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Ecological Geospatial Monitoring and Assessment of Surface Water Environment Using Remote Sensing Ecological Index Model (RSEI) in Freetown, Sierra Leone, from 2010 to 2018.

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Abstract

Over the last decade, Freetown saw massive infrastructural development that triggered depletion of forest cover due to deforestation. Concurrently, Civil Society Organizations and citizens claimed ecological degradation and surface water pollution. This paper used four indices (factors) to ascertain which of the factors contribute positively or negatively (ecological stressors) to the ecological environment of surface water using solely the idea of remote sensing. To achieve this purpose, a Remote Sensing Ecological Index (RSEI) model was built using Landsat 5 TM 2010 and Landsat 8 OLI 2018 satellite imageries. This model used four ecological indicators: Greenness, Wetness, Heat and Dryness. The Normalized Difference Vegetation Index (NDVI) was used to represent Greenness, WET to represent Wetness (Humidity), Land Surface Temperature (LST) to enhance Heat, and the Normalized Differential Build-up and bare land

Soil Index (NDBSI) to enhance dryness (Imperviousness). The RSEI model revealed that NDVI and WET have positive effect/contribution to the ecological environment of surface water; LST and NDBSI have negative effect/contribution to the ecological environment of surface water. The Principal Component Analysis (PCA) was used to evaluate the ecological quality of Freetown. Therefore, the model concluded that the ecological condition of Freetown increased slightly from 87.3% in 2010 to 89.3% in 2018. Overall, the ecological condition of surface water could be classed as good.

Keywords: Ecology, Remote Sensing & GIS, Remote Sensing Ecological Index (RSEI) model, Surface Water.

1. Introduction

The ecological environment plays a critical role in human life. Over the past ten years, Freetown has experienced rapid urbanization rate, which in turn changed the Land Use Land Cover (LULC) of the city. The most obvious of this change is the change from vegetation to built-up area. This change puts pressure and probably destroys the ecological environment. This poses a series of urban problems, such as: urban heat island effect, water logging, road traffic and air pollution. pointed out that a variety of ecological indicators for determining ecosystem health status has been proposed. For example, the Normalized vegetation difference index (NDVI) or leaf area index was used to monitor environmental change, land surface temperature (LST) was adopted to assess the effects of urban heat islands, the Normalized difference built-up index (NDBI), the index-based built-up index (IBI) and the Normalized difference impervious surface index (NDISI) were used to delineate the built-up and impervious surface area, the normalized difference water index (NDWI) and the modified NDWI (MNDWI) were used to extract water bodies, NDVI and LST were applied to monitor drought or soil moisture, a bare soil index (BI) and dry bare-soil index (DBSI) were employed to map bare soil areas. The uniform water difference index (NDWI) and updated NDWI (MNDWI) were used to extract water sources, NDVI and LST were used to track drought or soil moisture, the bare soil index (BI) and the DBSI were used to map bare soil areas. Because of the nature and variety of the influencing factors, it is not enough to follow just one or two ecological indicators to determine the ecosystem status.

In recent years, the use of remotely sensed data has been widespread in the study of natural resources as well as modeling, controlling and monitoring of environmental processes. Remotely sensed data is now available frequently from various platform sensors with a wide range of spatiotemporal, radiometric and spectral resolutions that can be applied in multiple fields [1]. According to [2] remote sensing technology can analyze the spatio-temporal change in ecological environmental quality objectively and quantitatively. [1–8] studied four essential indicators in the RSEI model (greenness, humidity, heat, and dryness) that are closely linked to human survival among several ecologically relevant natural factors. They can be interpreted directly by people, and are used to determine ecological efficiency/quality. They used the Normalized Difference Vegetation Index (NDVI) to represent Greenness, WET to represent Wetness (Humidity), Land Surface Temperature (LST) to enhance Heat, and the Normalized Differential Build-up and bare land Soil Index (NDBSI) to enhance dryness (Imperviousness). They found out that when the RSEI value is closer to 1 the efficiency/quality of the ecological system is higher/good. On the other hand, when the RSEI value is nearer to 0, the efficiency/quality of the ecological environment is low/poor. In their research, they concluded that NDVI (greenness) and WET (wetness) have positive effect/contribution to the ecological environment; LST (heat) and NDBSI (dryness) have negative effect/contribution to the ecological environment.

