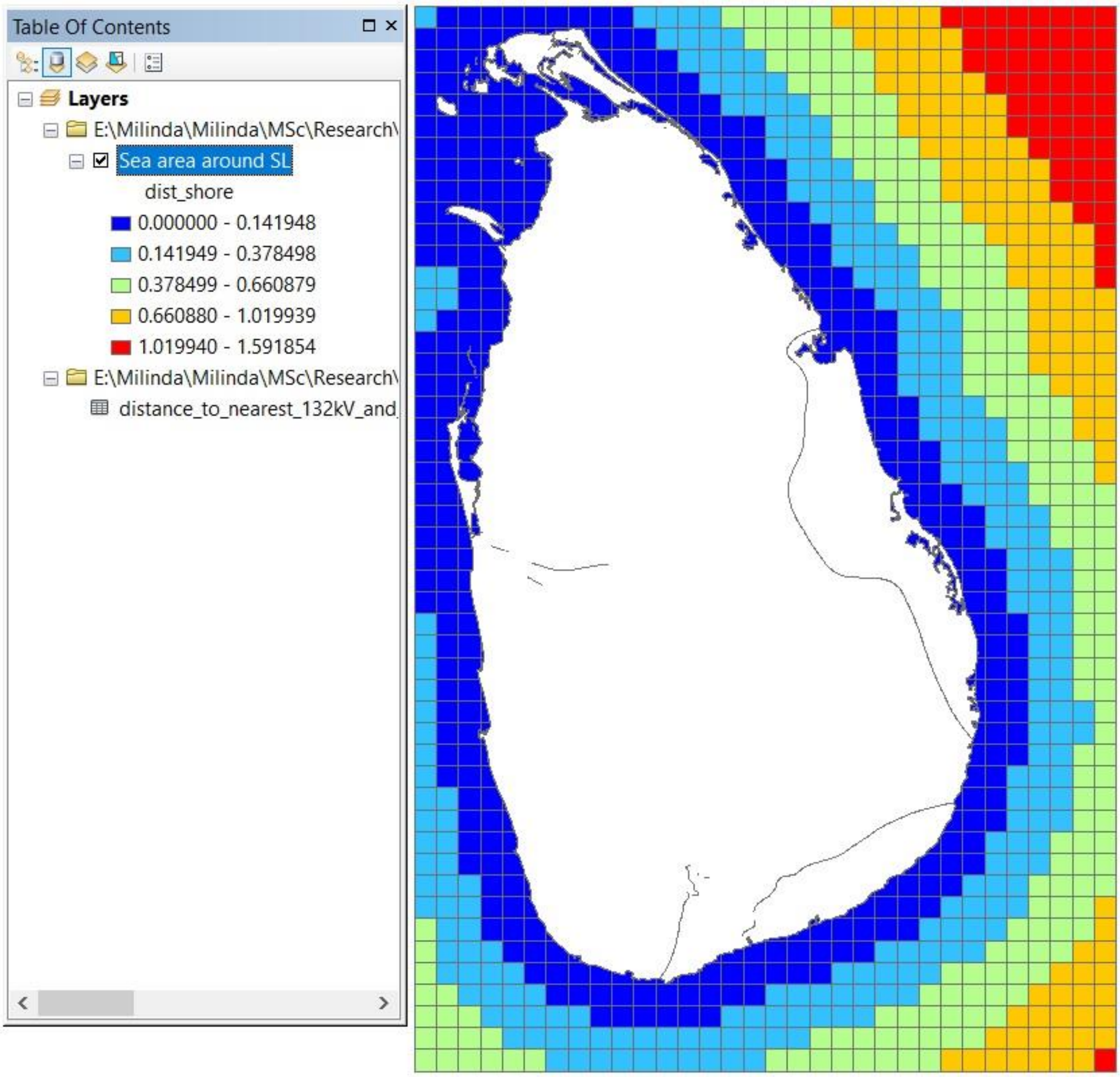


Figure 3-15 visualization of the distances to the shore for each cell

3.3 Identification of other constraints

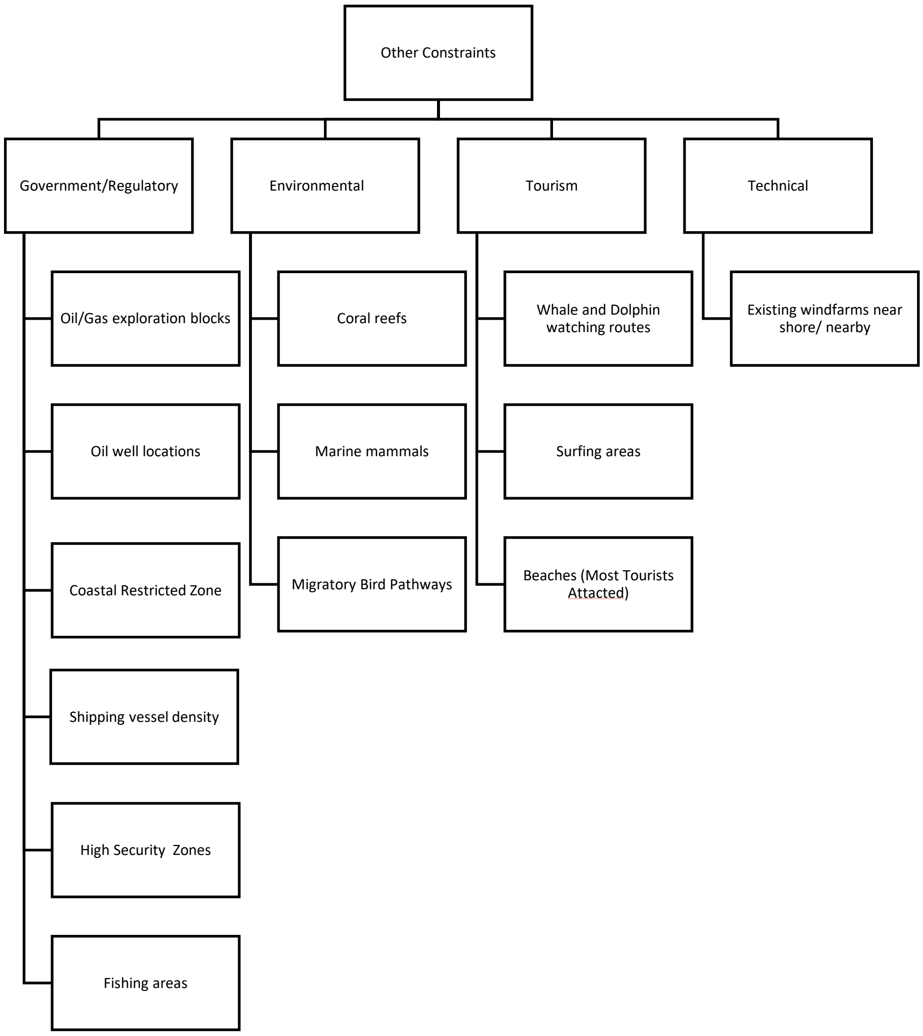


Figure 3-16 other constraints for selection of sites

3.3.1 Government/Regulatory constraints

3.3.1.1 Legal regulations

Here the intended area of study should be bound by the legal limits of the Sri Lankan territory. Basically, the Sri Lankan Sea territory limit is marked by the limit of the Exclusive Economic Zone (EEZ). Any area that is outside of this limit shall not be further evaluated. The intended area of study was selected in such way that all of the cells will be lying inside the boundary limit of the Sri Lanka Sea territory

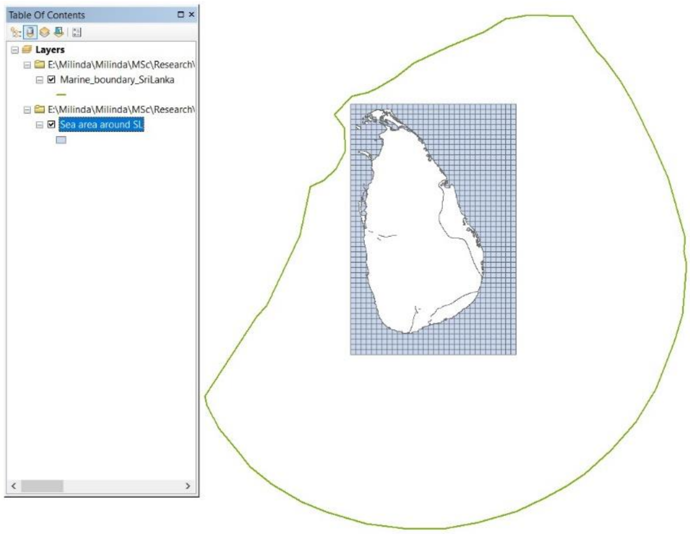


Figure 3-17 Intended area of study and the legal limits of Sri Lankan Sea territory

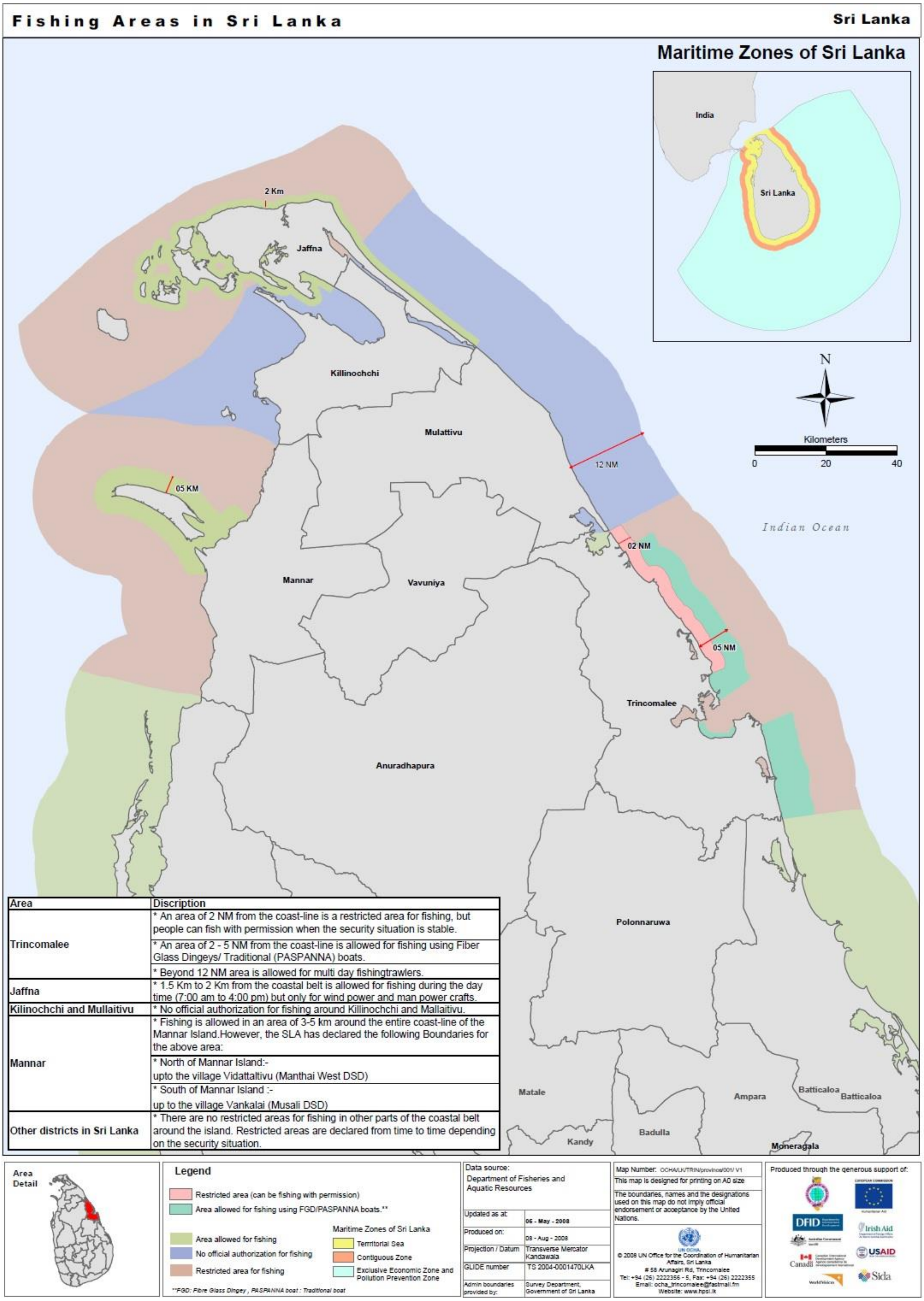
3.3.1.2 High security areas

In Sri Lanka there are few high security areas nearby the shore. Area nearby the Trincomalee harbor is the main high security area. (Sampoor). There are some other high security zones mentioned in some other websites as there are no information mentioned in ministry of defense website, those information were neglected.

It is required to avoid high security zones as much as possible as maintenance people will required to enter if the wind farm is constructed inside the HSZ. Frequent crossing of HSZ will endanger the zone.

3.3.1.3 Fishing industry and regulations

Some of the areas of Sri Lankan Sea is restricted for fishing (other than HSZs). Some of them are given the authenticity upon the request. Once the wind turbines are installed that particular site will be prohibited for fishing hence installation of wind turbines will act adversely on the fishing industry.



Area	Discription
Trincomalee	* An area of 2 NM from the coast-line is a restricted area for fishing, but people can fish with permission when the security situation is stable.
	* An area of 2 - 5 NM from the coast-line is allowed for fishing using Fiber Glass Dingeys/ Traditional (PASPANNA) boats.
	* Beyond 12 NM area is allowed for multi day fishingtrawlers.
Jaffna	* 1.5 Km to 2 Km from the coastal belt is allowed for fishing during the day time (7:00 am to 4:00 pm) but only for wind power and man power crafts.
Kilinochchi and Mullaitivu	* No official authorization for fishing around Killinochchi and Mallaitivu.
Mannar	* Fishing is allowed in an area of 3-5 km around the entire coast-line of the Mannar Island.However, the SLA has declared the following Boundaries for the above area:
	* North of Mannar Island:- upto the village Vidattaltivu (Manthai West DSD)
	* South of Mannar Island :- up to the village Vankalai (Musali DSD)
Other districts in Sri Lanka	* There are no restricted areas for fishing in other parts of the coastal belt around the island. Restricted areas are declared from time to time depending on the security situation.

Figure 3-18 Fishing restrictions around Sri Lanka

From the above map only the fishing restricted areas and the permission required areas were identified and digitized. There are some areas which described as “No official authorization for fishing” and “Allowed for fishing using FGD/PASPANNA boats”. Those areas were treated as same as areas allowed for fishing for the implementation purpose.

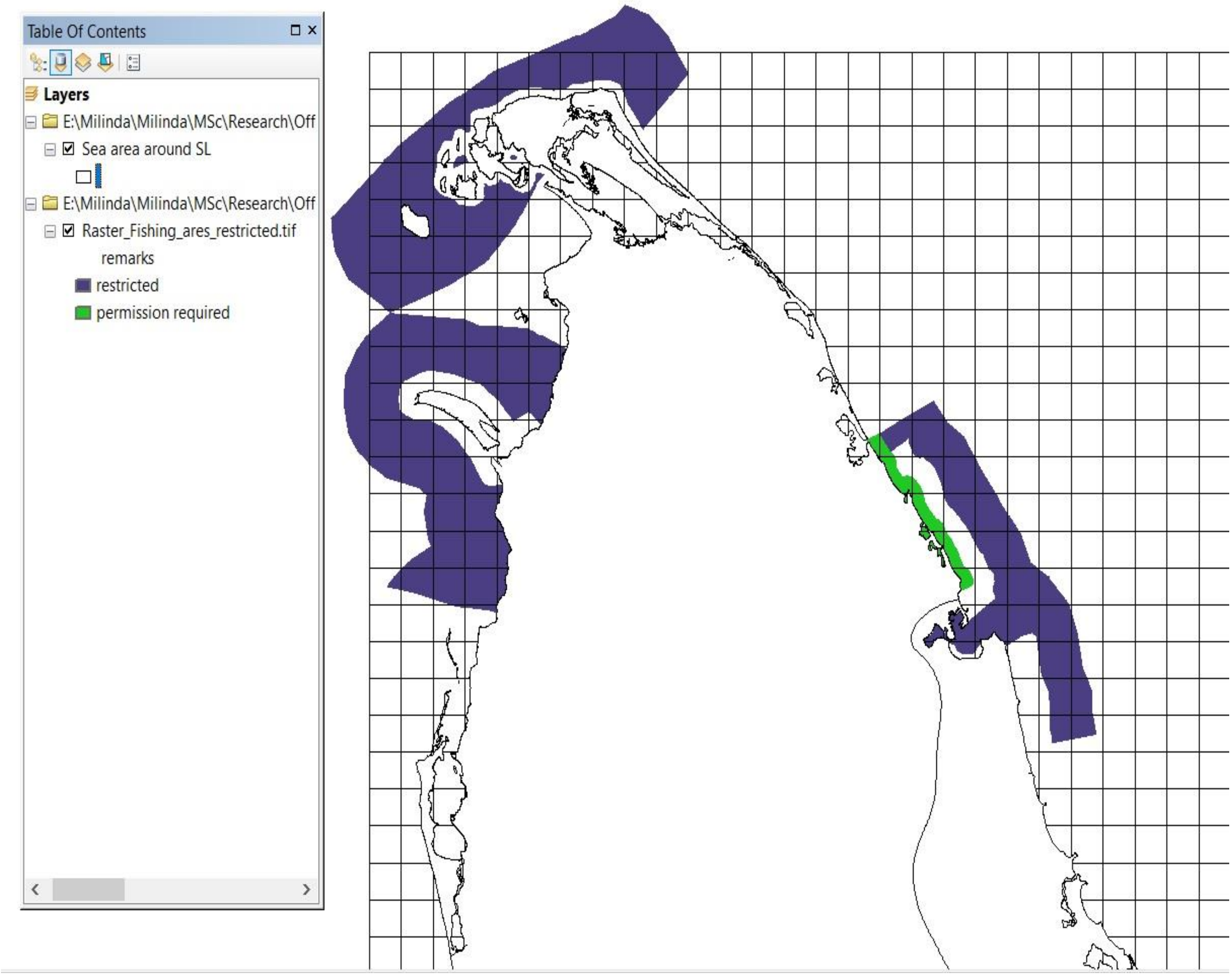


Figure 3-19 digitized map of fishing restricted areas around Sri Lanka

3.3.1.4 Shipping lines

Shipping vessel traffic is also a major constraint when selecting offshore wind farm sites. Passenger vessels were also considered as they were using the same routes.

The existing shipping vessel map (GIS file) was downloaded from the web site https://datacatalog.worldbank.org/dataset/global-shipping-traffic-density

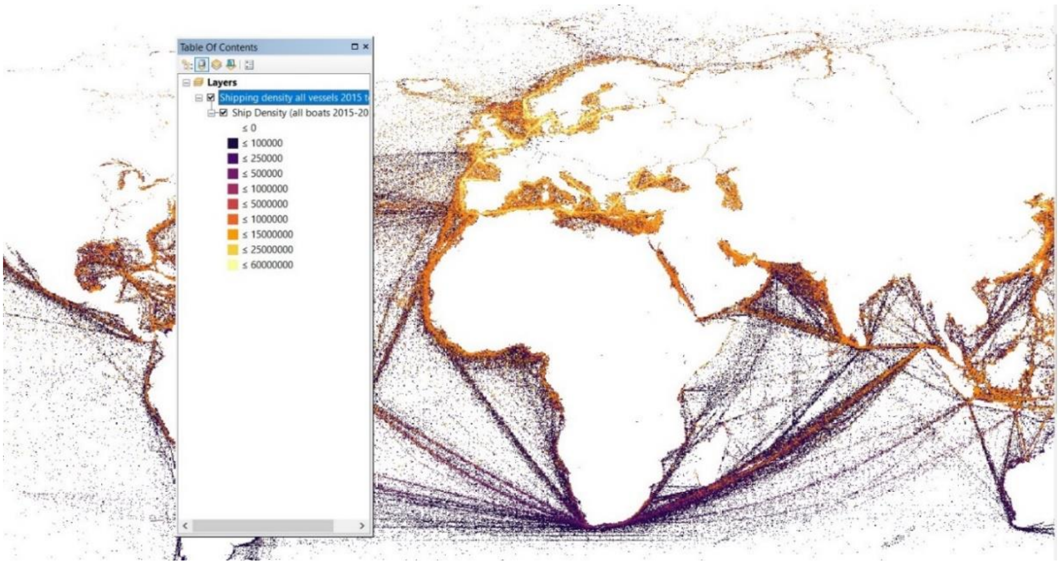


Figure 3-20 Shipping traffic of the world

Then localized the part which was related to Sri Lanka.

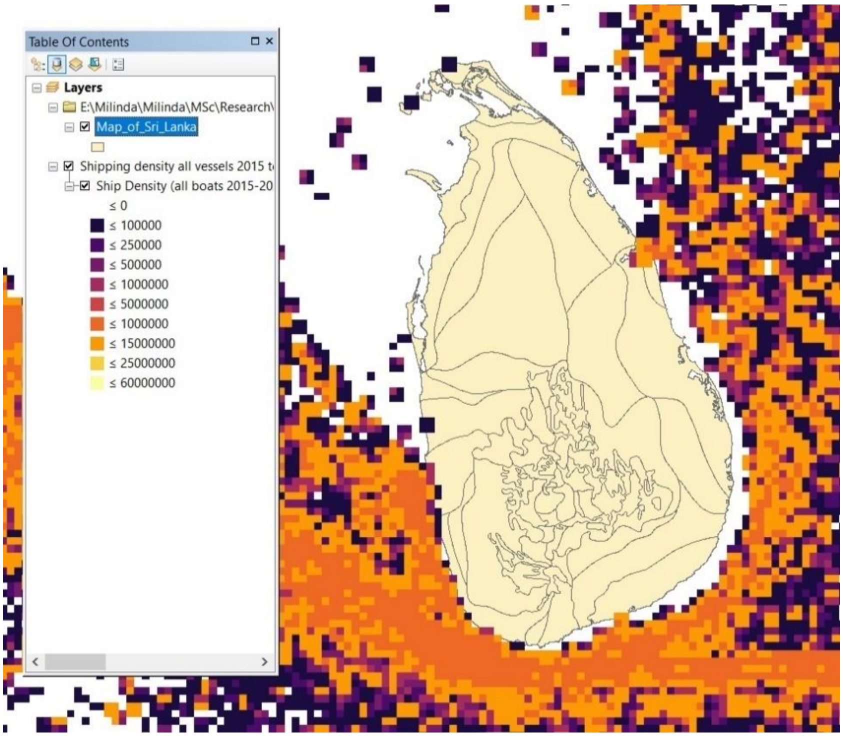


Figure 3-21 Shipping traffic related Sri Lanka – a localized image

This shipping traffic is a combination of vessel types mentioned below.

1. Commercial ships
2. Passenger ships
3. Fishing ships
4. Gas & Oil [note: this is just rigs, FPSOs, and platforms]
5. Leisure vessels

Then this raster image was used to extract the values for the shipping traffic in the intended area of study.

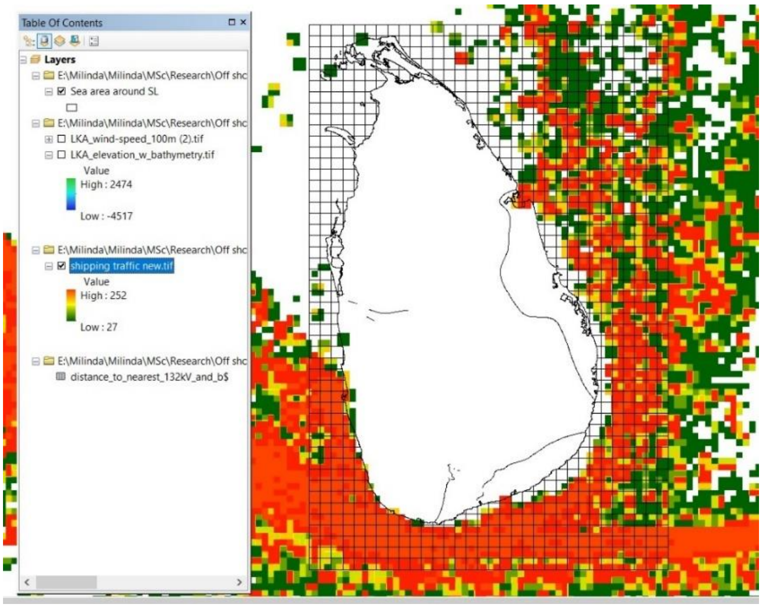


Figure 3-22 extraction of values for the shipping traffic

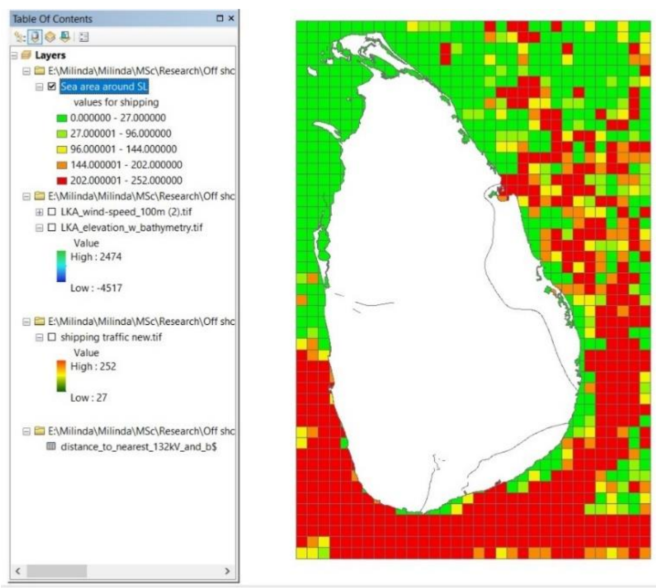


Figure 3-23 digitized map with shipping traffic

3.3.1.5 Oil/Gas exploration

Sri Lankan Sea area has been divided into several blocks for exploration of oil and Gas. This map is available with the Petroleum Development Secretariat.