2. Methods and Materials

2.1 Study Area

Freetown (8.4657° N, 13.2317° W) is Sierra Leone's capital, and largest city. It is a major port city on the Atlantic Ocean, and is located in the country's western region. Freetown is the main urban, commercial, diplomatic, cultural, educational, and political hub of Sierra Leone, as it is the seat of the Sierra Leone government. At the 2015 census, Freetown's population was 1,055,964.

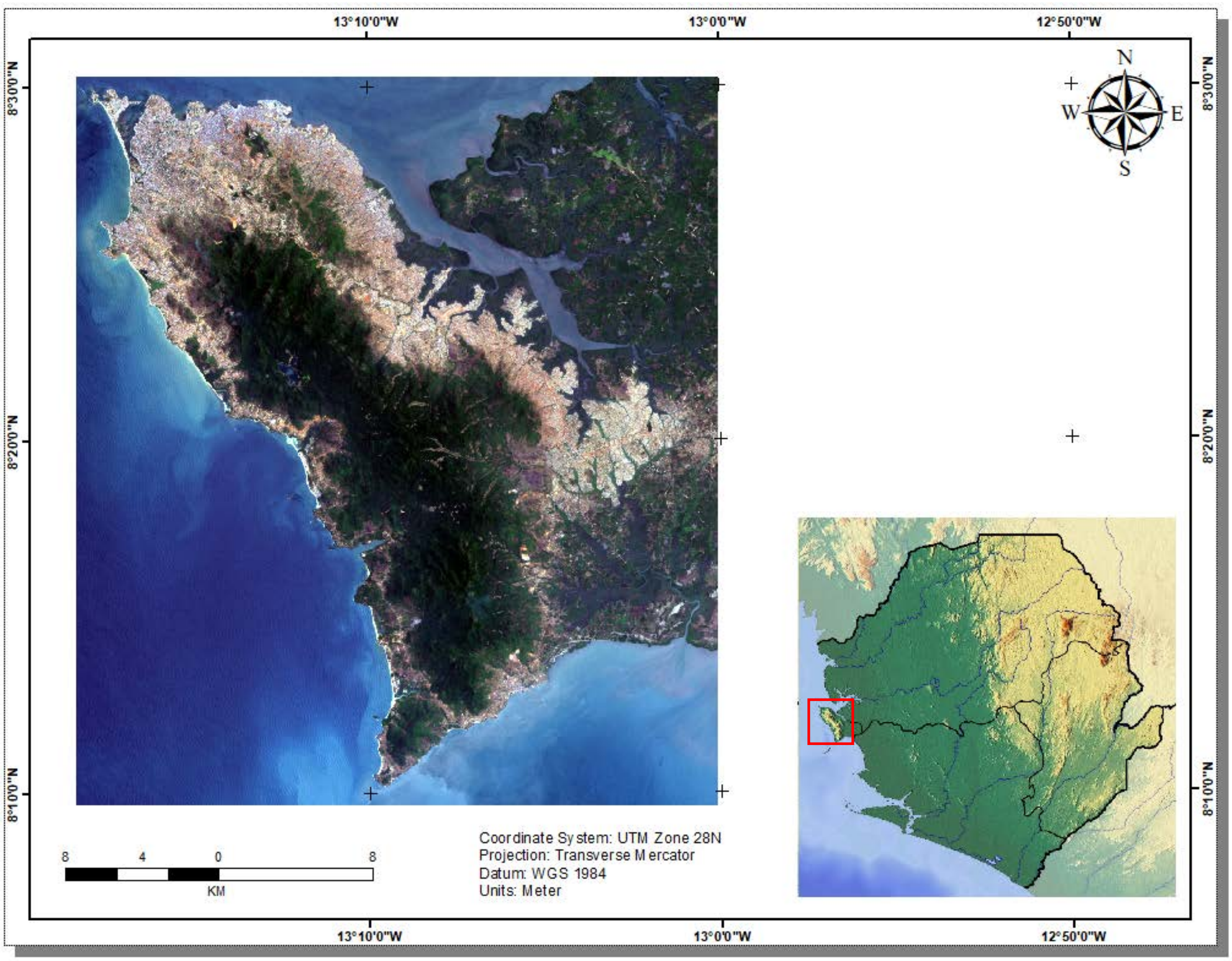

Figure 1. Location map of the Study Area.