The following image described how it was divided till recently

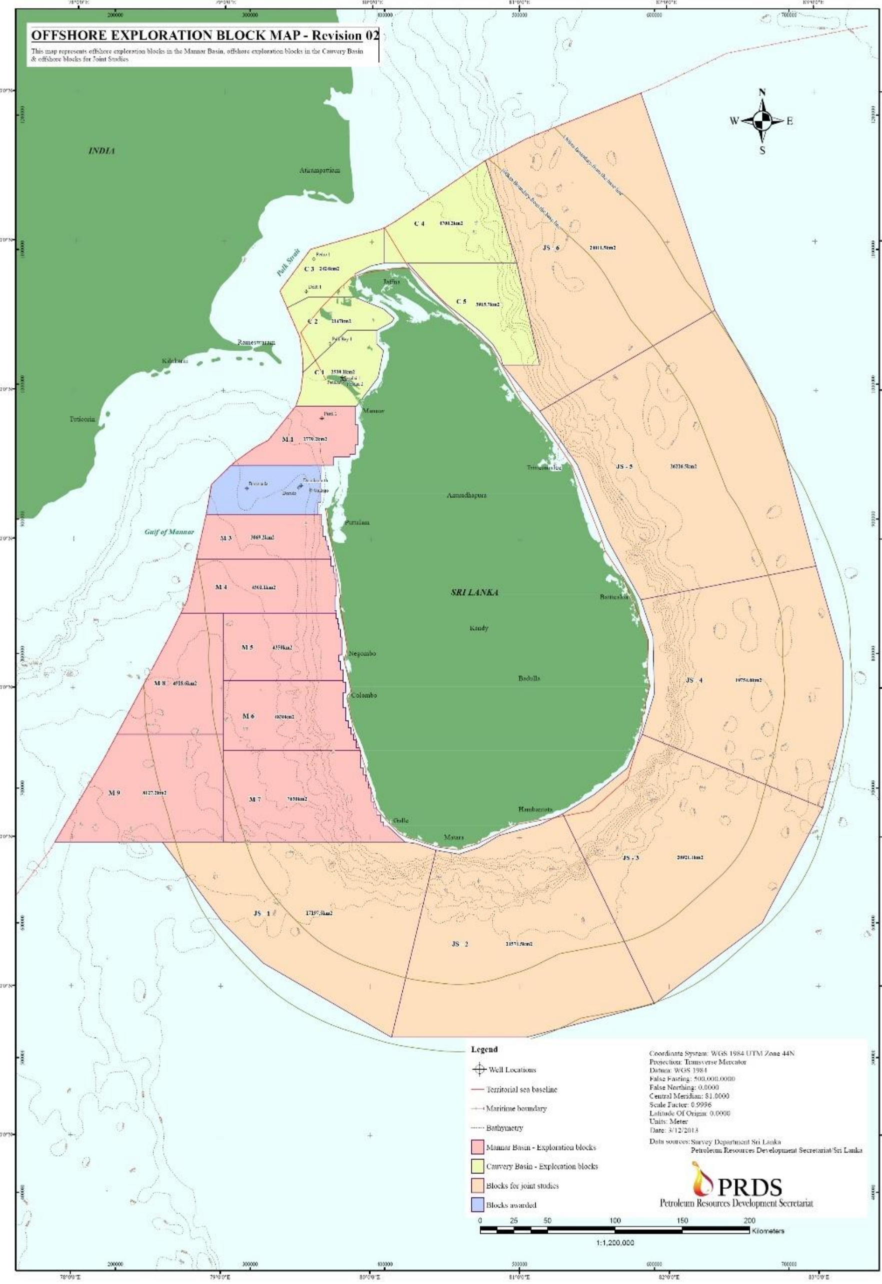


Figure 3-24 offshore exploration block map, 2013/3/12

One of the blocks was already awarded for oil exploration according to that image from PRDS. But this map was recently changed (2021/06/28) and by that the awarded block is mentioned as available for appraisal and development. When it is requested from the PRDS also it was mentioned that the block is not awarded to any party.

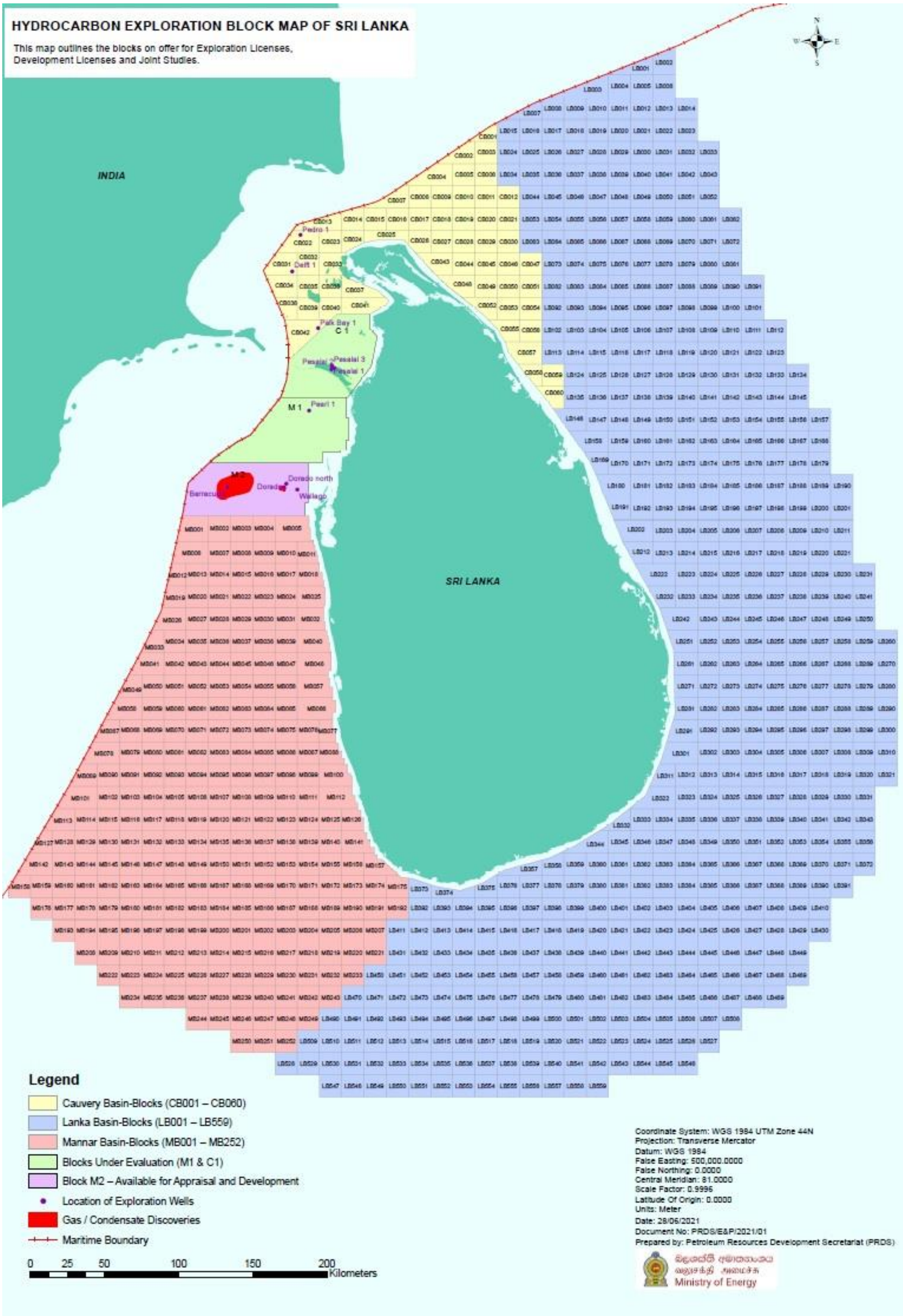


Figure 3-25 offshore hydrocarbon exploration block map, 2021/6/28

3.3.1.6 Oil wells

Oil wells also have been identified in the previous map, i: e Hydrocarbon exploration block map. However, these oil wells are still not being used for the excavation but kept as possible sources of energy for future use.

Figure 3-26 Oil well locations around Sri Lanka

3.3.1.7 Coastal security zone

Coastal Zone is described simply as area limited by 300 m landwards from the mean high-water line and 2km seaward from the mean low water line. The mean high-water line is 0.6 m above the mean sea level where the mean low water line is 0.6 m below the mean sea level. In the case of lagoons, streams, rivers, or anything of water connected to sea either periodically or permanently, the 300m landward boundary shall be extended to 2 km measured perpendicular to the base line drawn between the natural entrance points and further it shall include a 100 m buffer distance along the periphery.

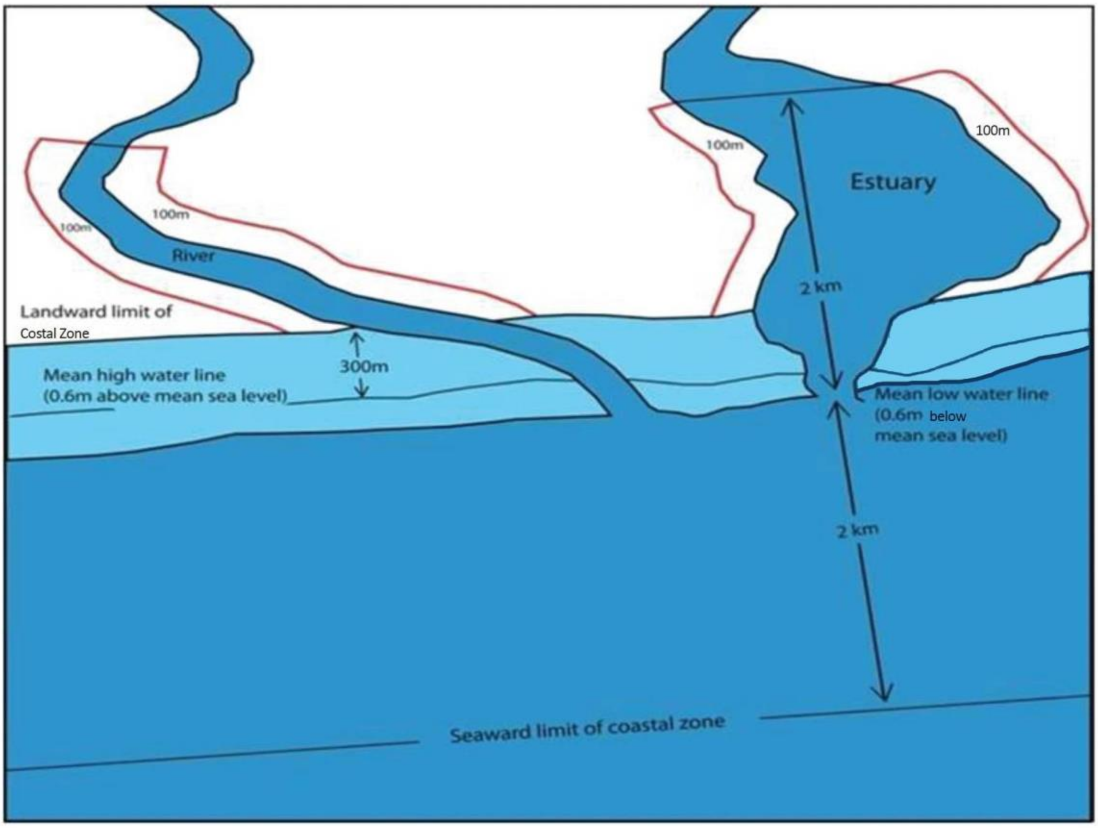


Figure 3-27 Coastal zone of Sri Lanka, Definition

This zone is further categorized into restricted and reserve areas for each and every area along the shore.

There the reserve area is not permitted for any external construction and in restricted zone approval for the requested can be granted but with the approval subjected to sole discretion of coastal conservation department. Normally the reserve area is limited to 30-40 m from the shore and restricted area is limited to 30-40 m from the reserve area. Some areas these values might be changed.

This data can be accessed via website of coastal conservation and coastal resource management department.

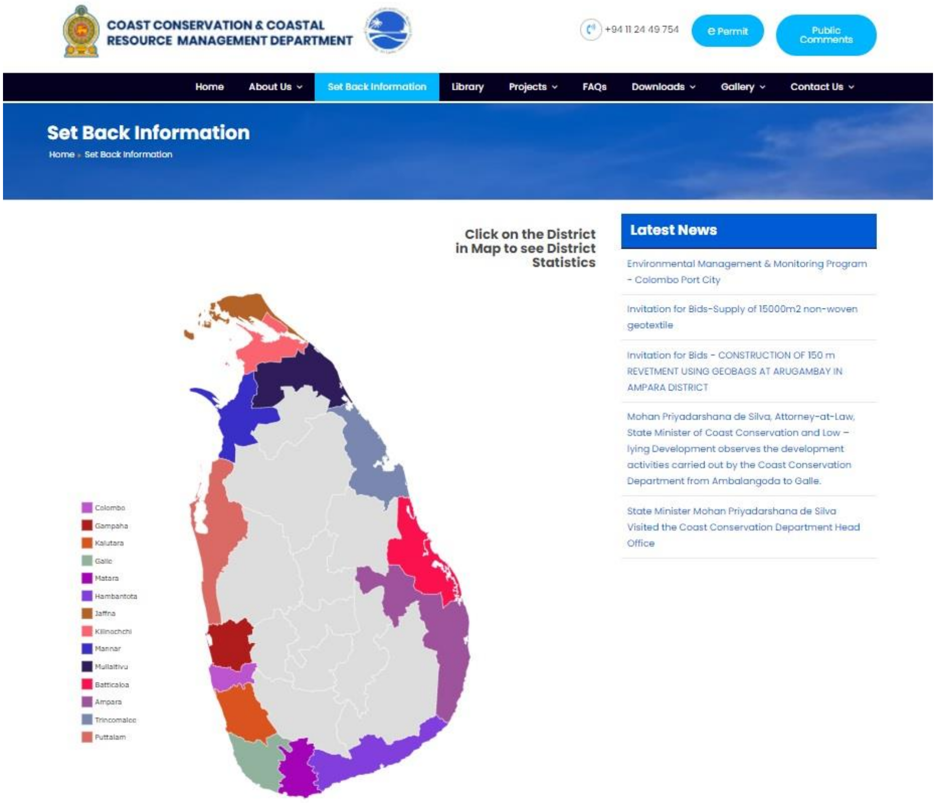
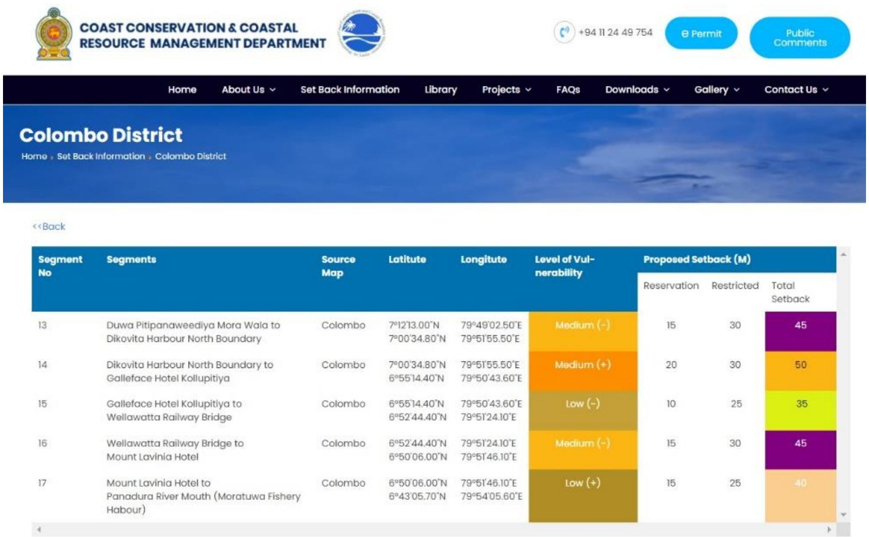


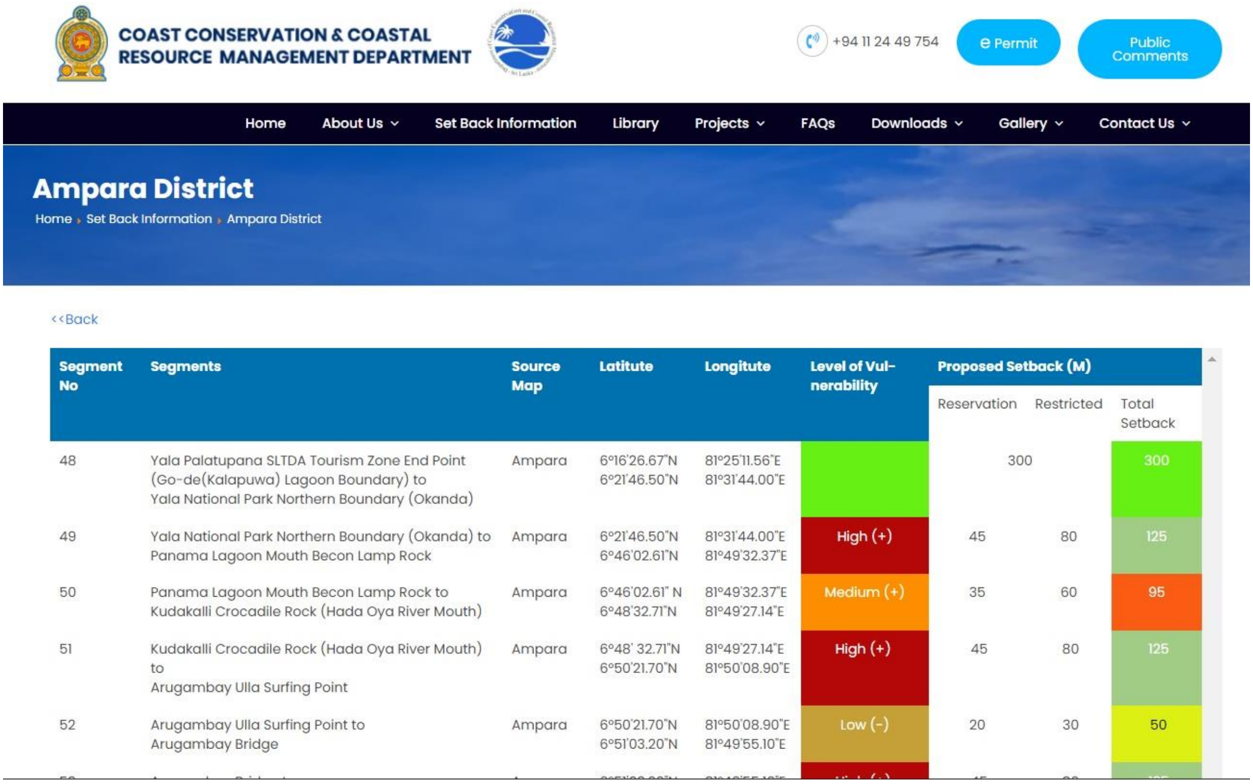
Figure 3-28 Coastal protected zone data access in website of coastal conservation and coastal resource management department.

By clicking each district data of the coastal reserve zone and restricted zone can be obtained.



Segment No	Segments	Source Map	Latitute	Longitute	Level of Vul-nerability	Proposed Setback (M)		
						Reservation	Restricted	Total Setback
13	Duwa Pitipanaweediya Mora Wala to Dikovita Harbour North Boundary	Colombo	7°12'13.00"N 7°00'34.80"N	79°49'02.50"E 79°51'55.50"E	Medium (-)	15	30	45
14	Dikovita Harbour North Boundary to Galleface Hotel Kollupitiya	Colombo	7°00'34.80"N 6°55'14.40"N	79°51'55.50"E 79°50'43.60"E	Medium (+)	20	30	50
15	Galleface Hotel Kollupitiya to Wellawatta Railway Bridge	Colombo	6°55'14.40"N 6°52'44.40"N	79°50'43.60"E 79°51'24.10"E	Low (-)	10	25	35
16	Wellawatta Railway Bridge to Mount Lavinia Hotel	Colombo	6°52'44.40"N 6°50'06.00"N	79°51'24.10"E 79°51'46.10"E	Medium (-)	15	30	45
17	Mount Lavinia Hotel to Panadura River Mouth (Moratuwa Fishery Habour)	Colombo	6°50'06.00"N 6°43'05.70"N	79°51'46.10"E 79°54'05.60"E	Low (+)	15	25	40

Figure 3-29 Coastal reserve and restricted zone data of Colombo district



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Ampara District

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Segment No	Segments	Source Map	Latitute	Longitute	Level of Vul-nerability	Proposed Setback (M)		
						Reservation	Restricted	Total Setback
48	Yala Palatupana SLTDA Tourism Zone End Point (Go-de(Kalapuwa) Lagoon Boundary) to Yala National Park Northern Boundary (Okanda)	Ampara	6°16'26.67"N 6°21'46.50"N	81°25'11.56"E 81°31'44.00"E		300		300
49	Yala National Park Northern Boundary (Okanda) to Panama Lagoon Mouth Becon Lamp Rock	Ampara	6°21'46.50"N 6°46'02.61"N	81°31'44.00"E 81°49'32.37"E	High (+)	45	80	125
50	Panama Lagoon Mouth Becon Lamp Rock to Kudakalli Crocadile Rock (Hada Oya River Mouth)	Ampara	6°46'02.61" N 6°48'32.71"N	81°49'32.37"E 81°49'27.14"E	Medium (+)	35	60	95
51	Kudakalli Crocadile Rock (Hada Oya River Mouth) to Arugambay Ulla Surfing Point	Ampara	6°48' 32.71"N 6°50'21.70"N	81°49'27.14"E 81°50'08.90"E	High (+)	45	80	125
52	Arugambay Ulla Surfing Point to Arugambay Bridge	Ampara	6°50'21.70"N 6°51'03.20"N	81°50'08.90"E 81°49'55.10"E	Low (-)	20	30	50

Figure 3-30 Coastal reserve and restricted zone data of Ampara district

Although the reserved zone is not approved for any construction works, as per the of coastal conservation and coastal resource management department, the restricted zone may be released for construction works if approval is granted. Further from restricted zone to end of coastal zone (2 km seaward from mean lower sea level) no approval from the coastal conservation and coastal resource management department is required.

Hence when considering a cell of 10 km by 10 km, rejecting the whole cell area just for a maximum of 300m and most of the time 100-150m objection, it seems to be too much. Hence the constraint of the coastal protection was omitted at the moment but still this has the possibility of incorporating this constraint when required.

3.3.2 Environmental Constraints

3.3.2.1 Impact to the Coral reefs

Coral reefs are natural habitats of many species providing a higher biodiversity. There are several sites of famous coral reefs around Sri Lanka situated near Hikkaduwa, Puttalam etc. conservating the biodiversity as well as attracting lot of tourists for the same reason. It takes a lot of time for the creation of coral reefs averaging in 0.2-2cm per year. Hence when construction works are carried out of offshore wind farm special attention should be provided to avoid sites containing coral reefs.