2.2 Data Sources

The data used are as follow: satellite imageries of Landsat 5 Thematic Mapper (TM) (22-02-2010)and Landsat 8 Operational Land Imager (OLI) (17-04-2018) of path and row 202, 054 respectively. They were downloaded from the United States Geological Surveys website (https://earthexplorer.usgs.gov/). The spatial Resolution of the imageries is 30 meters. Further details of these data are summarized in the table below (Table 1).

Table 1. The Raw Dataset.

Data	Path and Row	Collected Time	Source	Purpose
Landsat 5 TM	202/054	22-02-2010	USGS (https://earthexplorer.usgs.gov/)	LULC classification, Change detection, RSEI Model.
Landsat 8 OLI	202/054	17-04-2018	USGS (https://earthexplorer.usgs.gov/)	

2.3 Methodology

RSEI is a newly proposed aggregated ecological index, developed specifically to determine ecological status using remote sensing technology alone. The index incorporates four measures (greenness, wetness, dryness, and heat) that are mostly used to measure ecological conditions as they are closely linked to ecological quality and can be experienced directly by people [3,6].

The images used were preprocessed before analysis so that they are as closed as true. The aim of this step was to correct the distorted or degraded image data in order to create a more reliable or faithful representation of the real scene. In this research, the techniques of geometric (to convert satellite image coordinate system to a standard map projection to help obtain accurate location within an image) and radiometric corrections, and image enhancement were applied to remove all the noises and errors in the Landsat images.