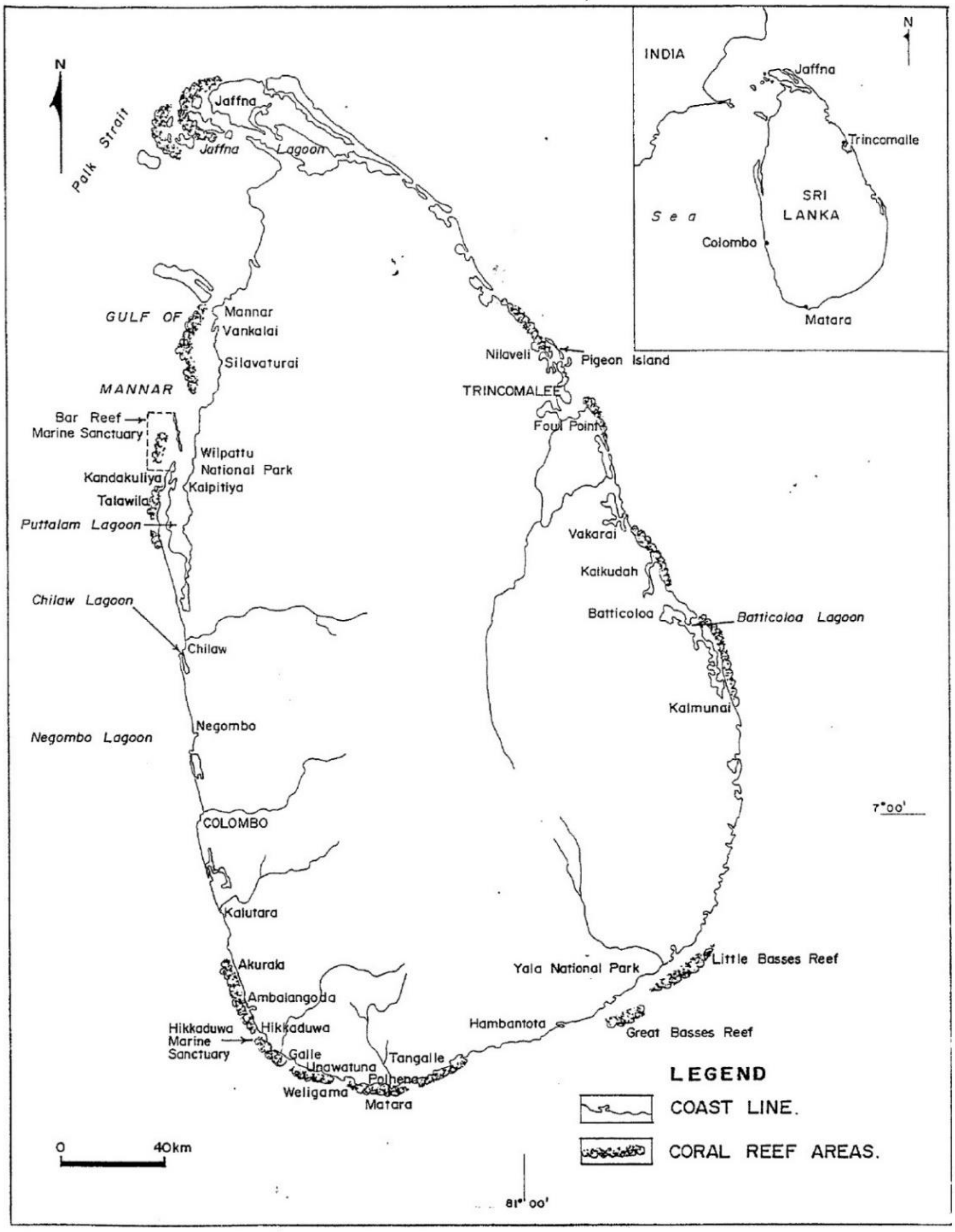

Figure 3-31 coral reefs around Sri Lanka

(Source: National Aquatic Resources Research and Development Agency (NARA))

The above image shows the existing coral reefs in Sri Lanka. This image was used to digitize the locations of coral reef and retrieve the data for the modelling.

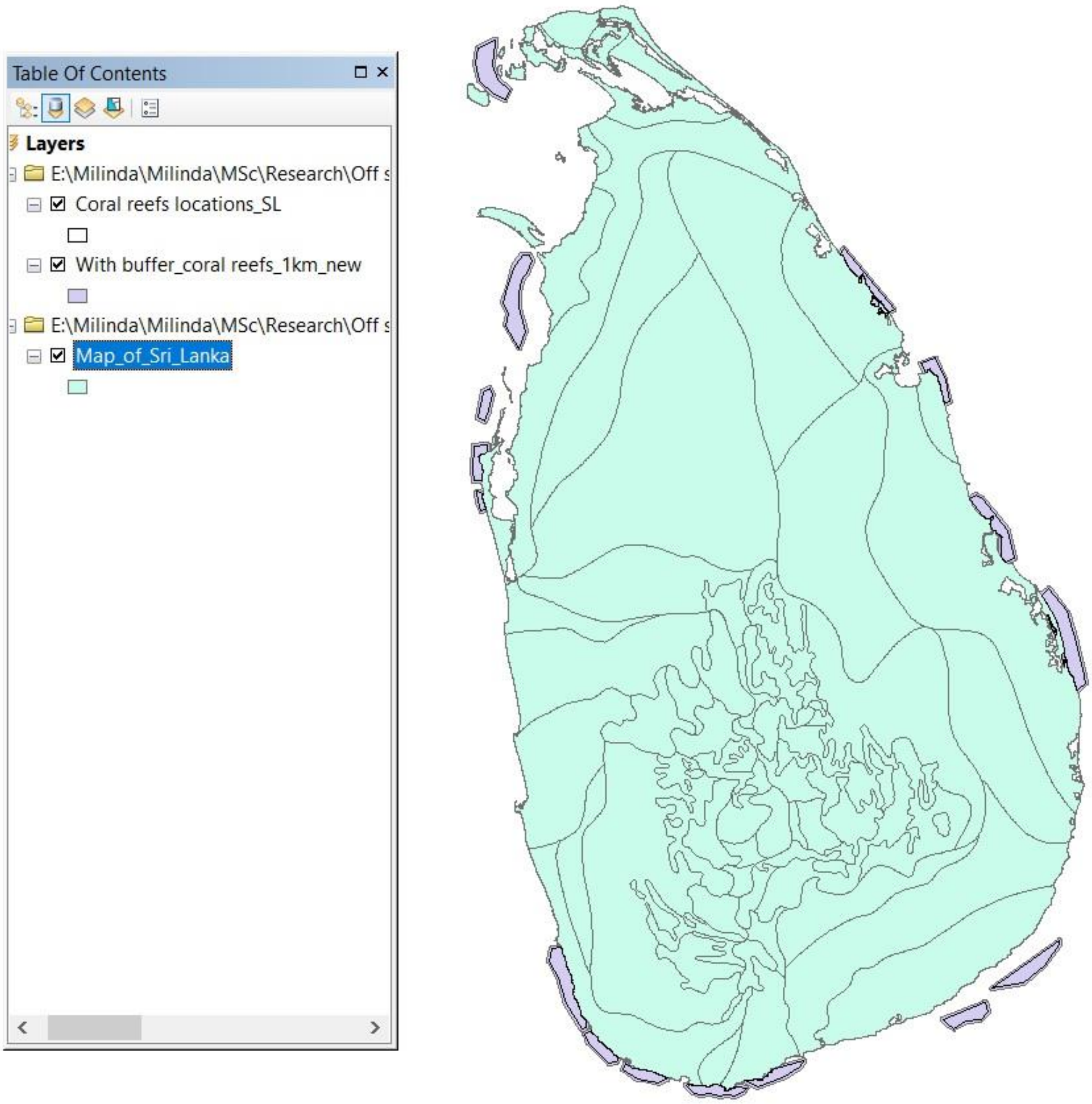

Figure 3-32 digitized coral reefs of Sri Lanka using ArcGIS Software

When determining a safety distance there was no solid established law or guideline. Hence it was further inquired from the Marine Environment Protection Authority. Since there is no such hard and fast rule, a 1km buffer was decided to be added as a safety distance. The above digitized map shows the digitized location of coral reefs and the 1 km buffer region.

Once the wind turbines are installed, they will also act as natural habitats for various sea creatures and called it as artificial reefs.

3.3.2.2 Impacts to Marine mammals, fishes and other sea creatures

Marine mammals, fishes and other sea creatures are also to be considered as a major environment constraint when selecting suitable sites for the offshore wind farms. As learnt in literature review, they more severely impacted during the construction phase. Although the long-term effects are still not very well known, it is accepted that most of sea creatures will return to their natural habitats once the construction phase is finished.

Although there is an impact from operational acoustic waves, studies which have been done on already established offshore wind farms shows that it is negligible. But it has to be stated that the still a very limited knowledge is available on the behavioral response of fish to noise and vibrations from offshore wind developments.

In order to cater the effect of construction phase of wind turbine installation on sea creatures, it was decided to avoid areas of major siting of especially the marine mammals. As it is difficult to pinpoint every type of fishes in the sea area around Sri Lanka it is very difficult to cater all sub areas of siting of different kinds of fishes. Studies/investigations have been done mainly on marine mammals and hence only marine mammals were considered.

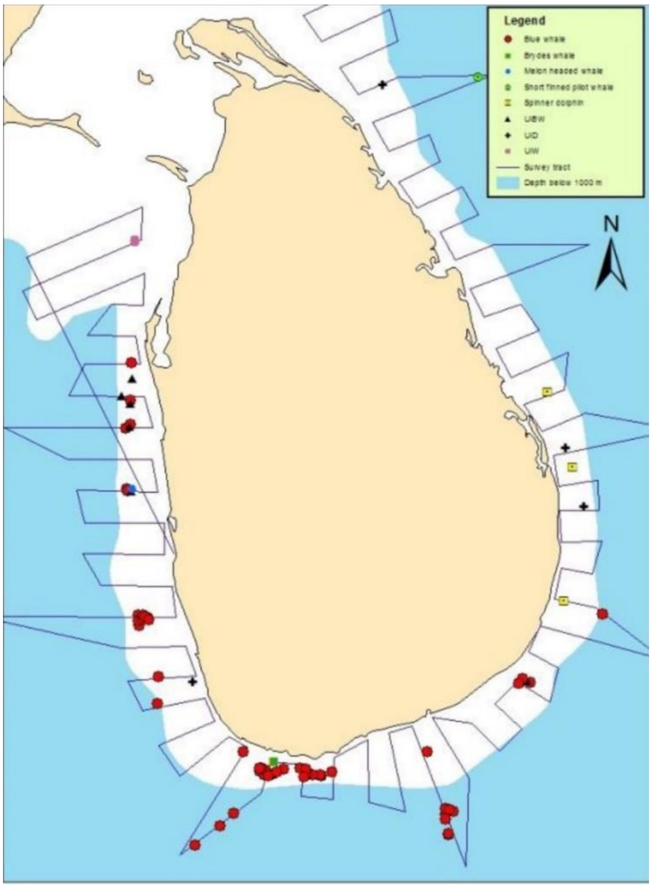

Figure 3-33 siting of marine mammals around Sri Lanka

Source: Brief Summary of findings "DR FRIDTJOF NANSEN". Ecosystem survey of Sri Lanka 2018 – NARA

According to “The Oceanography Society” (www.tos.org) the physical injuries to the fishes have been recorded over 200 dB re 1 μPa^2. Further in around 180-190 dB re 1 μPa^2 they have shown some behavioral changes. Hence when referring to the noise levels variation with the distance in construction phases of windfarms and the noise levels that will not harm the marine mammals around 2 km buffer distance was selected.

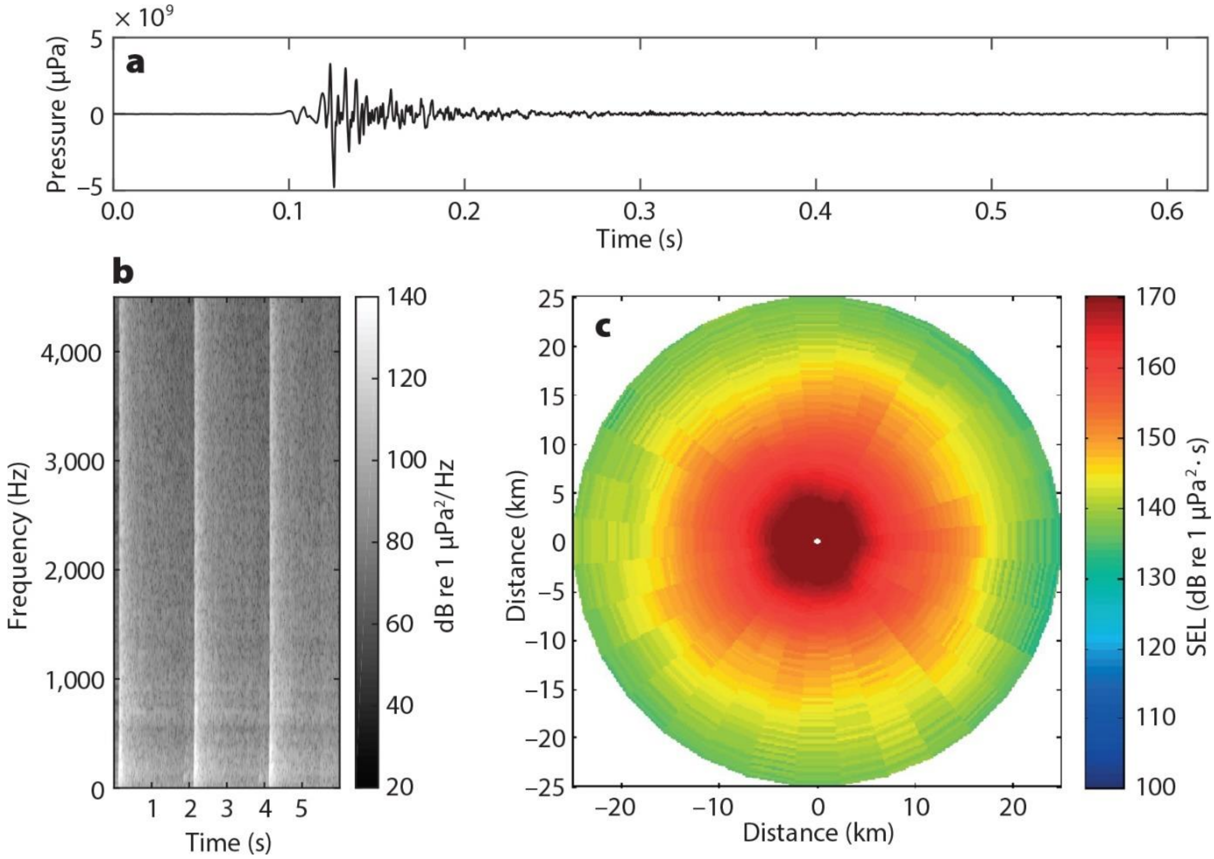

Figure 3-34 noise level variation with the distance during construction phase of windfarms

Source: https://tos.org/oceanography/article/acoustic-impacts-of-offshore-wind-energy-on-fishery-resources-an-evolving-source-and-varied-effects-across-a-wind-farms-lifetime

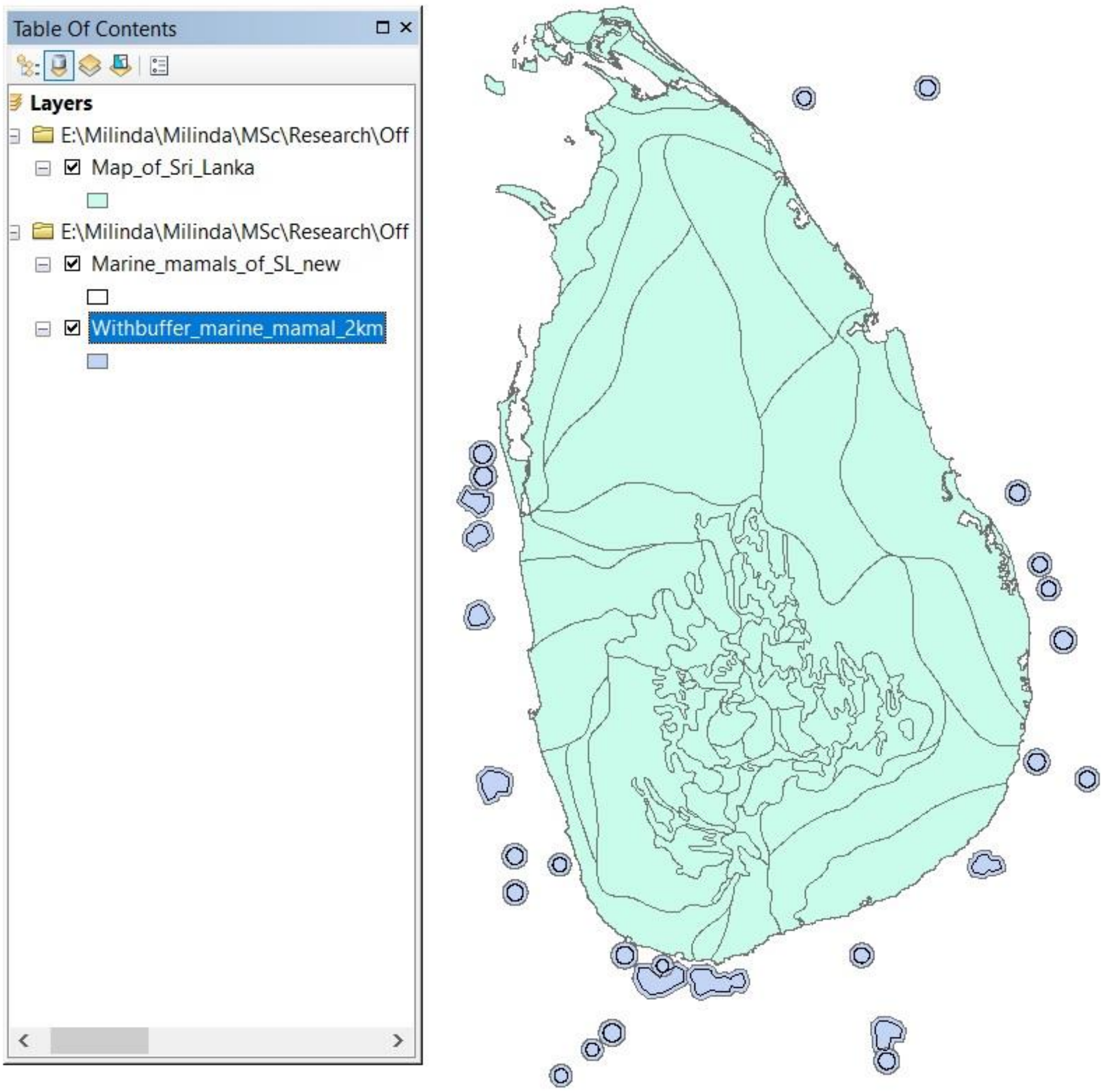

Figure 3-35 digitized map of marine mammals around Sri Lanka with indicating a 2 km buffer Zone

3.3.2.3 Migratory pathways of birds

Migratory birds will also have negative impacts from offshore wind farm if they are situated in their migratory pathways. There is possible chance of birds hitting on rotating rotor blades and been killed. So special attention is required to avoid those pathways as much as possible to reduce the negative impacts for the migratory birds.

There are no proper maps showing migratory pathways available and hence an image shown in a book named as “An Illustrated Guide to the Birds of Sri Lanka” by Gamini Ratnavira and Sarath Kotagama was used to digitize the paths.

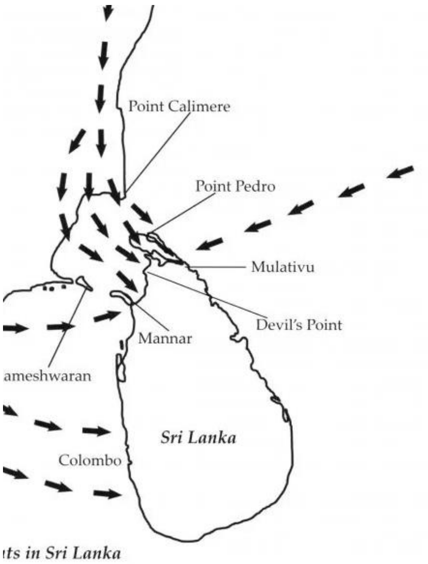

Figure 3-36 Migratory pathways of birds around Sri Lanka

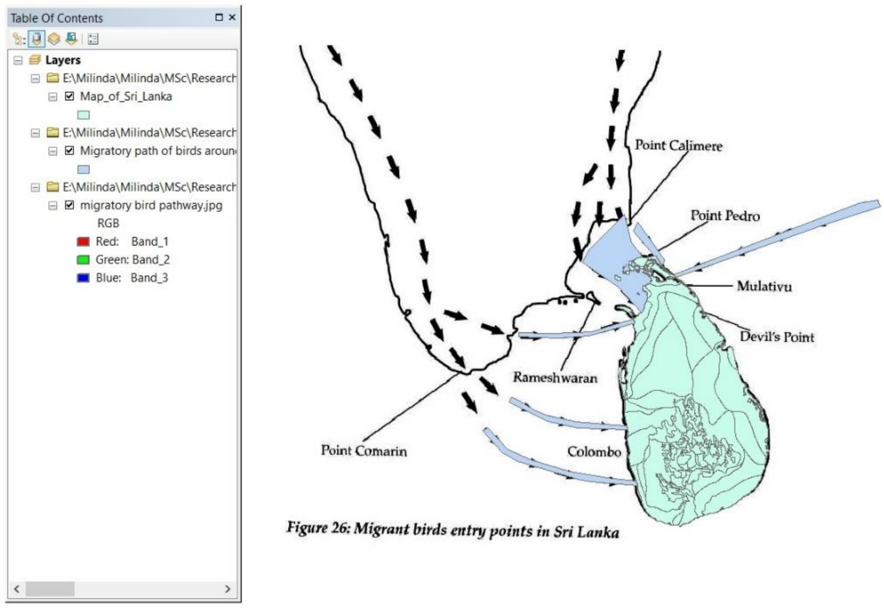

Figure 3-37 digitized migratory pathways of birds around Sri Lanka

3.3.3 Tourism related constraints

There are many tourism related activities in Sri Lanka based on the sea and the shore. Tourists provide a considerable portion of the earnings of Sri Lanka and hence it is important to minimize the adverse effects on tourism due to offshore wind farms when selecting the sites.

depending on the popularity among tourists based on their posts on travel blogs the following constraints have been extracted.

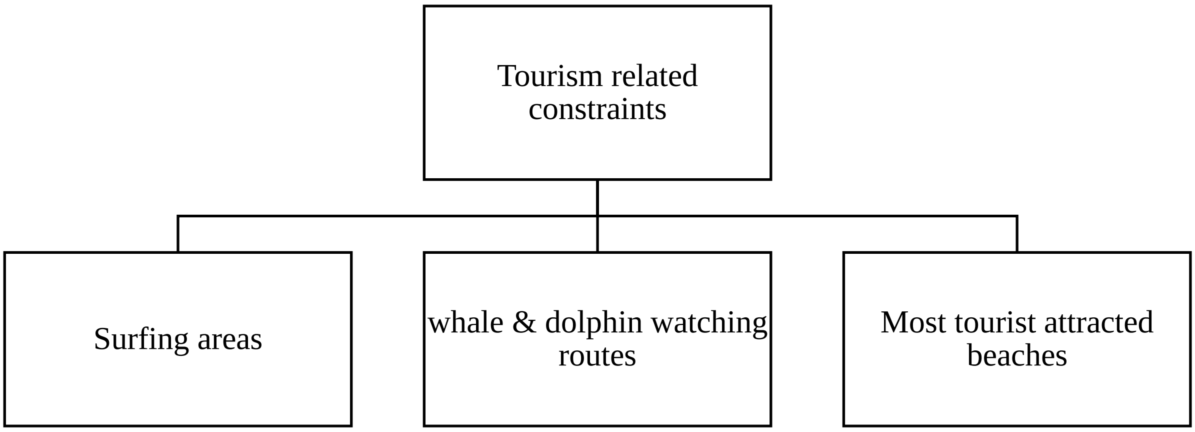

Figure 3-38 tourism related constraints to be adopted

Although mentioned above may not the only constraints, it is always possible to incorporate any identified constraint in future to this model.

3.3.3.1 Surfing areas

Eastern sea area around Arugam bay is the well-known site for the surfing. Apart from that there are sites in Hikkaduwa, Weligama , Mirissa, Matara etc

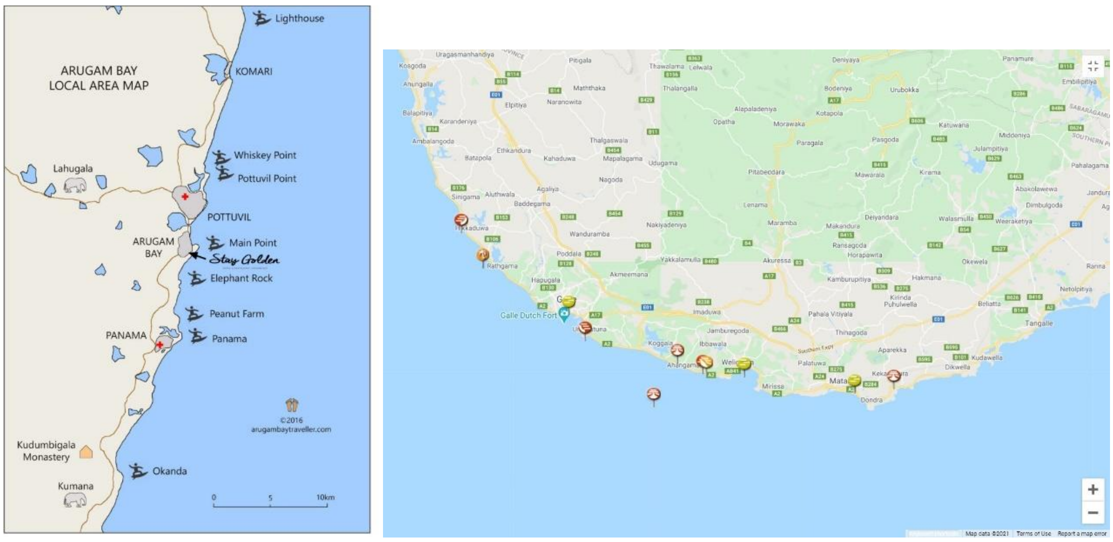

Figure 3-39 major surfing sites in Sri Lanka

The data was collected using several travel blogs and referring to internet as there are not any official information about this.

Since there are not any solid data on how far the surfing area is extended rough sketch enclosing the surfing positions of the images taken from internet was used. Then a safety zone of 1 km buffer was introduced. Hence the total distance of the entire zone is varying around 3-7 km from the shore in some places.

These maps were then digitized to identify the cells coincides with the surfing areas.

It is to be noted that, in any case where a proper/official map is found it is possible to extract the data and incorporate that with this model.

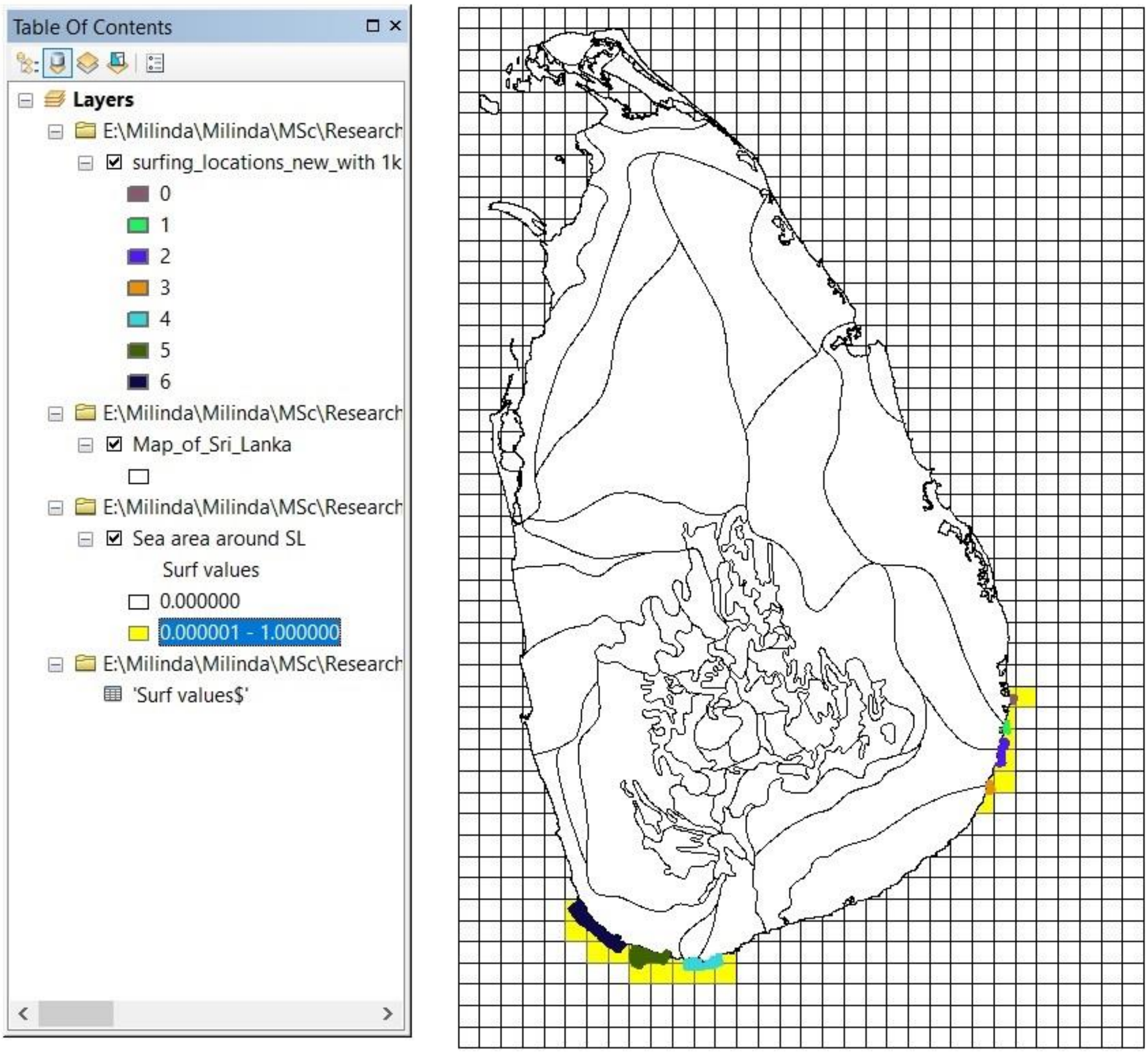

Figure 3-40 digitized surfing areas around Sri Lanka

3.3.3.2 Whale and dolphin watching routes

Whale and dolphin watching is another very famous tourism related activity. Many tourists as well as locals take this opportunity to travel into the sea and watch whales and dolphins at their natural behaviour.

Apart from the famous cruise ships, currently airplane rides are also offered in order to capture a bird eye view of whales and dolphins

There are 3 main sites have been identified.

1. Mirissa
2. Kalpitiya
3. Tricomalee

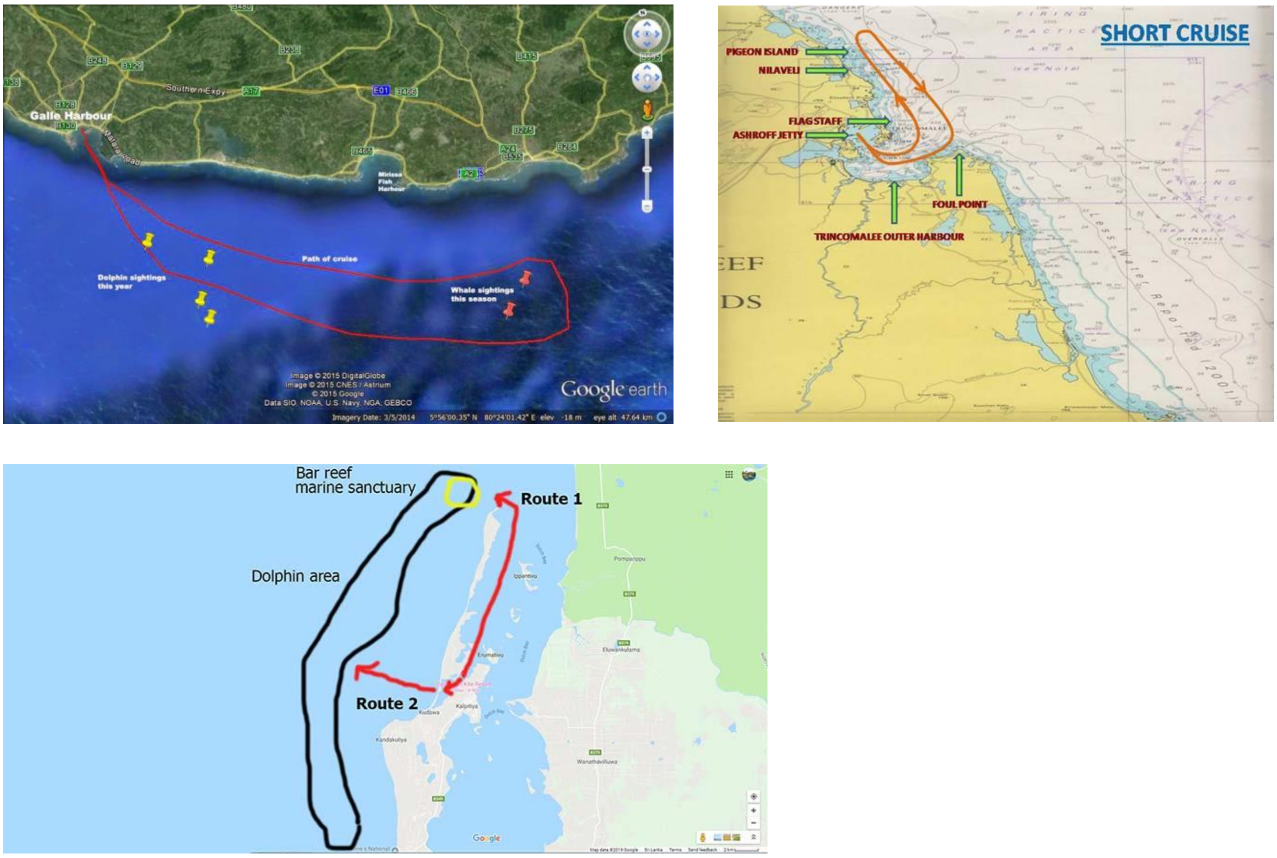

Figure 3-41 routes of whale and dolphin watching in 3 main sites

Since for some of these tours air crafts are also used, considering the risk, a 5 km buffer zone was arbitrary introduced. Then similarly those areas of the map were digitized in order to identify the coinciding cells of intended area of study with these areas.

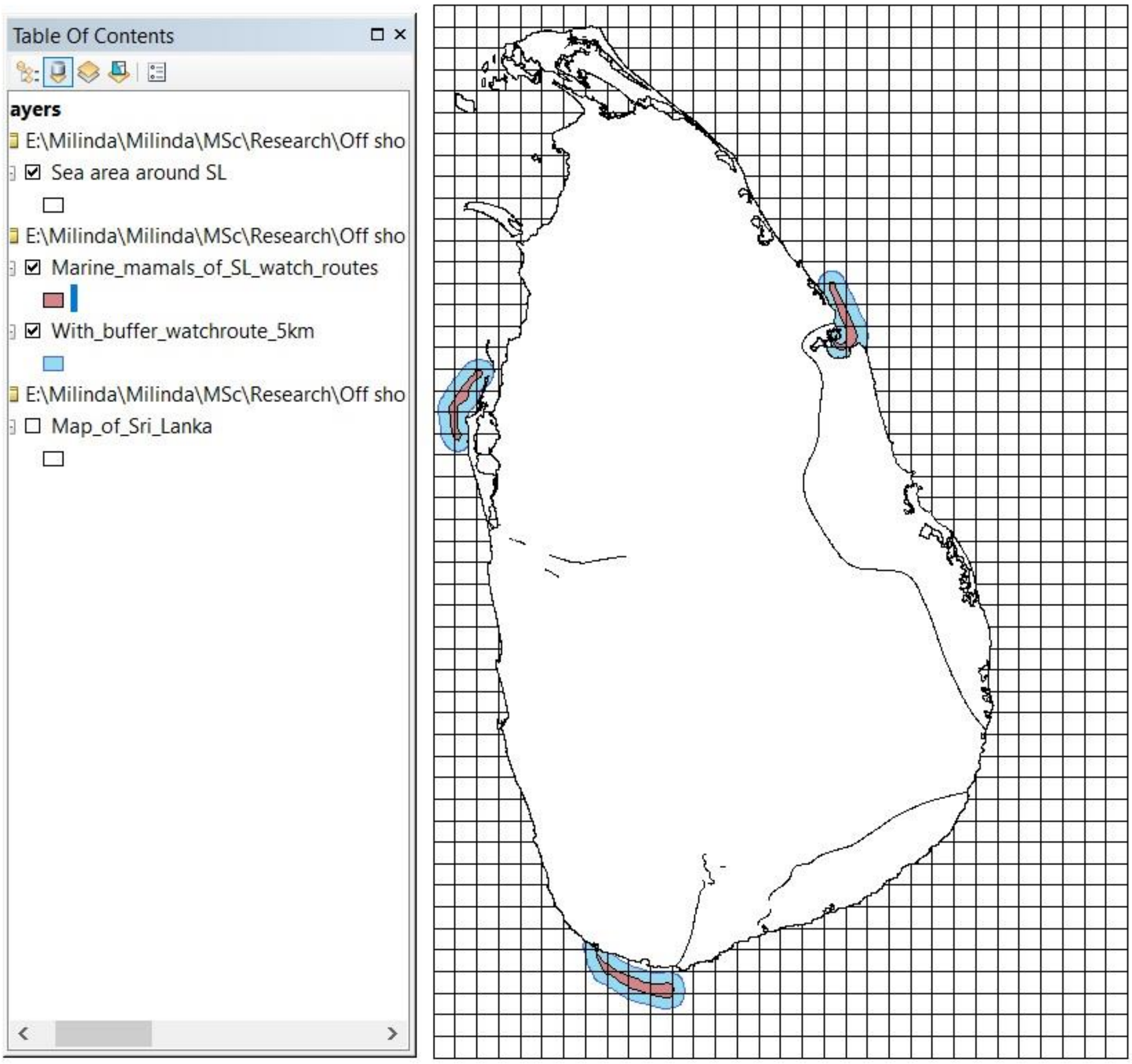

Figure 3-42 Whale and dolphin watching routes with 5km buffer zone

3.3.3.3 Most tourist attracted beaches

Sri Lanka is surrounded by the sea and hence contains beautiful beaches in most areas along the shore. Among them there are some extremely important beaches from the perspective of tourism. They are Nilaveli beach and the pasikudah beach.

Of course there are some other beaches which is very hard to tell them apart that which beach is more beautiful but with releating to the travel blogs of various people, I found that these two beaches are important to consider. Hence I am selecting these two beaches only and if there are additional beaches to consider, it is also possible.

Since when conservating the beauty of the beach, I feel that it is very important to not to disturb the visual beauty of that place. When distance to the shore is considered for already installed offshore wind farms in the world, it is obvious that when the distance is about 15 km it is still visible and may affect the visual impact negatively.

Figure 3-43 offshore wind farm burbo bank seen form shore 16.7 km

Hence an arbitrary areas of extending roughly around 20 km seaward from the shore are drawn for both beaches using ArcGIS software. These areas were also extended along the shore back and forth arbitrarily. Similary then the map was digitized to obtain the conciding cells of study area with those beaches.

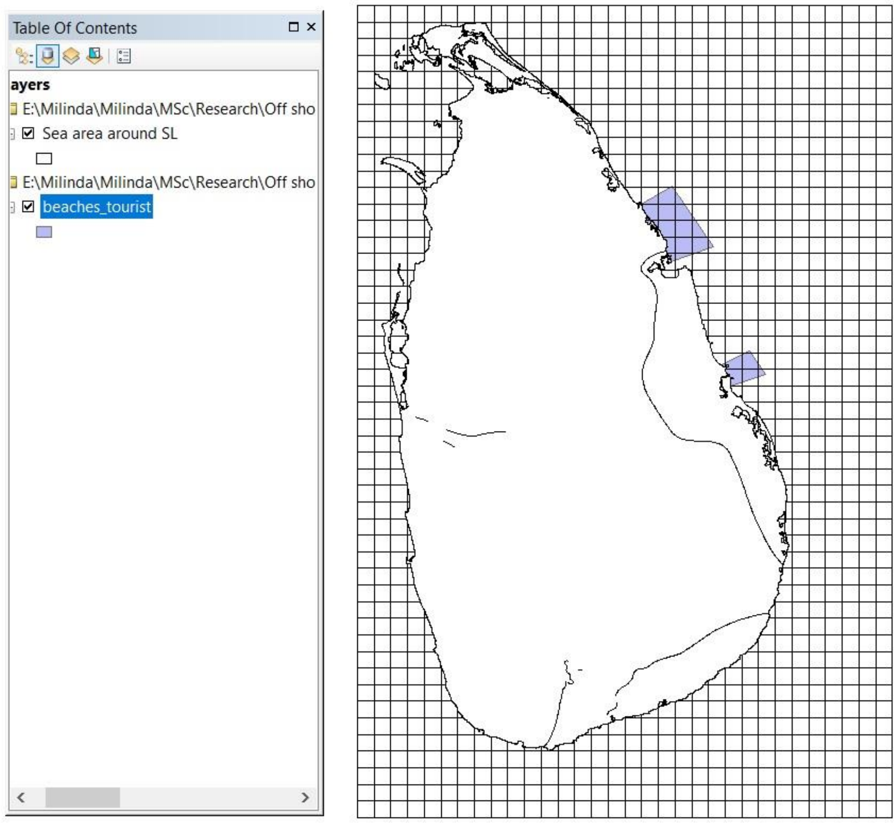

Figure 3-44 Selected digitized beaches of Sri Lanka

3.3.4 Technical constraints

3.3.4.1 Existing nearshore windfarms

Sri Lanka coast is having some already installed windfarms mainly near Puttalam & Mannar. It is essential to keep a reasonable gap between two turbines to avoid power reduction.

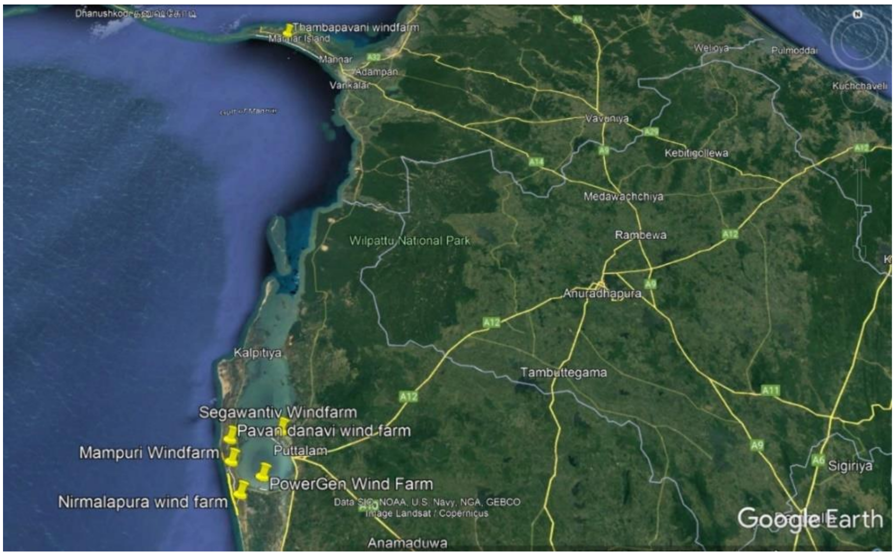

Figure 3-45 existing nearshore windfarms in Sri Lanka

Normally the rule of thumb is to keep them 7 rotor diameters apart. But in some literatures, it has been mentioned as 10 rotor diameters.

Further as the diameter of the wind turbines which are to be installed in the selected site is still to be decided, it is required to select a proper buffer zone considering a safety margin. Hence to be on the safe side 2 km buffer distance was selected considering 10 rotor diameters and maximum of 200m rotor diameter.

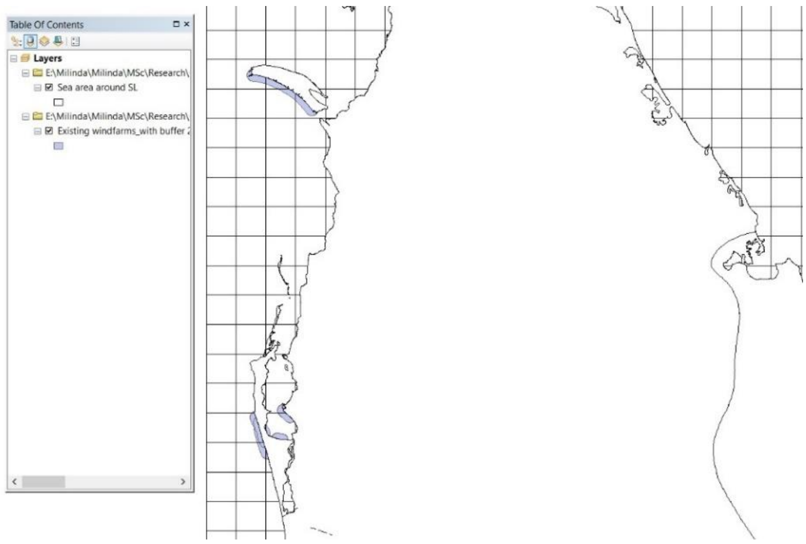

Figure 3-46 Buffer distance of 2 km from Existing windfarms

3.4 Modelling

In the selection of intended area of study, the area of interest was broken into 10 km by 10 km cells. There were 1047 Nos of cells with numbering FID 0 – FID 1046. Each cell represents smaller 100 km^2 area.

In the modelling part, the identified selection factors and constraints were used to evaluate each cell area's suitableness to be selected as a potential site for offshore wind power farm development. Weightage factors for each selection factor of each cell were obtained based on the model derived from the data of already developed offshore wind farms.

3.4.1 Wind speed

Wind power is proportional to the cubic value of wind speed.

$$P = \frac{1}{2}\rho A v^3$$

P = Wind power

ρ = desity of Air

v = wind speed

A = Area swept by the rotor blades

Since there are two variables ie: rotor diameter and the wind speed, the wind power per unit area swept by the rotor is considered

$$\frac{P}{A} = \frac{1}{2}\rho v^3$$

This leads to

$$\frac{P}{A} \propto v^3$$

Hence the power output of unit area swept by rotor is proportional to the cubic value of wind speed. Depending on the increasing rotor diameter there may be slight variations of the efficiency, but it was neglected for site selection process.

Hence the marks for each cell for the selection factor of wind speed was calculated by the cubic value of extracted value of wind speed from the GIS software.

3.4.2 Water depth

In calculating the weightage for the water depth there were no direct impacts from the water depth to the power output. In fact, it affects only for the turbine installation. As learnt in the literature review different ranges of water depth requires different types of foundations for the wind turbines. Depending on the type of the foundation the cost is varied. In fact, the cost for the foundations of the wind turbine is a major cost component. Hence the water depth in fact affects the total cost of construction.

To obtain a relationship between total cost and the water depth there were no established equation. Hence data of the existing offshore wind farms were used to obtain such a relationship.

	Wind farm	**Location**	Site coordinates	**Capacity (MW)**
1	Hornsea 1	United Kingdom	53.885°N 1.791°E	**1218**
2	Borssele 1&2	Netherlands		752
3	Borssele 3&4	Netherlands		731.5
4	East Anglia ONE	United Kingdom	52°14′53.8573″N 2°30′23.4094″E	714
5	Walney Extension	United Kingdom	54°5′17″N 3°44′17″W	659
6	Gemini Wind Farm	Netherlands	54°2′10″N 05°57′47″E	600
7	Beatrice	United Kingdom	58°7′48″N 3°4′12″W	588
8	Gode Wind (phases 1+2)	Germany	54°04′N 7°02′E	582
9	Gwynt y Môr	United Kingdom	53°27′00″N 03°35′00″W	576
10	Race Bank	United Kingdom	53°16′N 0°50′E	573
11	Greater Gabbard	United Kingdom	51°52′48″N 1°56′24″E	504
12	Hohe See	Germany	54°26′N 6°19′E	497
13	Borkum Riffgrund 2	Germany	53°57′7″N 6°29′17″E	450
14	Horns Rev 3	Denmark	55°49′N 7°42′E	407
15	Dudgeon	United Kingdom	53°14′56″N 1°23′24″E	402
16	Veja Mate	Germany	54°19′1″N 5°52′15″E	402
17	Anholt	Denmark	56°36′00″N 11°12′36″E	400
18	BARD Offshore 1	Germany	54°22′0″N 5°59′0″E	400
19	Global Tech I	Germany	54°30′00″N 6°21′30″E	400
20	Rampion	United Kingdom	50°40′N 0°06′W	400
21	Merkur	Germany	54°2′N 6°33′E	396

22	West of Duddon Sands	United Kingdom	53°59′02″N 3°27′50″W	389
23	Arkona	Germany	54°46′55.200″N 14°7′15.600″E	385
24	Norther OWF	Belgium	51°31′40″N 3°1′55″E	370
25	Walney (phases 1&2)	United Kingdom	54°02′38″N 3°31′19″W	367
26	Galloper	United Kingdom	51°52′48″N 1°56′24″E	353
27	Wikinger	Germany	54°50′2″N 14°4′5″E	350
28	Nordsee One	Germany	53°58′0″N 06°48′00″E	332
29	Thorntonbank (phases 1–3)	Belgium	51°33′00″N 2°56′00″E	325
30	Sheringham Shoal	United Kingdom	53°7′0″N 1°8′0″E	315
31	Borkum Riffgrund 1	Germany	53°58′0″N 06°33′00″E	312
32	Rentel	Belgium	51°35′27.6″N 2°56′38.4″E	308.7
33	Amrumbank West	Germany	54°30′0″N 07°48′00″E	302
34	Thanet	United Kingdom	51°26′0″N 01°38′0″E	300
35	Nordsee Ost	Germany	54°26′00″N 7°41′00″E	295
36	Butendiek	Germany	54°54′0″N 07°45′00″E	288
37	DanTysk	Germany	55°9′00″N 7°10′30″E	288
38	Baltic 2	Germany	54°58′24″N 13°10′40″E	288
39	Meerwind Süd / Ost	Germany	54°23′00″N 7°42′00″E	288
40	Lincs	United Kingdom	53°11′00″N 00°29′00″E	270
41	Burbo Bank Extension	United Kingdom	53°28′48″N 3°15′36″W	258
42	Humber Gateway	United Kingdom	53°38′38″N 0°17′35″E	219
43	Northwind	Belgium	51°37′08″N 02°54′03″E	216
44	Westermost Rough	United Kingdom	53°48′0″N 0°9′0″E	210
45	Horns Rev 2	Denmark	55°36′00″N 7°35′24″E	209
46	Trianel Borkum West II (Phase 1 & 2)	Germany	54°2′30″N 6°28′0″E	400
47	Donghai Bridge	China	30.770°N 121.994°E	100
48	Lillgrund	Sweden	55°31′N 12°47′E	110
49	Hywind Tampen	Norway	61° 19' 47.9" 2° 42' 0"	88
50	Hywind Scotland	Scotland	57°29′N 01°21′W	30

Table 3-1 List of existing wind farms

In some cases, the site coordinates were not available. In such situation geo referencing of particular site maps was used to identify the location.

For each of these wind farms the water depth and total cost was taken from the internet with referring to the particular web site of offshore power plant where possible. Also, the bathymetry function of global wind atlas was used to verify the water depth (minimum, maximum and average)

The cost was found in different currencies such as USD, Euro and Sterling pounds. Since it is difficult to compare the costs using several currencies all of them were converted to USD. Then to remove the effect of the capacity from the cost component due to type of turbine foundation, cost/MW term was considered for each offshore wind farm. Ie: the total cost/capacity.

General cost component for turbine foundation was found to be around 22% of the total cost for the reference project No 1(2017) and 27.5% for the reference project No 2 (2019). For Floating foundation this was found to be around 33.4% of the total cost for the reference project No 1(2017) and 37.6% for the reference project No 2 (2019)

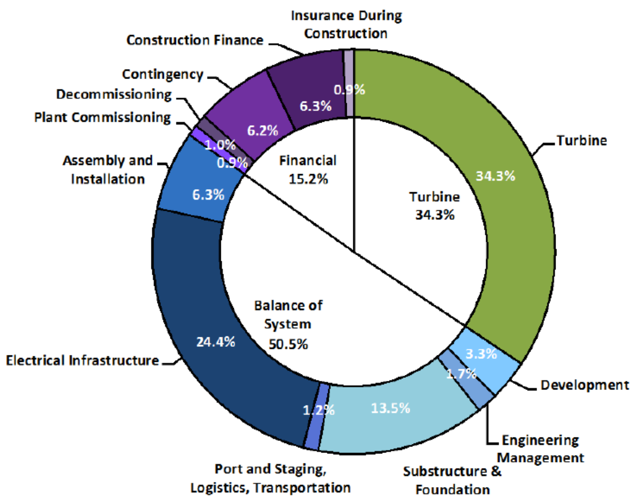

Figure 3-47 Capital Expenditure for the fixed-bottom offshore reference wind power plant project (Source – NREL 2017)

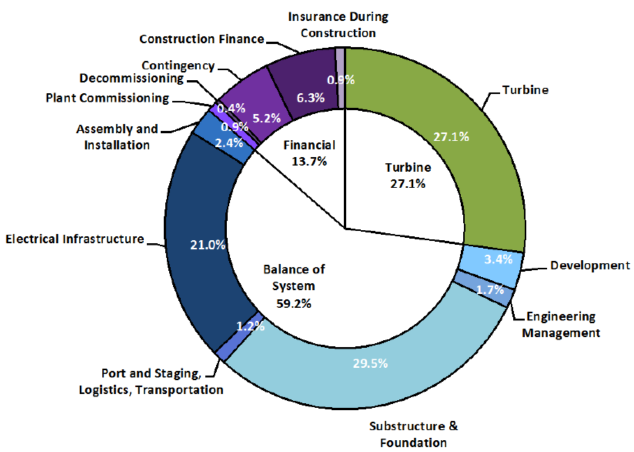

Figure 3-48 Capital Expenditure for the floating offshore reference wind power plant project (Source – NREL 2017)

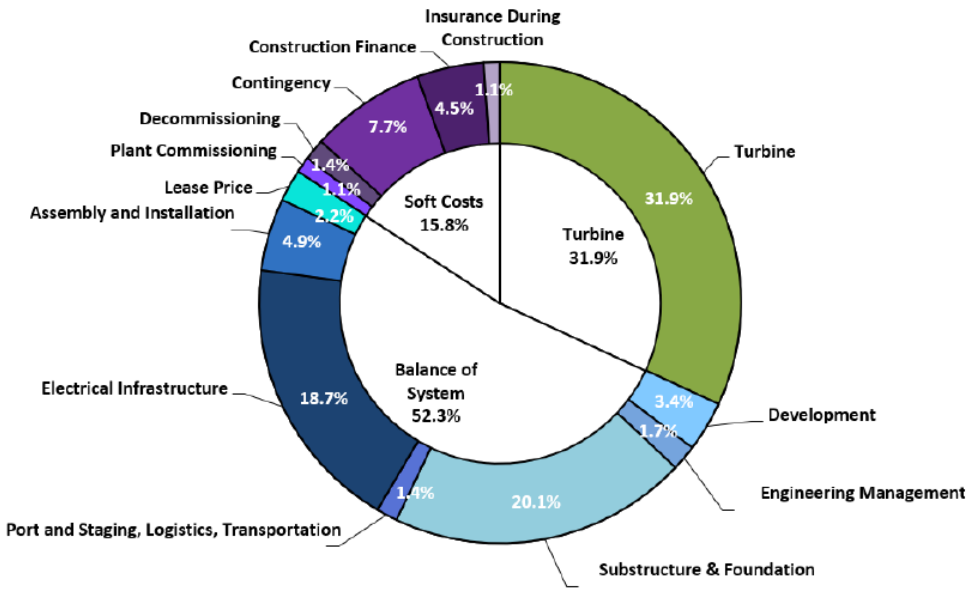

Figure 3-49 Capital Expenditure for the fixed-bottom offshore reference wind power plant project (Source – NREL 2019)

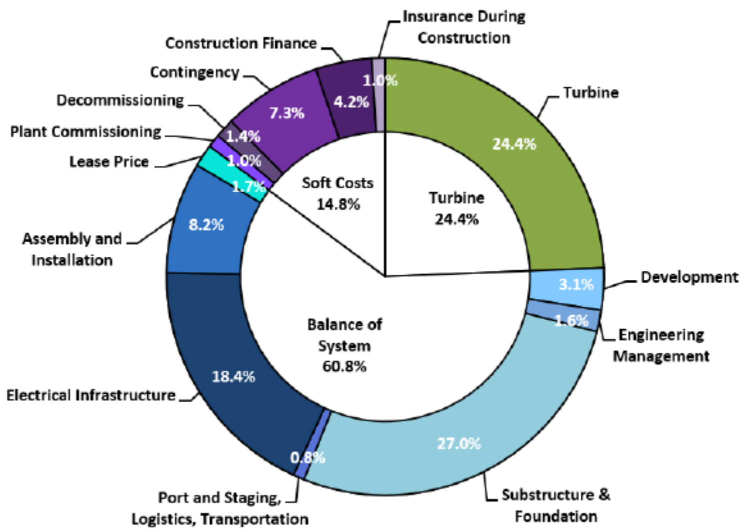

Figure 3-50 Capital Expenditure for the floating offshore reference wind power plant project (Source – NREL 2019)

Hence average value was selected as 24.75% which is approximately 25% for fixed bottom foundation & the installation and 35.5% which is approximately 36% for the floating foundation structure.

By using these values, cost for the turbine foundation & installation (per MW) were calculated for each wind farm.

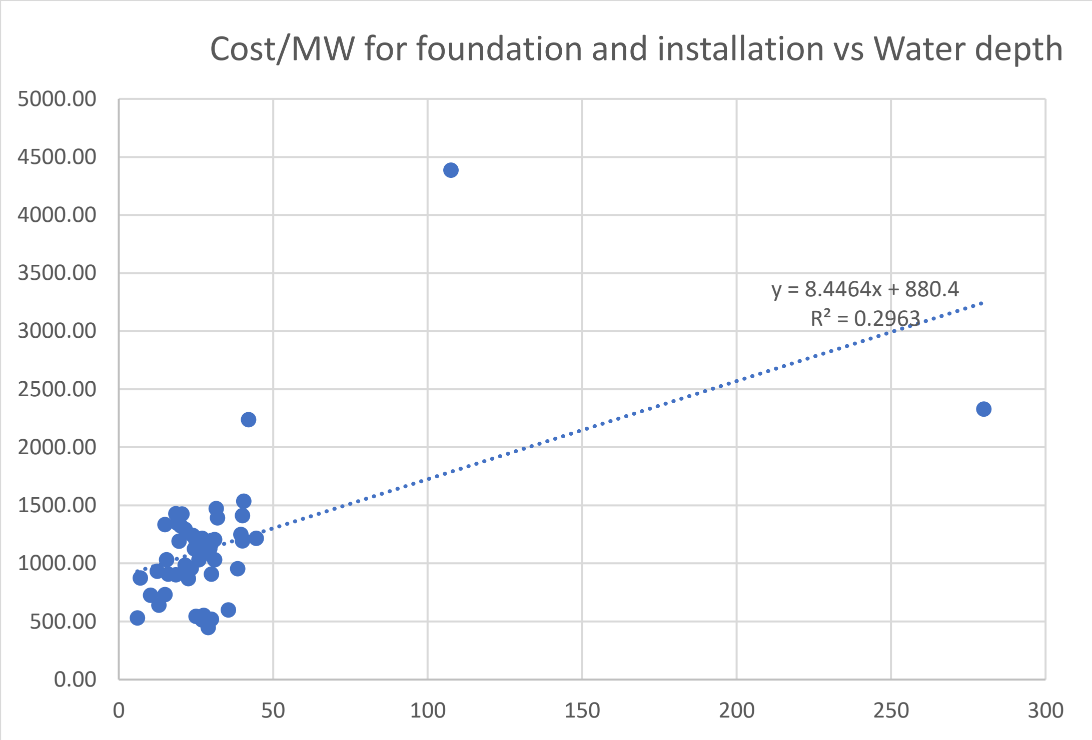

Figure 3-51 Plotted graph of Cost for foundation and installation per unit capacity against the water depth

The R^2 value for this trendline is 0.2963 and this value can be affected by cost conversion for USD from various currencies.

Hence the effect of the water depth was assumed as inverse of this function where lower depths cause lower cost component and becomes more economical. For the time being the relationship between cost and appropriate weightage was assumed to be inversely proportional.

$$\text{Weightage} \propto \frac{1}{Cost\ component\ for\ wind\ turbine\ foundation\ \&\ installation}$$

$$weightage = \frac{C}{Cost\ component}$$

Where C= constant

Depending on the total marks from the wind speed the C was assumed to be 10000

C=1000

$$weightage = \frac{10000}{(8.4464 \times water\ depth) + 880.4}$$

The determination of constant was a trial-and-error method, and it was dependent on the total marks obtained from the wind speed.

3.4.3 Distance from the onshore substation

As learnt in the literature review, on shore substation is an essential part of an offshore wind farm where it provides solid connection point to the existing power grid. The stability of the connection is changes depending on the voltage level which the wind farm is connected. Further depending on the distance between the onshore substation and the OWF, length of the export cable is affected and hence the cost for the export cable and the installation. So, when considering the onshore substation, both the distance and the available maximum voltage level needs to be considered.

As same as the previous procedure for deciding the weightage of water depth, data was collected for the deciding of the weightage for the distance and the voltage level of the onshore substation.

All the above wind farms were place on google earth and maps /images were overlayed to identify the cable route for the export cable. Data of the onshore substation including the location were taken from the internet/official web pages.

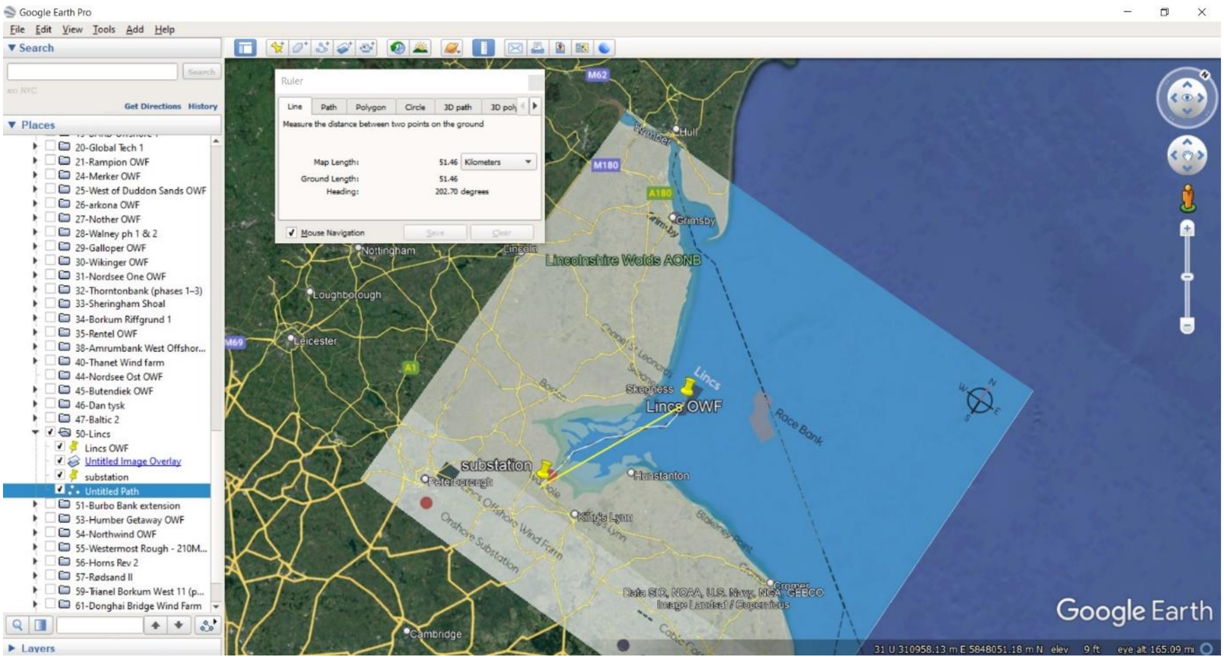

Figure 3-52 data collection for onshore substation distance

By geo referencing the simplified maps with the google earth maps original points of the onshore substations were identified and by using the measurement tool, the direct distance to the onshore substation was measured. It is to be noted that all these distances were not available on the internet and in order to have a large set of data samples to improve the correctness of the outcome, all the offshore wind farm data were obtained using this method.

Similarly, as for the turbine foundation and installation, the general cost component for Electrical infrastructure and installation was found to be around 32.6 % of the total cost for the reference project No 1(2017) and 26.1% for the reference project No 2 (2019). For Floating foundation this was found to be around 24.7% of the total cost for the reference project No 1(2017) and 29% for the reference project No 2 (2019)

Hence average value was selected as 28.1 % which is approximately 28% for Electrical infrastructure, assembling and installation, commissioning and decommissioning.

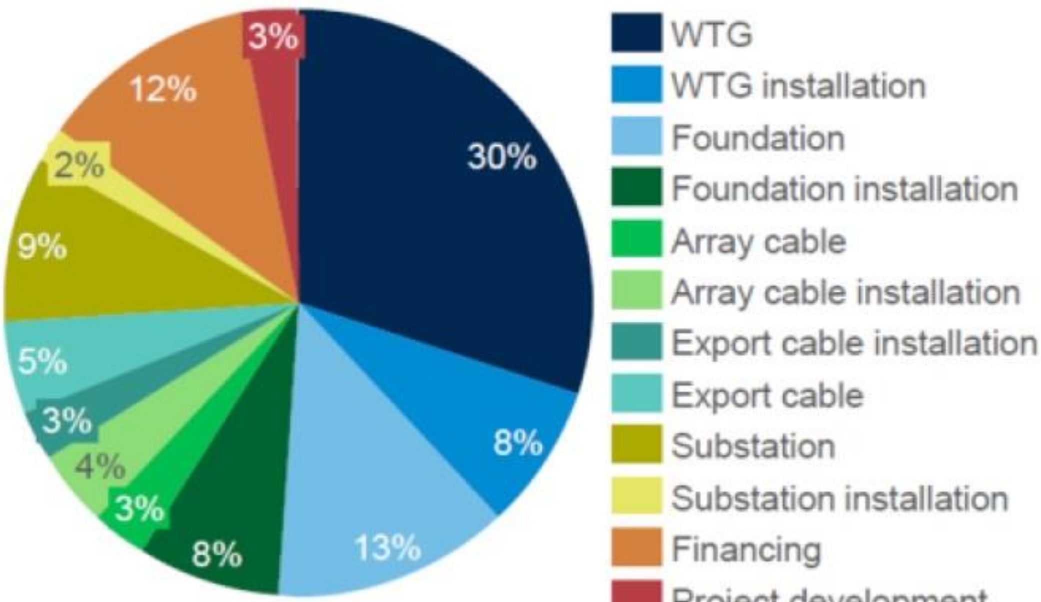

Figure 3-53 Breakdown of Costs - typical offshore bottom-fixed wind farms in Europe
Source - Zhen Gao, Harry B. Bingham, David Mark Ingram, Athanasios J Kolios, OFFSHORE RENEWABLE ENERGY, ISSC 2018 committee V.4, Proceedings of the 20th International Ship and Offshore Structures Congress (ISSC 2018) Volume II [24]

According to the above pi chart also it is converged to around 26% of total cost for the electrical infrastructure including installations. Out of it, the export cable and the installation accounts for around 8%. Hence cost for the export cable & installation are estimated to be 8% of the total cost of the offshore wind farm.

Based on this assumption the costs for the export cable length & installation were calculated for the above list of offshore wind farms and cost component is plotted against the distance to the substation (direct distance).

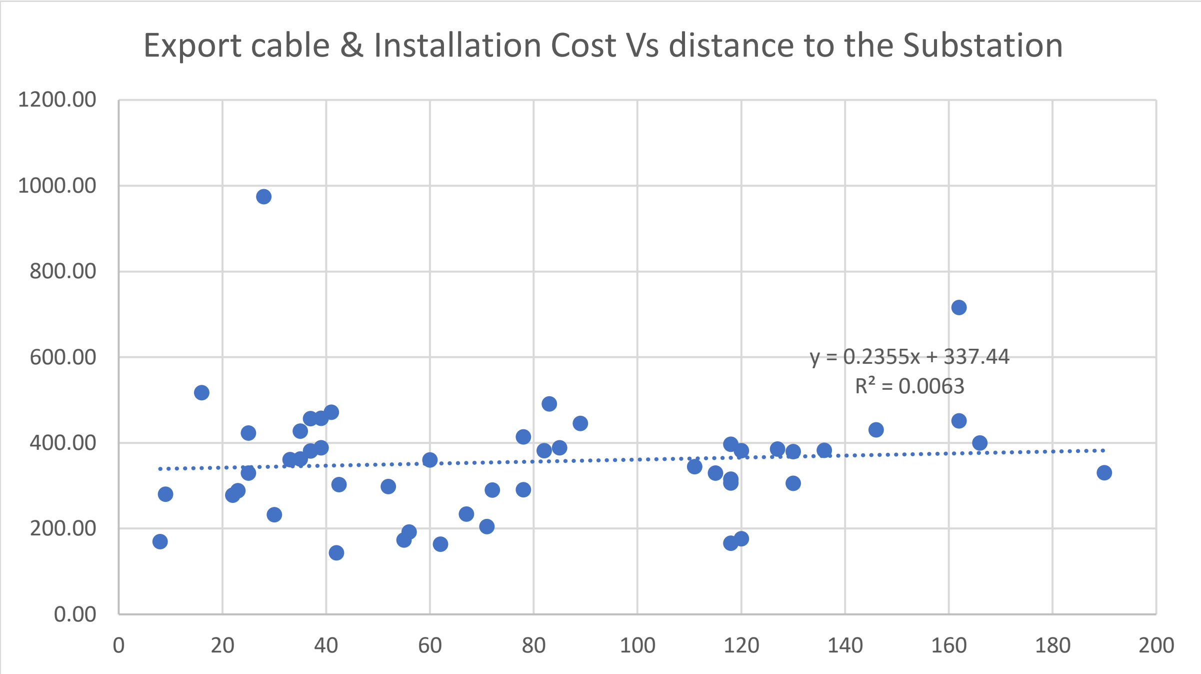

Figure 3-54 Plotted graph of Cost for export cable and installation per unit capacity against the distance to the nearest substation

The R^2 values was observed to be very low but relatively higher than logrthimic curve fittings. However due to unavailability of very precise data at the moment, the above curve fitting was accepted.

Similar to the weightage calculation for the water depth, weightage for the distance to the substation was calculated assuming it is inversely proportional to cost.

$$Weightage\ for\ the\ distance\ to\ the\ substation \propto \frac{1}{(0.2355 \times distance\ to\ the\ substation\ in\ km) + 337.44}$$

$$Weightage\ for\ the\ distance\ to\ the\ substation = \frac{C'}{(0.2355 \times distance\ to\ the\ substation\ in\ km) + 337.44}$$

Where C’ is a constant.

Further as mentioned it is required to consider the voltage level of the substation in onshore. Hence it is required to consider a combination of distance and voltage when considering the weightage of the factor of having a nearby grid substation.

With considering the total weightage values obtained from the wind speed and the water depth, C' was assumed to be 10000. Further was decided to have the following method to evaluate the total weightage.

Cell No	Dist 132kV	Weightage _132kV	Dist 220kV	Weightage _220kV	Dist 400kV	Weightage _400kV	Total Weightage

Table 3-2 sample table for calculating the total weightage for the selection factor "distance from the substation"

Each cell will have nearest 132 kV, 220 kV and 400 kV (in future) substations at particular distances. Weightage of each voltage level for each cell is calculated by the above derived equation.

However when calculating the each weightage the advantage of the grid voltage has to be considered. Moreover having a nearby grid substation is not a mandatory as it is always possible to have a dedicated grid substation. Hence considering the above facts the above equation was slightly changed for calculation of weightages for the higher voltages.

$$Weightage\ (132kV) = \frac{10000}{(0.2355 \times distance\ to\ the\ substation\ in\ km) + 337.44}$$

$$Weightage\ (220kV) = \frac{10000}{(0.2355 \times distance\ to\ the\ substation\ in\ km) + 337.44 - 10}$$

$$Weightage\ (400kV) = \frac{10000}{(0.2355 \times distance\ to\ the\ substation\ in\ km) + 337.44 - 20}$$

The logic behind the alteration was the cost comparison of augmentation of the existing lower voltage grid substation to higher level and the cost of cabling to higher voltage level grid substation at a higher distance.

When calculating the final weightage, the maximum of these 3 were considered. However in Sri Lanka still 400kV is not implemented and hence at this research, maximum of weightages of 132kV and 220kV was considered.

3.4.4 Visual Impact

Visual impact is mostly affecting the tourism industry of the Sri Lanka. With the unique appearance of the turbine blades over the horizon can reduce the perfect of the scenery. Hence there is a possibility of reduction of tourist income at that perspective.

With the changing distance from the shore, the level of appearance is drastically reduced.

The logic was applied as learnt in the literature review. [25]

- 0-8 km from the shore provides high visual impact.
- 8-13 km from the shore provides moderate visual impact
- 13-24 km, the impact is low
- At the distances greater than 24 km the impact is insignificant.

Considering the marks obtained by each cell for the other selection factors mentioned above, marks were decided for the visual impact as follows.

If the cell (area) is

- Less than 8 km from the shore, 50 marks to be deducted
- More than 8 km and less than 13 km from the shore, 35 marks to be deducted.
- More than 13 km and less than 24 km from the shore, 10 marks to be deducted.
- More than 24 km from the shore, 0 marks to be deducted

Evaluating the marks obtained by each cell for the above-mentioned main selection factors and considering the importance of each selection factor at this stage the following equation was formed to calculate the total resultant marks for each cell.

Total marks for each cell (Without considering the constraints) = (A x B) + C - D

where,

A = marks for the water depth

B = marks for the wind speed

C = marks for the nearest substation distance and the voltage level

D = marks for the visual impact

Total marks were calculated as a percentage of its maximum marks.

3.4.5 Other constraints

Marks for the other constraints were derived using the geo referenced image-based maps generated during this research. Constraints were valued between 0 & 1 including both. However, for some constraints it is difficult to rotate only between 0 & 1 and hence numbers in between them were incorporated.

3.4.5.1 Shipping lines

According to the shipping vessel density GIS file generated during this study, vessel density is shown in values between 27 and 252 where it is a mathematical representation generated from ArcGIS software for the actual vessel density values.

Depending on the values rough model to extract weightage values were generated as follows.

For the lowest vessel density value (27), the weightage value is 1. (no restrictions were assumed.)

For highest value of vessel density (252), the weightage value was assumed to be 0. (Assumed to be restricted for wind farm development). To be on the safe side more, it was assumed to be 0 for vessel density values more than 240.

For an intermediate value of 126 the weightage value was assumed to be 0.8 where it is 20% restricted to windfarm development.

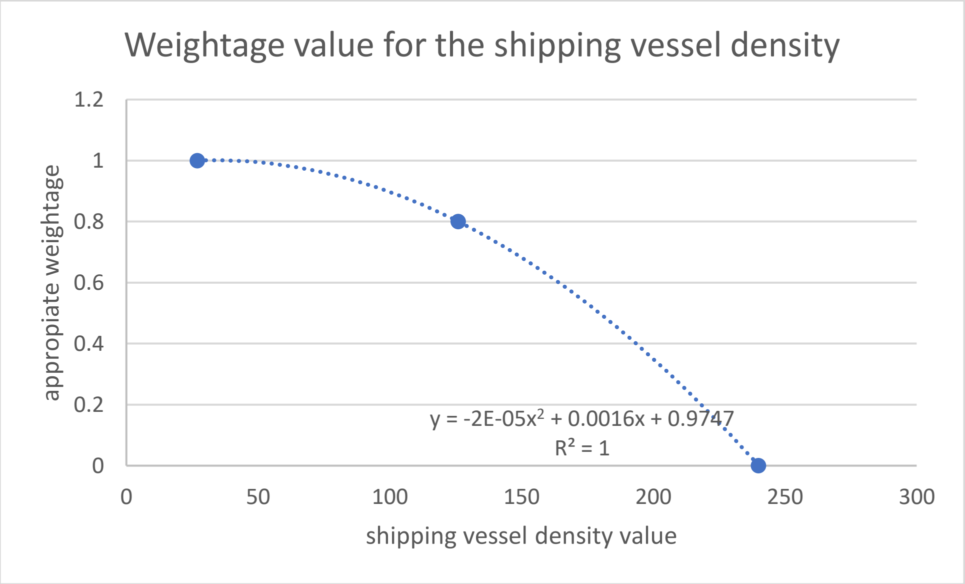

Figure 3-55 Weightage for shipping vessel density

Using the above function, the weightage values were calculated for each and every cell for the shipping vessel density constraint.

3.4.5.2 Fishing areas

Using the digitized map for the fishing areas detection around Sri Lanka following marking scheme was formed.

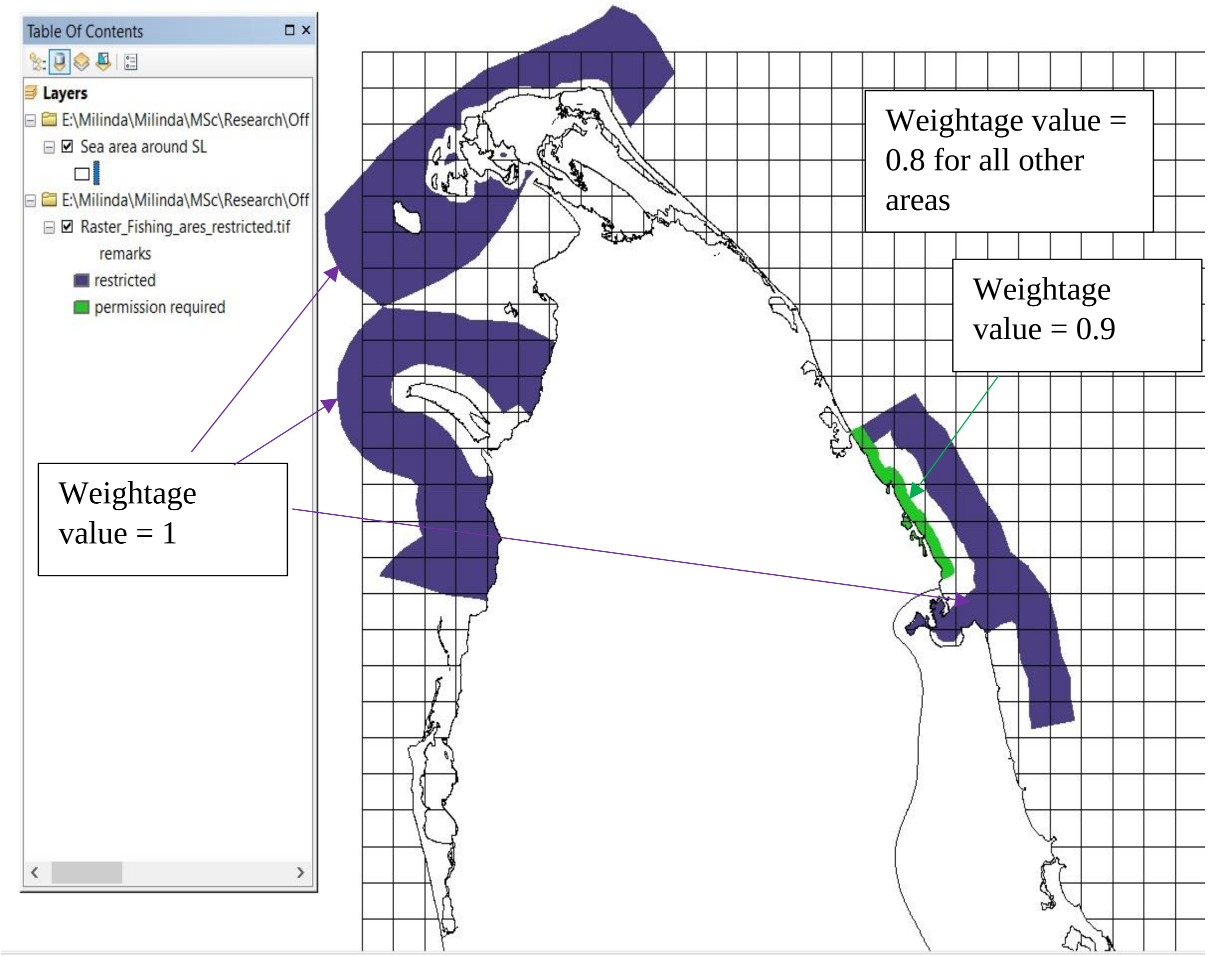

Figure 3-56 Weightages for fishing areas

As learnt in the literature review most of the fishermen do not oppose the development of wind farms. Hence for all the fishing allowed areas only 20% restriction was allowed for the wind farm development.

3.4.5.3 Oil exploration blocks

Using the map given by the Petrolium Resources Development Secretariat Sri Lanka, weightages for each cell was assumed.

Accordingly, only the block M2 in the manner basin, was mentioned as available for appraisal and development. That particular area was previously mentioned as an awarded block but in the new map it is yet open. So as the same block also opens Sri Lanka for the doorway for more indigenous energy sources, was weighted as 0.5 considering the 50% restriction for the wind farm development.

The blocks which are under evaluation and to be evaluated was weighted at 1 considering zero restriction.

3.4.5.4 Migratory Pathways of the Birds

Since there were very few studies have been done in this regard it is extremely difficult to pinpoint what are the actual birds' migratory pathways around Sri Lanka. So, during the analysis only a general image of a map extracted from a book was referred.

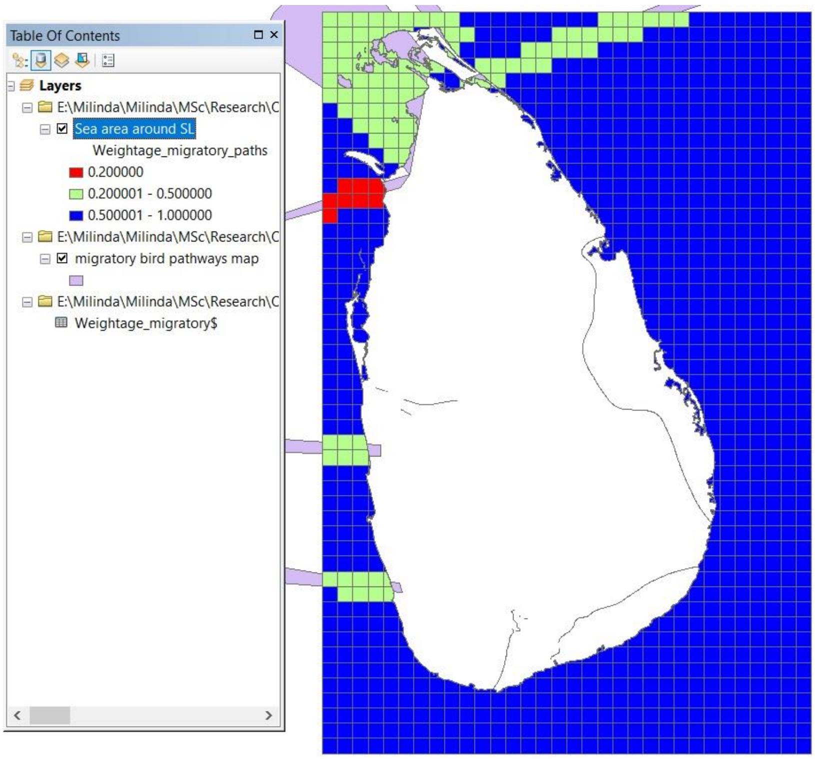

Figure 3-57 Weightage for migratory paths using the digitized map

Accordingly migratory path near the manner was given 0.2 weightage considering 80% restriction as there is a bird sanctuary situated very much near to the manner.

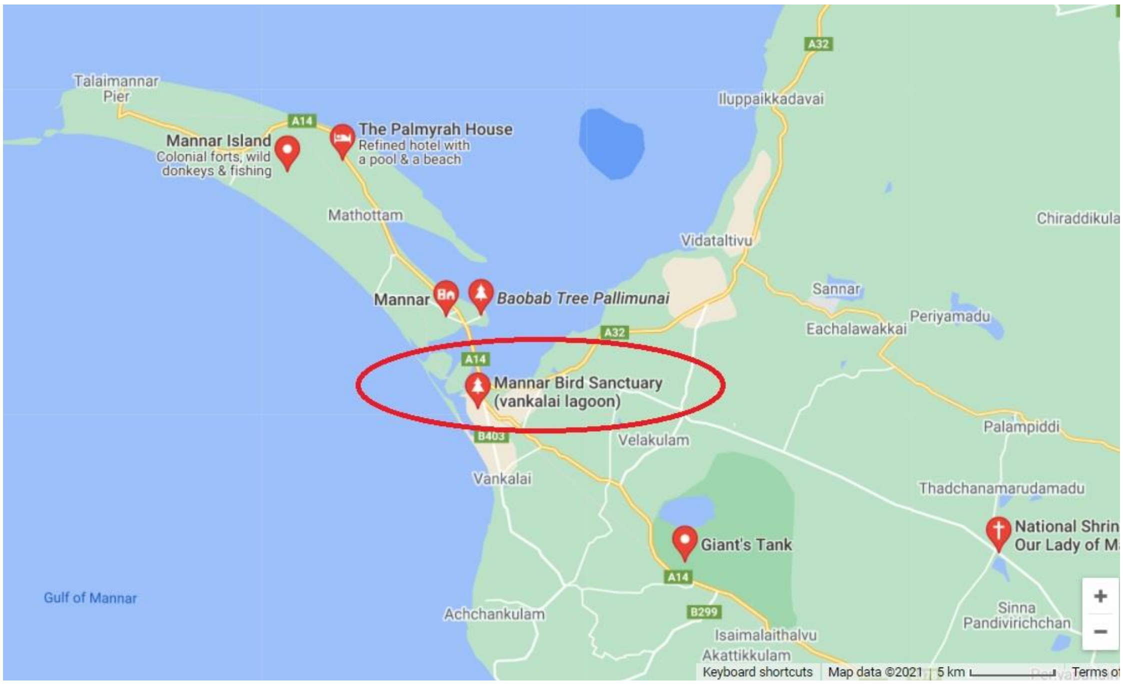

Figure 3-58 Location of bird sanctuary in Mannar

Other migratory paths were valued at 0.5 considering 50% restrictions and areas which do not overlap with the migratory paths were valued at 1 considering zero restrictions.

3.4.5.5 Other restrictions

As same as above mentioned constraints all the other constraints were valued using the same principle. Accordingly, all the constraint maps were separately digitized, and they were overlapped with the study area of this research. All the cells of study area, which overlap with the restricted area, were valued as 0 otherwise 1. Buffer distances were incorporated as mentioned in the section under 3.3.

By multiplication of the marks of each constraint, the total marks for the constraints were obtained. Final marks for the cells were obtained by multiplication of the Total marks for main selection factors and the total marks for constraints.

$$Final\ marks\ for\ ith\ Cell = M_i \times (C_{1i} \times C_{2i} \times .. \times C_{ni})$$

M_i = Total marks of the ith cell for the **Main Selection Factors** as the percentage of the Maximum value

C_{ni} = Marks of the ith cell for the nth constraint

3.5 Evaluation

3.5.1 Evaluation of the First Screening

Using the above methodology, a database was created using mirosoft excel containing the individual cells' marks for each and every section factor/constraint. Using the same database final marks for each cell was calculated using the above mentioned equation. This database was joined with the attribute table of the study area file in Arc GIS to visualize the location and marks of each cell.

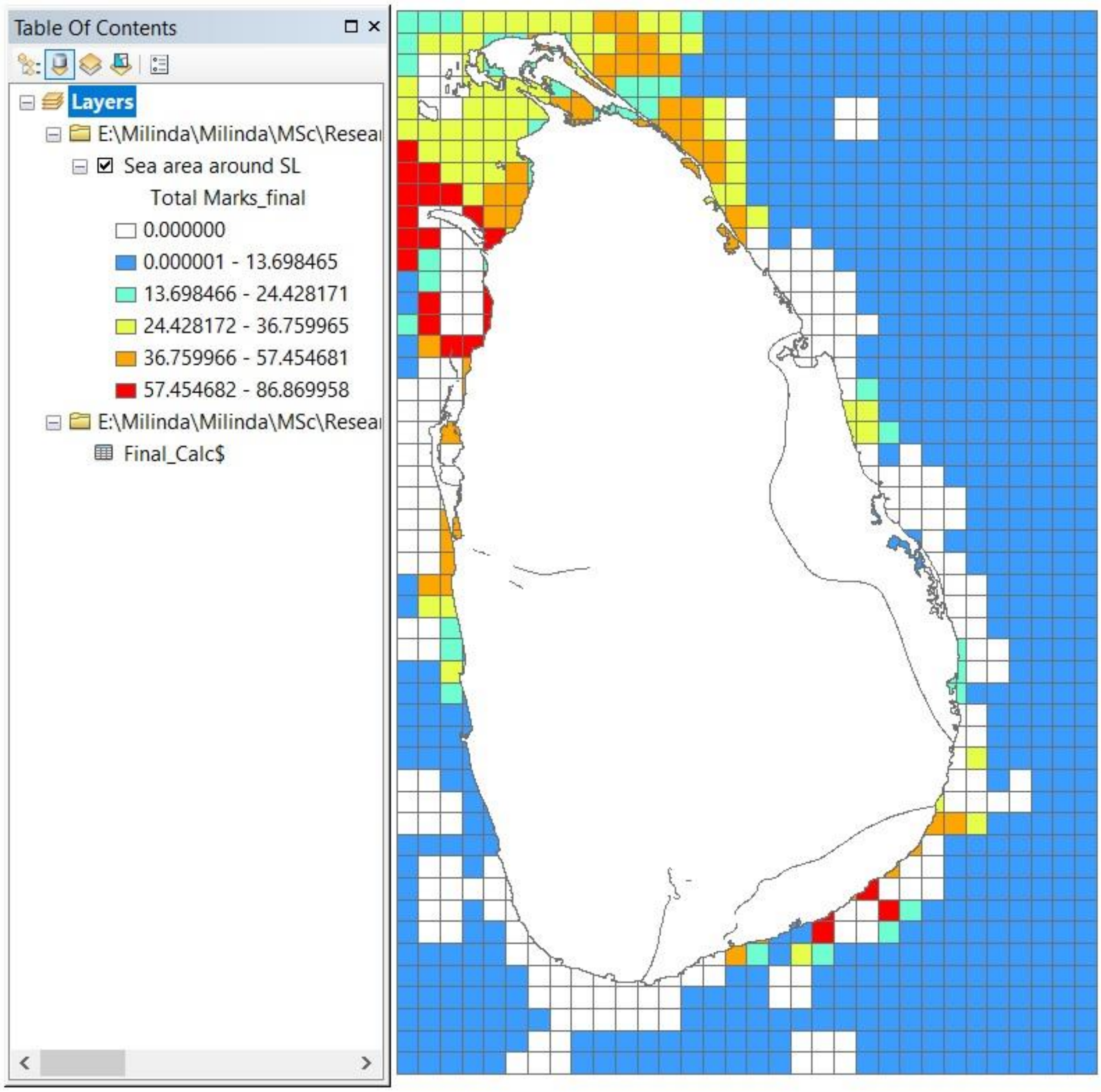

Figure 3-59 results of the first screening process

Here some of the areas were having zero values where they may be restricted due to any of the constraints mentioned above. It is possible to identify them using the database.

Each cell which has gained high marks (above 57.454682) was then evaluated for total power output possible. For the calculation purpose generally the rotor diameter was assumed to be 100m and as per the literature review, it was assumed that the turbines are 5 & 7 times of rotor diameters are apart.

$$Power = \frac{1}{2} \times \rho \times \frac{\pi \times D^2}{4} \times v^3 \times n_t \times n_g$$

The efficiency of the wind turbine was assumed to be 40% where generator was assumed to to 90% efficient. Air density reduces with the increasing height. Here to have the 100m rotor diameter, 100m hub height was assumed. Hence at 100m height air density is slightly reduced. However for the calculation purpose air density was assumed to be constant over the area of rotor and assumed to be 1.225 kg/m^3. Hence the power output of a single turbine having 100m rotor diameter can be calculated as follows.

$$Power = \frac{1}{2} \times 1.225 \times \frac{\pi \times 100^2}{4} \times v^3 \times 0.4 \times 0.9$$

$$Power = 1731.803 \times v^3$$

As it was assumed that each wind turbine is 5-7 rotor diameters are apart, it is approximated as each turbine takes 500m and 700m apart from each other

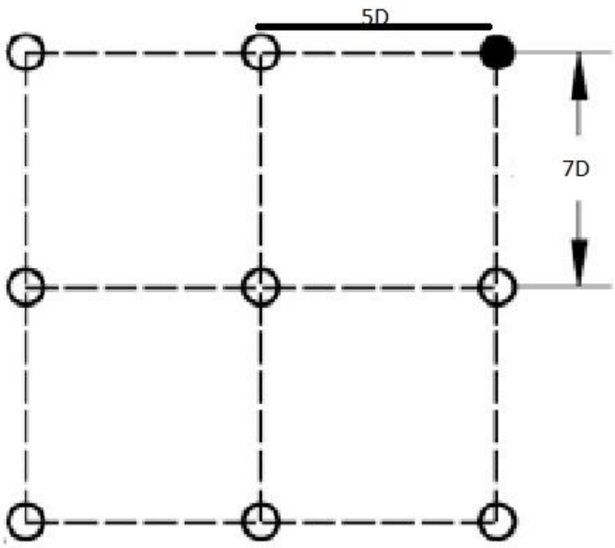

Figure 3-60 Wind farm spacing (assumed)

Hence each wind turbine will have approximate area of 500 m x 700 m which is equal to 0.35 km^2. Since each cell is 100 km^2, the power generated from a cell can be approximated as

$$Power\ from\ a\ cell = \frac{1731.803 \times v^3 \times 100}{0.35 \times 10^6}\ MW$$

Using the above equation power from each cell was calculated.

FID	windspeed_Mean	Total Marks_final	Power from Cell (MW)
202	8.72218	65.60329	328.33
225	7.99133	61.52389	252.52
228	8.91226	61.87117	350.26
249	8.20285	66.55387	273.10
627	8.68614	84.93549	324.27
628	8.20912	77.32659	273.73
647	8.70482	78.33211	326.37
650	7.49707	63.46468	208.50
667	8.70136	86.86996	325.98
670	8.01887	77.7224	255.14
690	8.04177	78.39527	257.33
707	8.4991	79.53965	303.77
729	8.31294	77.71649	284.25
730	8.33505	80.99631	286.52
733	8.22424	68.99464	275.24
753	8.08617	76.74307	261.61
756	7.89297	73.79561	243.31
777	7.86637	66.53532	240.85
778	7.94874	70.71353	248.50
779	7.88941	67.87766	242.98
802	7.7075	59.48577	226.55
803	7.81421	65.44591	236.09
828	7.57669	58.94379	215.21
Total Power Potential			5309.31

Table 3-3 Results table of 1st screening

Hence as per the 1st screening the most suitable areas (highest marks obtained areas has the ability to produce nearly 5.3 GW of power considering a 100 m diameter rotors.

3.5.2 Evaluation of the Second Screening

From the 1st screening process the intended idea of the research has been fulfilled. However, as a secondary objective it is decided to discuss the inland properties for the intended offshore wind farms.

To achieve this, each inland area near to the intended windfarm, need to be considered. As an onshore substation is a must for all the large-scale offshore wind farms, it is required to investigate the possibility of the formation of a dedicated grid substation on the ground/shore connecting the existing grid, in case where the existing nearby substation cannot absorb the power generation directly due to limitations of the equipment.

As this process requires the consideration of all ground geological conditions/ terrain conditions etc. it is not possible to extend this for all identified suitable areas in 1st screening. Hence the cells were further tuned to 1km-by-1km grid to identify the most suitable area.

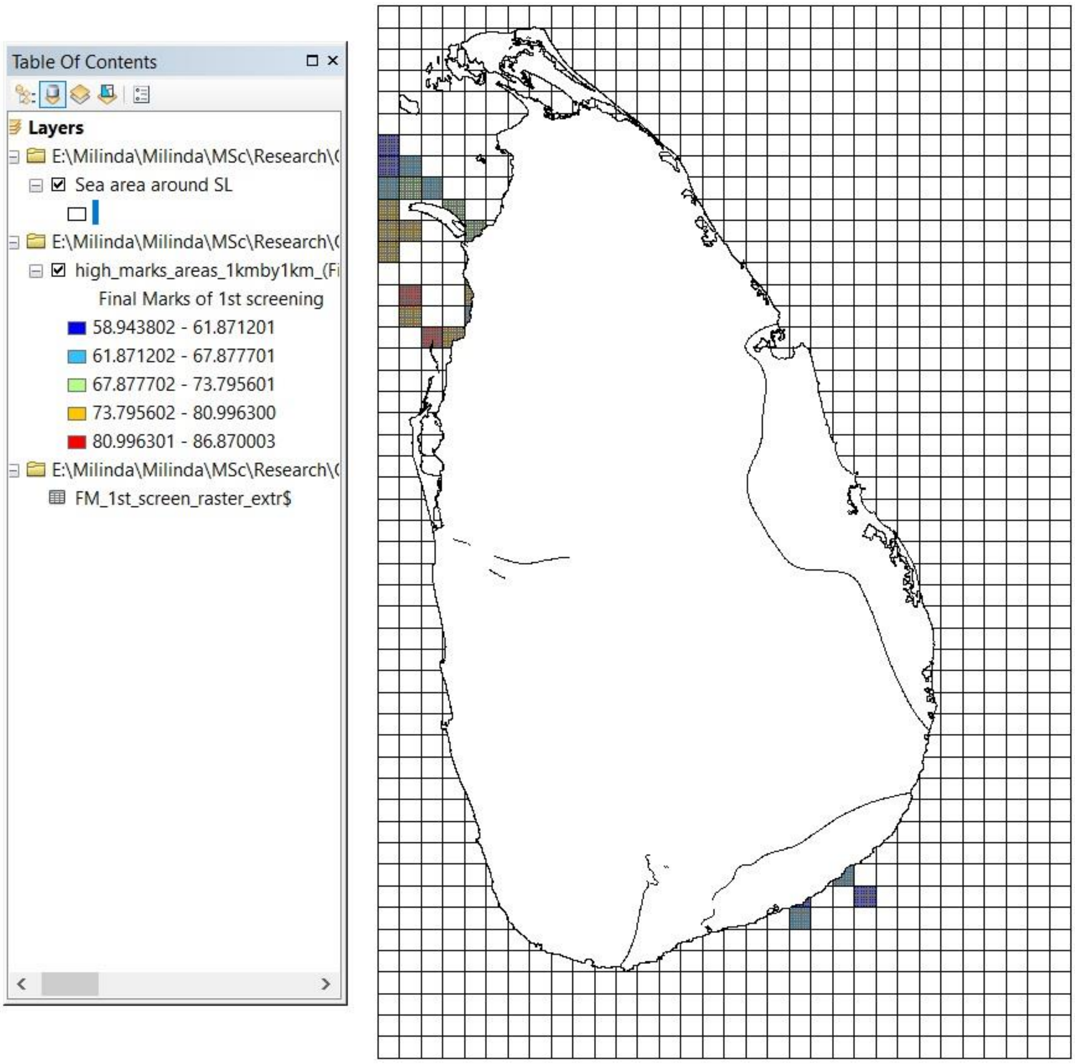

Figure 3-61 High marks areas of 1st screening (grid resolution 1 km by 1 km)

As per the new high-resolution simulation the highest potential areas are lying with near the Mannar. Hence for the secondary screening only the Mannar area was considered. The area of study for the secondary screening is arbitrary selected generally about same distance aside from the existing grid substation. Selection of area was purely visual.

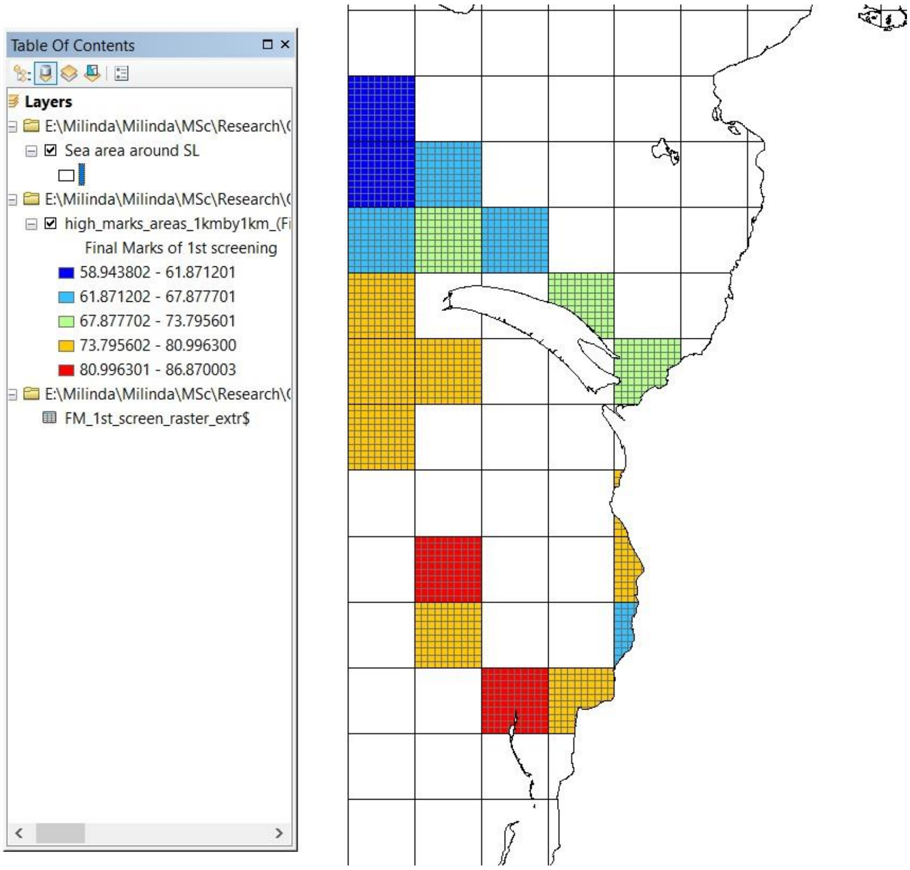

Figure 3-62 Mannar area selected for secondary screening

When the resolution is increased it is observed that among the selected area for offshore wind farms, there exist new highest marks areas. (Marked in red color). Those bigger areas have been broken apart into 1 km by 1km squares. Hence by comparing the wind speed data and the new high-resolution area, wind speeds can be obtained for the high-resolution areas

By assuming the similar data for the offshore wind farm, i.e., rotor diameter to be 100m, hub height to be 100m density of the air to be 1.225 kg/m^3, 500m and 700m distance apart for two wind turbines, the new total estimated power generation can be predicted. The only difference from the previous calculation is that new area is 1 km^2.

$$Power\ from\ a\ cell = \frac{1731.803 \times v^3}{0.35 \times 10^6}\ MW$$

Using the above equation, the new power potential of the highest marks obtained areas of the high-resolution map can be obtained.

FID	Wind speed	Power
0	8.65	3.20
1	8.65	3.20
2	8.65	3.20
3	8.64	3.20
4	8.65	3.20
5	8.64	3.20
6	8.64	3.20
7	8.67	3.23
8	8.71	3.27
9	8.74	3.31
15	8.66	3.21
16	8.66	3.21
17	8.65	3.21
18	8.65	3.20
19	8.65	3.20
20	8.65	3.20
21	8.65	3.20
22	8.68	3.23
23	8.71	3.27
24	8.75	3.31
30	8.66	3.22
31	8.66	3.21
32	8.66	3.21
33	8.65	3.21
34	8.65	3.21
35	8.66	3.21
36	8.66	3.21
37	8.67	3.23
38	8.71	3.27
39	8.76	3.32
45	8.67	3.22
46	8.67	3.22
47	8.66	3.22
48	8.66	3.21
49	8.66	3.21
50	8.66	3.22
51	8.66	3.22
52	8.68	3.24
53	8.71	3.27
54	8.74	3.31
62	8.67	3.23
63	8.67	3.23
64	8.67	3.22
65	8.67	3.22
66	8.67	3.23
67	8.67	3.23
68	8.69	3.24
69	8.71	3.27
70	8.75	3.31
71	8.78	3.35
82	8.68	3.23
83	8.68	3.23
84	8.68	3.23
85	8.68	3.23
86	8.68	3.24
87	8.69	3.25
88	8.72	3.28
89	8.75	3.31
90	8.77	3.34
91	8.79	3.36
102	8.68	3.24
103	8.68	3.24
104	8.68	3.24
105	8.69	3.24
106	8.69	3.24
107	8.70	3.26
108	8.72	3.28
109	8.74	3.30
110	8.77	3.34
111	8.78	3.35
122	8.69	3.25
123	8.69	3.25
124	8.69	3.25
125	8.69	3.25
126	8.69	3.25
127	8.70	3.26
128	8.72	3.28
129	8.74	3.30
130	8.77	3.33
131	8.77	3.34
142	8.69	3.25
143	8.69	3.25
144	8.70	3.25
145	8.70	3.26
146	8.70	3.26
147	8.71	3.27
148	8.72	3.28
149	8.74	3.30
150	8.76	3.32
151	8.77	3.34
162	8.70	3.25
163	8.70	3.26
164	8.70	3.26
165	8.70	3.26
166	8.70	3.26
167	8.71	3.27
168	8.72	3.28
169	8.73	3.30
170	8.75	3.32
171	8.77	3.33
1532	8.70	3.26
1533	8.70	3.26
1534	8.70	3.26
1535	8.70	3.26
1536	8.71	3.27
1537	8.72	3.28
1538	8.73	3.29
1539	8.73	3.29
1540	8.73	3.29
1541	8.70	3.26
1542	8.70	3.26
1543	8.70	3.26
1544	8.70	3.26
1545	8.70	3.26
1546	8.71	3.27
1547	8.72	3.28
1548	8.72	3.28
1549	8.72	3.29

1550	8.73	3.29	1578	8.70	3.26	1606	8.69	3.25
1551	8.70	3.26	1579	8.71	3.27	1607	8.70	3.25
1552	8.70	3.26	1580	8.71	3.27	1608	8.70	3.26
1553	8.70	3.26	1581	8.69	3.24	1609	8.70	3.26
1554	8.70	3.26	1582	8.69	3.24	1610	8.70	3.26
1555	8.70	3.26	1583	8.69	3.25	1611	8.67	3.23
1556	8.70	3.26	1584	8.69	3.25	1612	8.67	3.23
1557	8.71	3.27	1585	8.69	3.25	1613	8.68	3.23
1558	8.71	3.27	1586	8.69	3.25	1614	8.68	3.23
1559	8.72	3.28	1587	8.70	3.25	1615	8.68	3.24
1560	8.72	3.28	1588	8.70	3.26	1616	8.69	3.24
1561	8.70	3.25	1589	8.70	3.26	1617	8.69	3.25
1562	8.69	3.25	1590	8.71	3.27	1618	8.70	3.26
1563	8.70	3.25	1591	8.68	3.24	1619	8.70	3.26
1564	8.70	3.26	1592	8.68	3.24	1620	8.71	3.27
1565	8.70	3.26	1593	8.69	3.24	1621	8.59	3.13
1566	8.70	3.26	1594	8.69	3.24	1622	8.59	3.14
1567	8.71	3.26	1595	8.69	3.25	1623	8.59	3.14
1568	8.71	3.27	1596	8.69	3.25	1624	8.60	3.14
1569	8.71	3.27	1597	8.69	3.25	1625	8.60	3.15
1570	8.71	3.27	1598	8.70	3.25	1626	8.60	3.15
1571	8.69	3.25	1599	8.70	3.26	1627	8.61	3.16
1572	8.69	3.25	1600	8.70	3.26	1628	8.62	3.16
1573	8.69	3.25	1601	8.68	3.23	1629	8.61	3.16
1574	8.70	3.25	1602	8.68	3.24	1630	8.61	3.16
1575	8.70	3.25	1603	8.68	3.24	1631	8.62	3.17
1576	8.70	3.26	1604	8.68	3.24	Total Power		649.97
1577	8.70	3.26	1605	8.69	3.24			

Table 3-4 Calculation of total potential of the secondary screening using high resolution cells

As per the calculation there is a possibility of having a potential of around 650 MW offshore wind power. Obviously, this is affected by the rotor diameter. Higher diameters cause higher power.

To evaluate the suitability of the lands nearby the existing grid substation, mainly, availability of agricultural lands in the vicinity, availability of streams, population, towns, and villages nearby, protected forests/sanctuaries, tanks etc. were considered

Moreover, the soil condition also has a big impact when selecting a location for a grid substation. Soil needs to be hard enough for the construction and having a good resistivity will also be an added advantage.

To evaluate the soil condition a geological map by the irrigation department in Sri Lanka was used. It defines the soil type by various names, some of them are,

1. Alluvial soils
2. Beach and dune sand
3. Reddish brown earth

Etc.

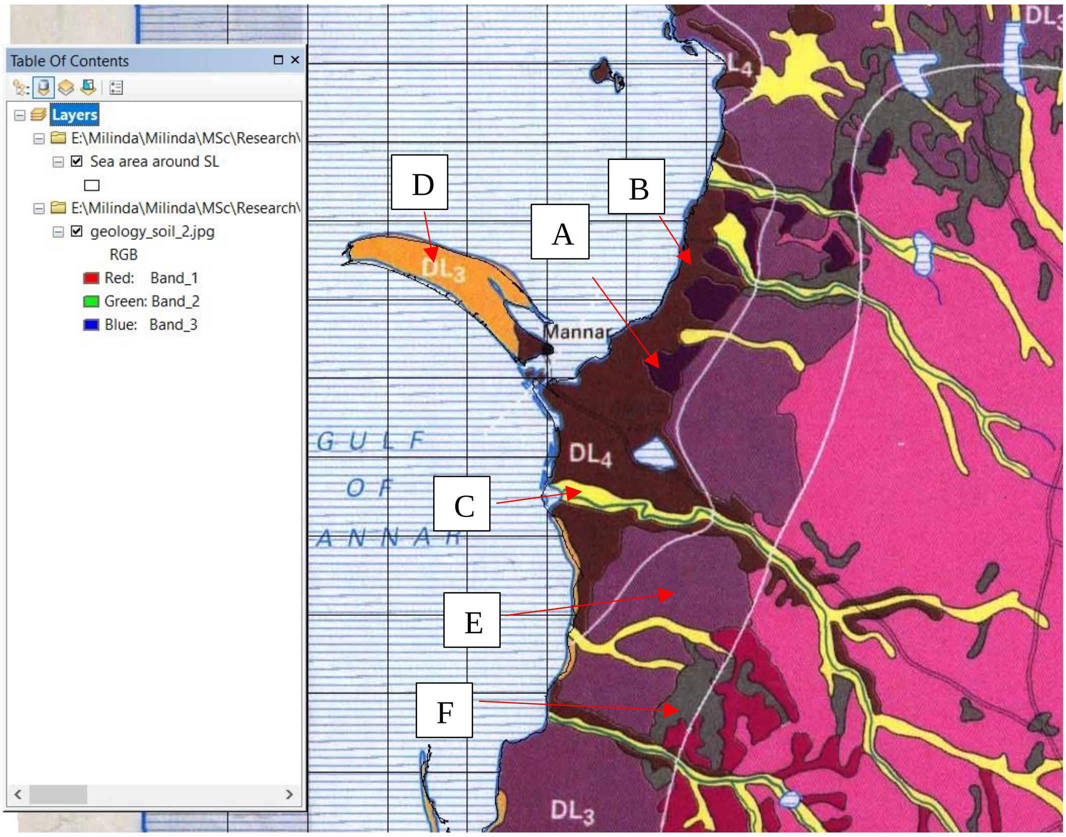

Figure 3-63 Soil condition in Mannar – Source: Irrigation Department, Sri Lanka

Legend of the above soils as per the map is

A – Grumusol soil

B - Red yellow podzolic soils

C – Alluvial soils of variable drainage and texture

D – Beach and dune sand

E – Calcic red yellow latosols

F – Red yellow podzolic soils with dark B horizon & red yellow podzolic soils with prominent A1 horizon

The map is annexed as Appendix 1.

As per the study carried out about the soil types it was learnt that

- Grumusol is soil that is black in color, containing high amount of calcium and magnesium. It is having a high clay content and hence water drainage is low.
- Red-yellow podzolic soils are strongly acidic in reaction. Commercial crops are widely grown in this soil.
- Alluvial soils are the soils which are deposited by surface water. They are found basically in floodplains, along rivers, and in deltas stream terraces etc.
- Beach and dune sand basically formed in the beach due to wind- or water-driven sand
- Calcic Red-Yellow Latosols contains less amounts of organic materials, nitrogen, phosphorous, potassium and magnesium. They are highly erosive of nature and have a low retention of moisture.
- Red-yellow podzolic soils with dark B horizon and Red yellow podzolic soils with prominent A1 horizon are strongly consisting a high content of organic matters abd have leached and strongly weathered.

Generally, Alluvial soils and clay soils will have a lower soil resistances where beach sand, coarse & gravel etc. will cause relatively high soil resistance.

To find out the location of streams, forests etc. topographic map of Sri Lanka in the ArcGIS software was used.

Apart from that in order to find the portion of bare lands archeological sites should also be considered. Archeological department of Sri Lanka has already published a detailed map of archeological sites with description in the internet. It was used to identify the corresponding sites on the in-land areas desired in the second screening process.

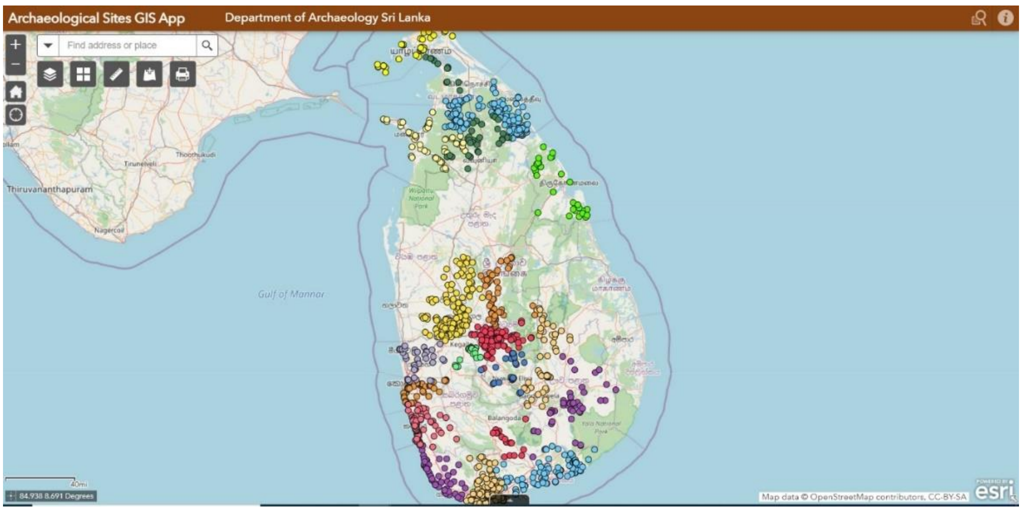

Figure 3-64 archeological sites in Sri Lanka (Source- Archeological department of Sri Lanka)

Using all the data gathered detailed map of the intended area of study for the secondary screening was digitized.

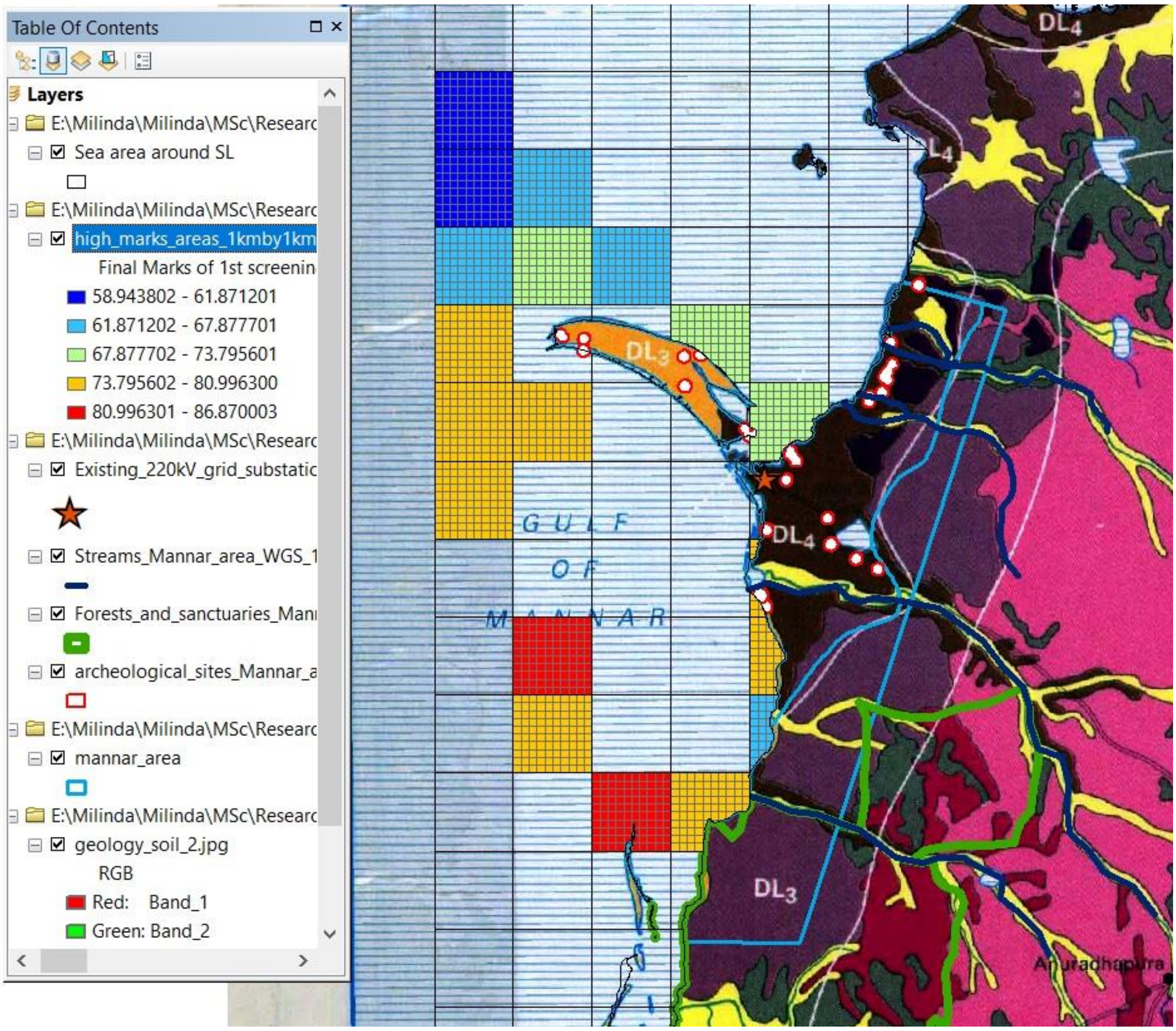

Figure 3-65 Detailed digitized map of intended area of study of the secondary screening – Mannar area

Selection of the areas for the onshore grid substation requires more data such as current usage of the lands, possibility of clearing the land etc. which requires a separate detailed study. With a result of such study, it is possible to pinpoint land locations for a dedicated onshore substation. However, with the help of the current study it will be easier for finding locations for a dedicated grid substation whenever there is a detailed land survey of the area.

4. Validation of the Model

Further to the validation the model for the Sri Lanka, the same model was validated for Sweden. Sweden was having 5 offshore windfarms of different capacities with different commissioning years as mentioned in the following table

Name	Location	Capacity	Commissioning Year
Lillgrund	55°31′N 12°47′E	110	2008
Karehamn	56°58′48″N 17°01′12″E	48	2013
Vänern	59°15′40″N 13°23′10″E	30	2010
Utgrunden	56°20′38″N 16°16′48″E	11	2000
Bockstigen	57°2′N 18°9′E	2.75	1998

Table 4-1 Existing offshore windfarms in Sweden

From the above list, “Vänern” was situated not in the sea but in a lake and hence it is not applicable for the area of intended study.

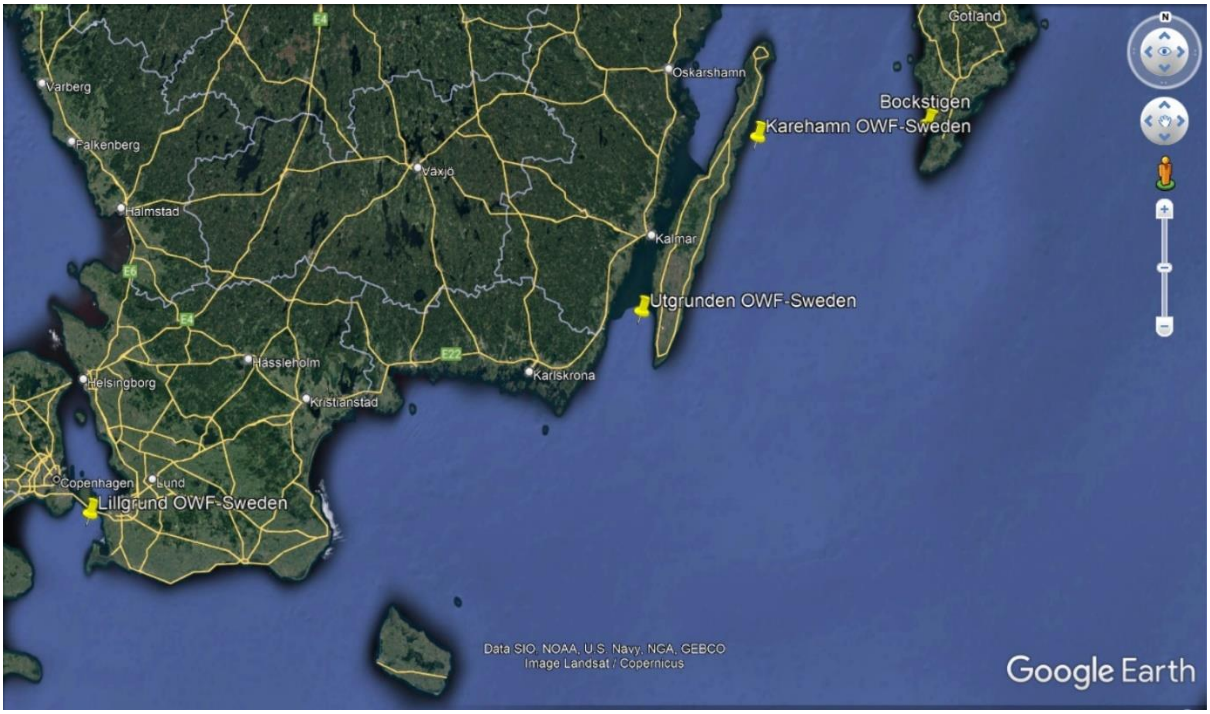

Figure 4-1 Offshore windfarm to be considered in Sweden

For the initial stage data was validated for Sweden using the main selection factors discussed in this research. I: E wind speed, water depth, distance from the nearest substation and the distance to the shore. The result of the initial validation is attached as appendix II and as per the results all the wind farms mentioned above except the “Vänern” which is outside the intended area of study were situated on the high marks areas.

As a secondary validation, shipping vessel density was considered from 2015-2020 around Sweden to incorporate it also a constraint. The most appropriate OWF considering the commissioning time was “Karehamn” and it was noted that when the shipping vessel density is incorporated, the “Karehamn” was still in the high marks areas.

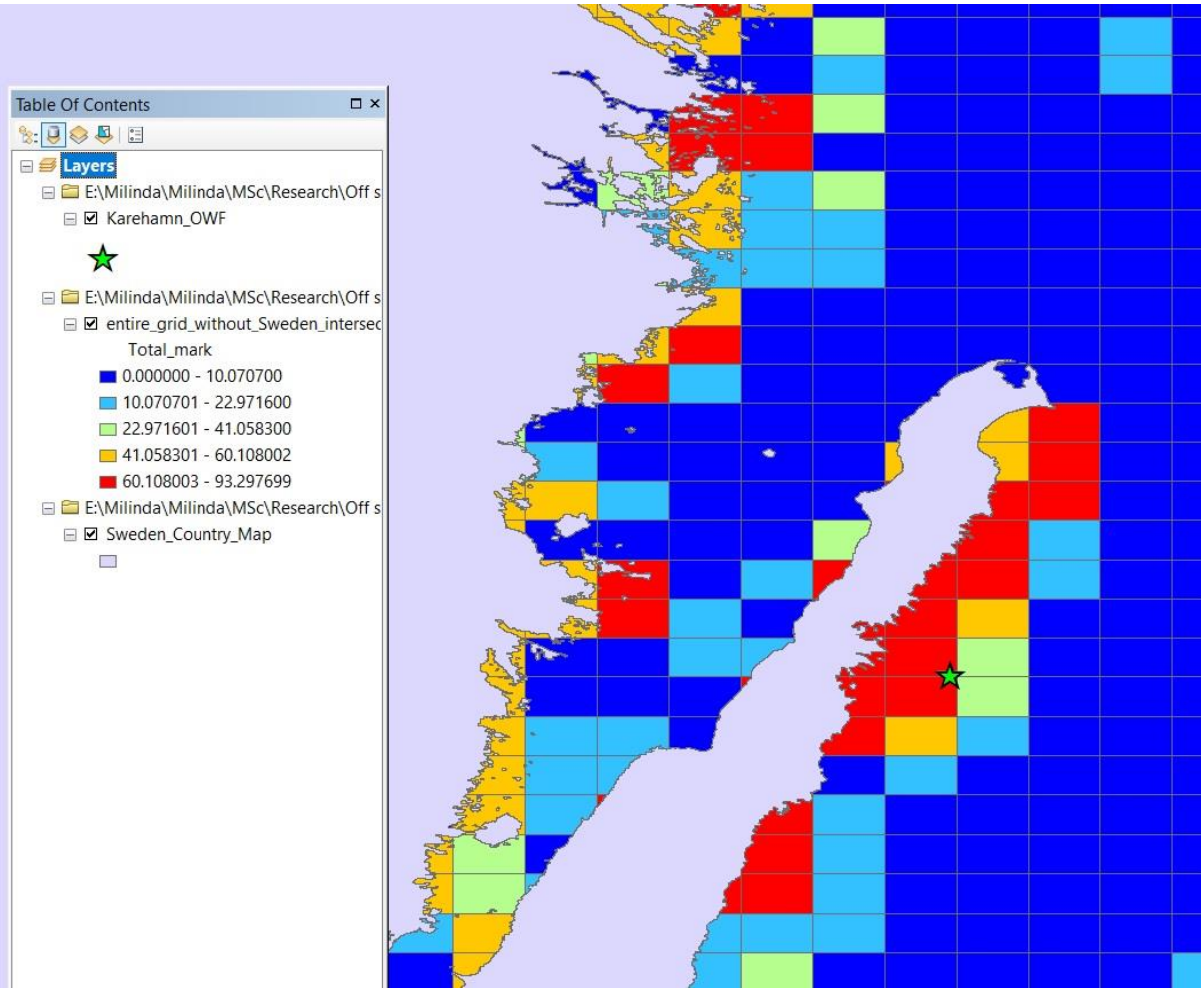

Figure 4-2 Location of Karehamn Offshore wind farm (in the vicinity of highest marks obtained areas as per the model)

5. Sensory Analysis

A sensory analysis was also carried out just to see the impact on the potential sites. For this analysis following 2 constraints were considered.

a. Constraints due to coral reefs
b. Constraints due to Marine Mammals

5.1. Sensory Analysis on Constraints due to Coral Reefs

Initially the weightage value for constraints due to coral reefs was assumed to be 0. However, during the sensory analysis, it was changed to 0.3, 0.5 and 0.7 respectively to observe the impact on the total marks of each cell within the intended area of study.

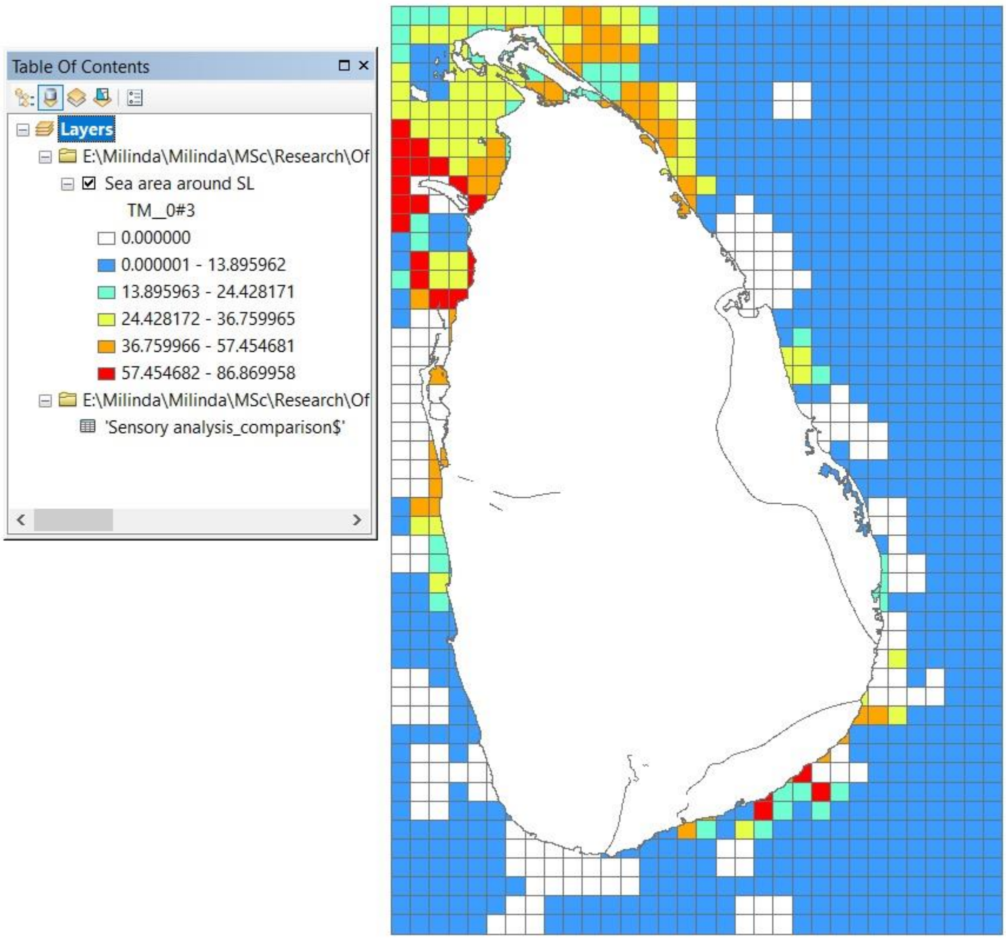

Figure 5-1Total marks for each cell with weightage value of 0.3 for coral reefs

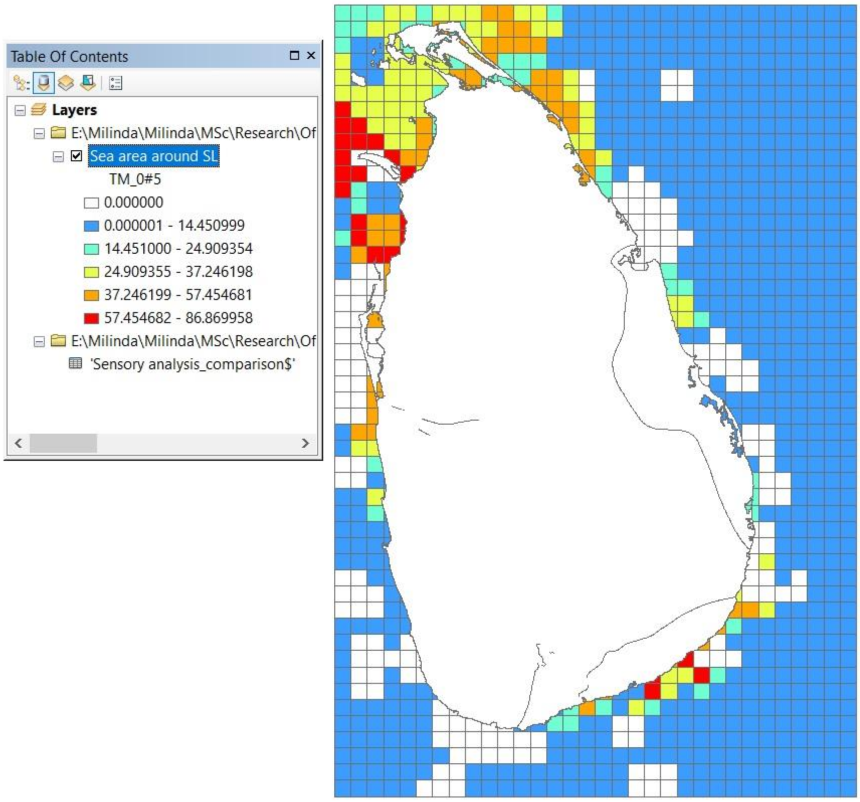

Figure 5-2 Total marks for each cell with weightage value of 0.5 for coral reefs

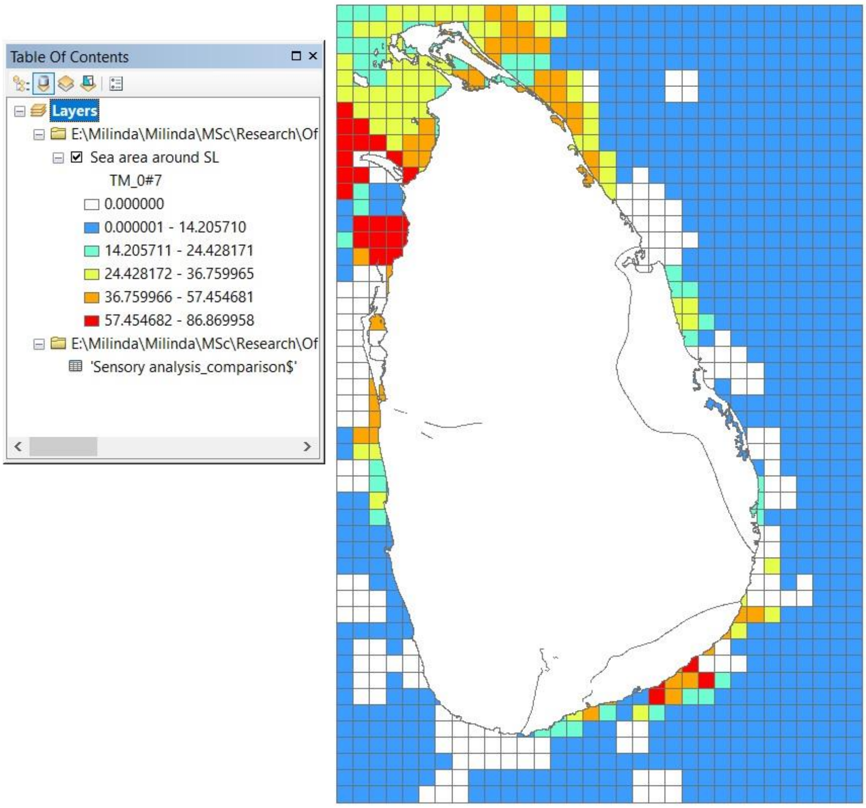

Figure 5-3 Total marks for each cell with weightage value of 0.7 for coral reefs

It is to be noted that buffer distance of 1km was remain unchanged during this sensory analysis for coral reefs.

5.2. Sensory Analysis on Constraints due to Marine Mammals

Similarly for the constraint due to marine mammals, calculations were carried out using weightage values 0.2, 0.5 and 0.7 respectively and final visual output was obtained based on the total marks of each cell. The weightage value due to constraint of coral reef was kept as 0 similar to the initial value.

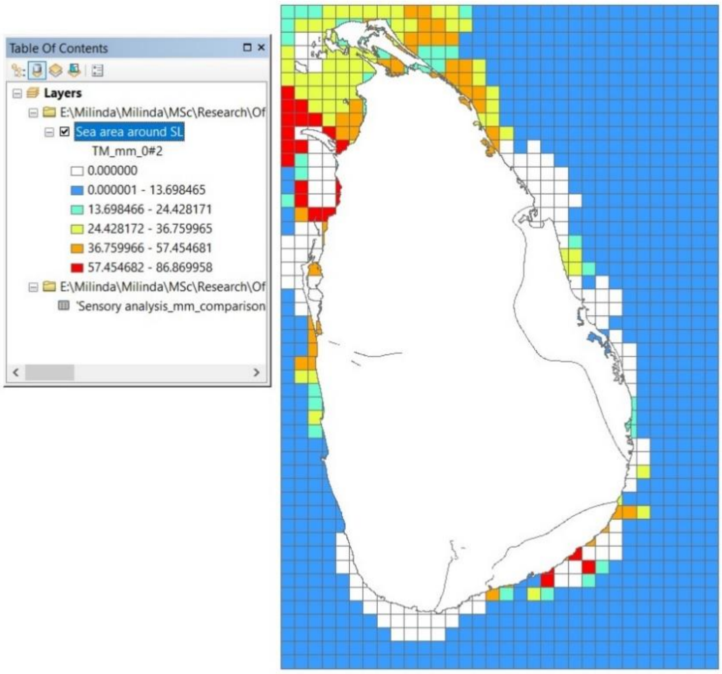

Figure 5-4 Total marks for each cell with weightage value of 0.2 for marine mammals

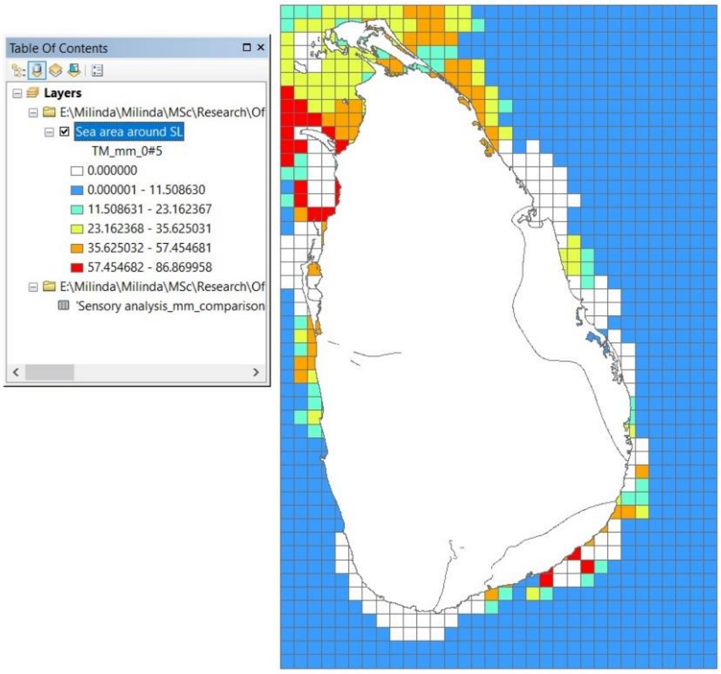

Figure 5-5 Total marks for each cell with weightage value of 0.5 for marine mammals

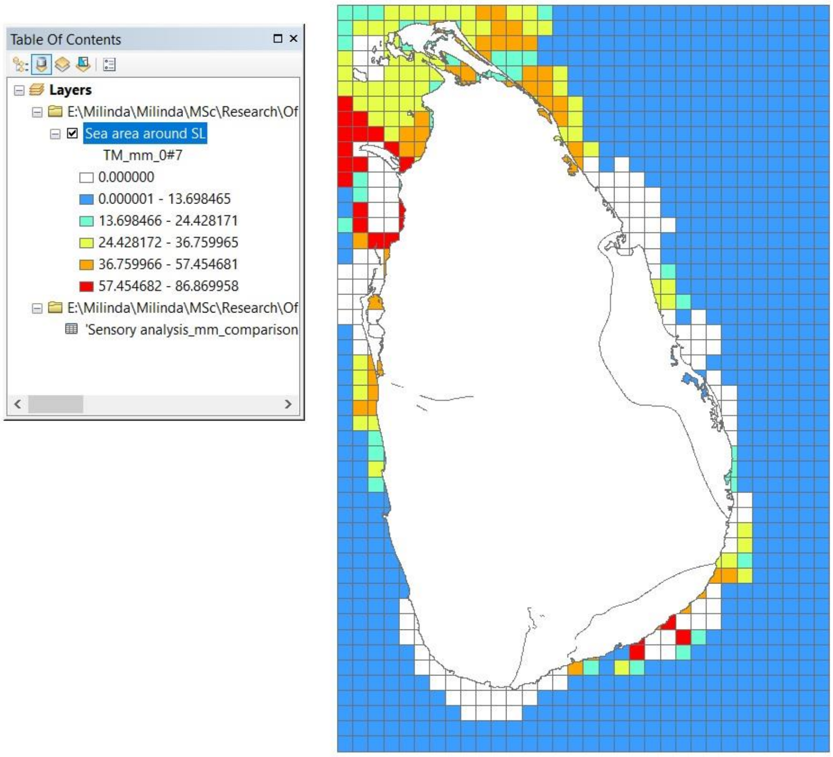

Figure 5-6 Total marks for each cell with weightage value of 0.7 for marine mammals

It is to be noted that buffer distance of 2 km was remain unchanged during this sensory analysis for coral reefs.

5.3. Results of the Sensory Analysis

It was evident that the sensory analysis of the constraint due to Coral reef indicates a higher impact to the final result. This can be due to the most basic reason of coral reefs being located on the highest windy areas around the island. However, coincide of coral reefs with the marine mammal located area and coinciding of other constraints can also have an impact on the output of this sensory evaluations.

6. Conclusion

As per the simulations the summery of the findings of this research are as follows.

- Potentially highest sites are located around Mannar and Hambanthota. But around most of its sites in Hambanthota are restricted due to economic and environmental constraints
- Mannar seems to be more promising around all places as it is having higher wind speed, shallow waters, existence of nearby 220 kV grid substation and less affection by the other constraints
- The buffer space kept away are arbitrary values considering lesser affections to existing constraints and can be altered and weightages of corresponding constraints will be changed accordingly
- Coastal restriction zone is not considered in this research as it will be only around 25-40m from shore and if it is considered it will further reduce the potentiality of sites unnecessarily
- The total estimated wind potential of the Sri Lanka is over 5.3 GW (of the most suitable sites). However, the most suitable areas with highest marks leads to a total power potential of 650MW. (Rotor diameter 100m & hub height 100m) (This figure strictly depends on the intended area of study, rotor diameter and the hub height).

Depending on the Transmission plan, the final marks of each cell can get changed due to new introduction of substations at different voltage levels. Hence it is recommended to run the model again when the transmission plan gets renewed.

During this research many constraints were considered for the selecting sites for the offshore wind farms. However, if there are any constraints which haven’t been identified in this research, it is possible to incorporate that as well and modify the final outcome. The visual output of the possible sites indicates that although it seems that many locations are possible for the offshore wind power development around Sri Lanka, there are also many places where it is not possible for offshore wind power development.

The Site selection for the onshore grid substation was not fully discussed during this research but have provided sufficient data to carry out a separate research with having collected some data.

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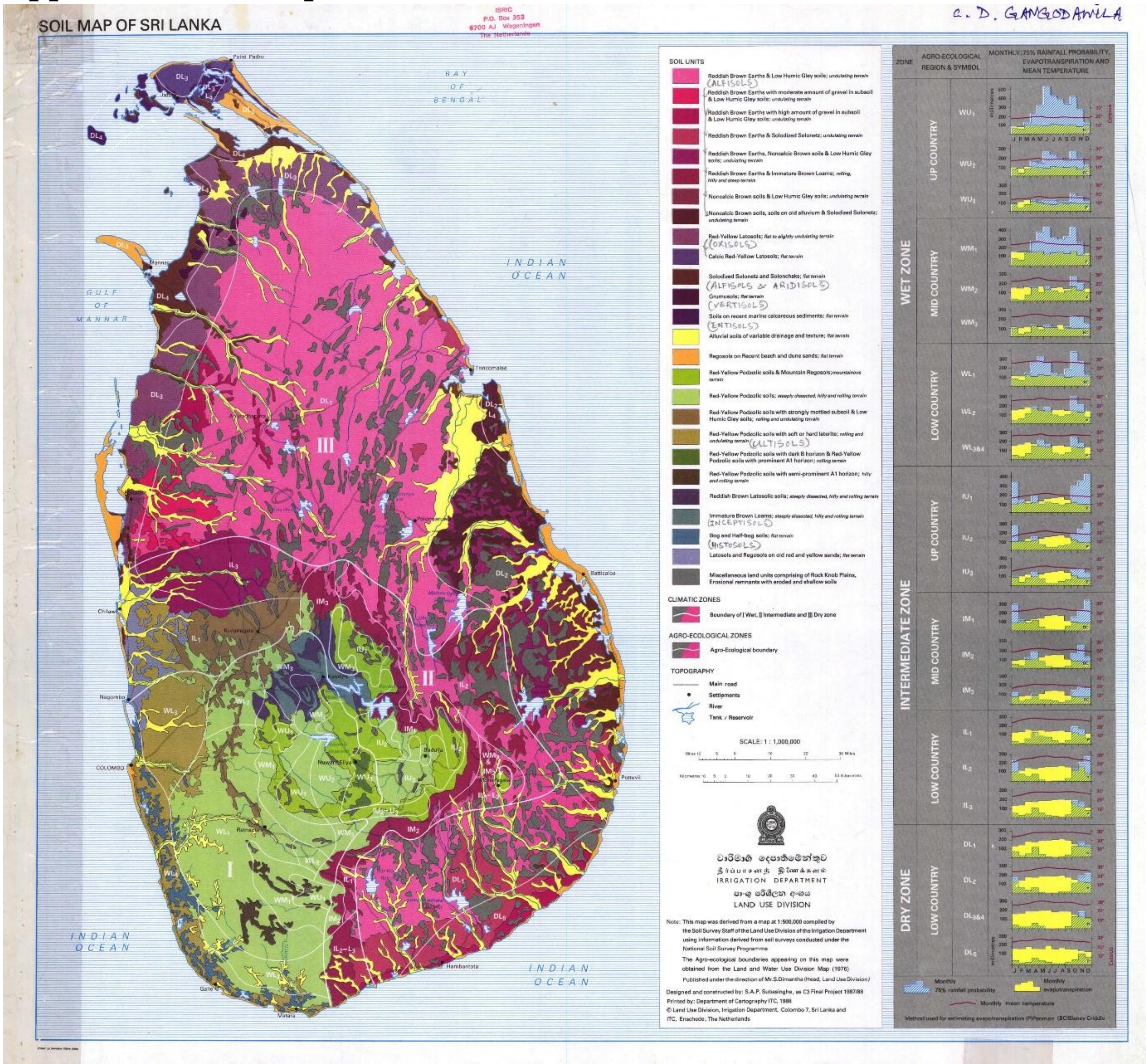
Appendix 1 Soil Map of Sri Lanka



Appendix II Initial validation of model for Sweden – Considering only the main selection factors