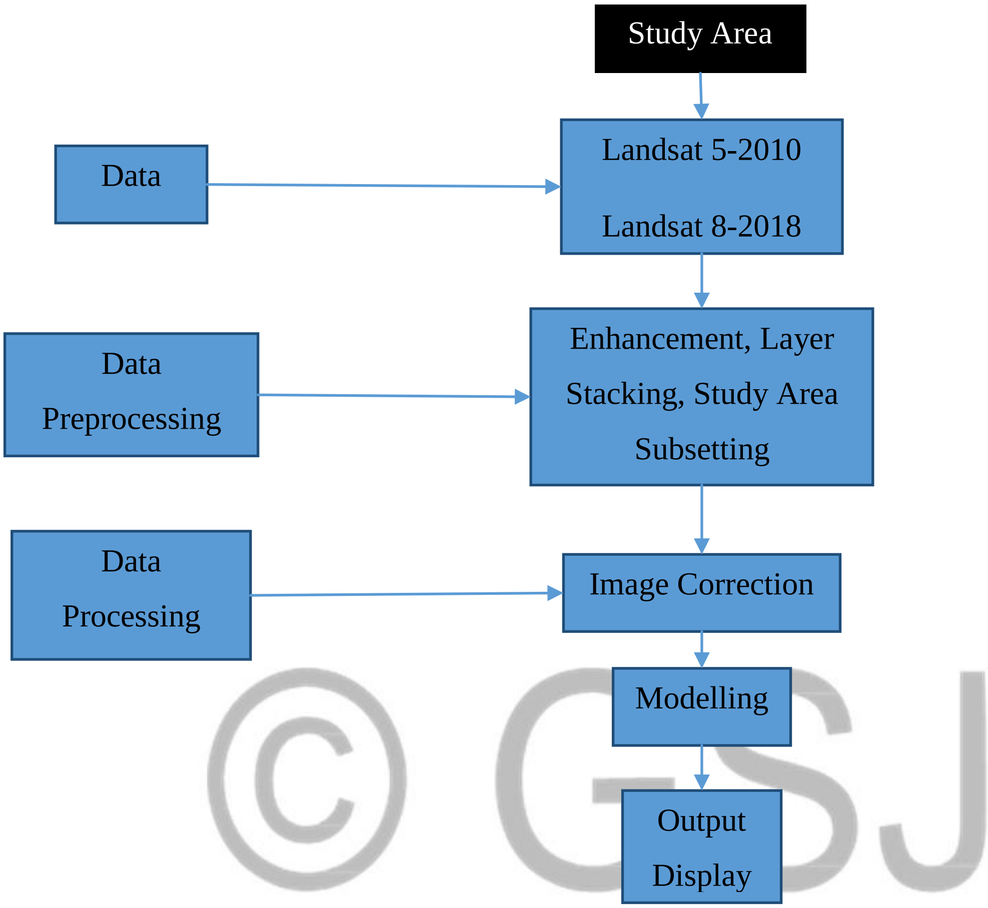

Figure 2. Flowchart of the Methodology

The methods used in calculating the indexes of NDVI, NDBSI and WET were adopted from [2] and the LST calculation method was adopted from [2,9] . In the research of [2], they considered four important factors for the RESI model. The factors were: Greenness, Wetness (humidity), Heat, and Dryness (Imperviousness). These factors can be interpreted directly by individuals and are used to determine the ecological efficiency. Therefore, RSEI uses these four factors using the associated thematic remote sensing indexes as in the equation below.

$$\boldsymbol{RSEI = f\,(NDVI, WET, LST, NDSI)} \qquad (1)$$

Where **NDVI** = Greenness

WET = Wetness

LST = Heat

NDSI = Dryness

The NDVI (Normalized Difference Vegetation Index) can be calculated as in the equation below for both images.

$$\boldsymbol{NDVI = \frac{(NIR - R)}{(NIR + R)}} \qquad (2)$$

Where **NIR**= Near Infrared Band

R = Red Band for both Landsat 5 and 8.

- **WET (Wetness)**

The Landsat5 TM Wetness variable can be calculated using the equation below.

$$\boldsymbol{WET_{\,TM} = 0.0315_{\,\rho blue} + 0.2021_{\,\rho Green} + 0.3102_{\,\rho Red} + 0.1594_{\,\rho NIR} - 0.6806_{\,\rho SWIR1} - 0.6109_{\,\rho SWIR2}} \qquad (3)$$

Where *ρBlue, ρGreen, ρRed, ρNIR, ρSWIR1, and ρSWIR2* are the corresponding bands of Landsat 5 TM (2010) of Blue, Green, Red, Near Infrared (NIR), short wave infrared one (SWIR1), and short wave infrared two (SWIR2) respectively.

The Landsat 8 OLI Wetness variable can be calculated using the equation below.

$$\boldsymbol{WET}_{\boldsymbol{OLI}} = \mathbf{0.1511}_{\boldsymbol{\rho blue}} + \mathbf{0.1972}_{\boldsymbol{\rho Green}} + \mathbf{0.3283}_{\boldsymbol{\rho Red}} + \mathbf{0.3407}_{\boldsymbol{\rho NIR}} - \mathbf{0.7117}_{\boldsymbol{\rho SWIR1}} - \mathbf{0.4559}_{\boldsymbol{\rho SWIR2}} \quad (4)$$

Where *ρBlue, ρGreen, ρRed, ρNIR, ρSWIR1, and ρSWIR2* are the corresponding bands of Landsat 8 OLI (2018) of Blue, Green, Red, Near Infrared (NIR), short wave infrared one (SWIR1), and short wave infrared two (SWIR2) respectively.

[2] represented Land surface temperature (LST) as heat. The heat of Landsat5 TM images is therefore derived from the temperature of the surface of the earth. The heat of Landsat8 OLI images is obtained from the Parameter Calculator of Atmospheric Correction based on the date and time of the satellite overpass and the study area's geographic location. Radiation transmission equation is expressed as below;

$$\boldsymbol{L_{10}} = \left[\boldsymbol{\varepsilon_{10} B_{10}(T_s)} + (\mathbf{1} - \boldsymbol{\varepsilon_{10}})\boldsymbol{I_{10}^{\downarrow}}\right] + \boldsymbol{I_{10}^{\uparrow}} \quad (5)$$

$$\boldsymbol{B_{10}(T_s)} = \left[\boldsymbol{L_{10}} - \boldsymbol{I_{10}^{\uparrow}} - \boldsymbol{\tau_{10}}(\mathbf{1} - \boldsymbol{\varepsilon_{10}})\boldsymbol{\varepsilon_{10}^{\downarrow}}\right]/\boldsymbol{\tau_{10}\varepsilon_{10}} \quad (6)$$

Where $\boldsymbol{I_{10}^{\uparrow}}$= Upwelling Atmospheric Radiance

$\boldsymbol{I_{10}^{\downarrow}}$ = Downwelling Atmospheric Radiance

$\boldsymbol{\tau_{10}}$= Atmospheric Transmittance in the Thermal Infrared Band

$\boldsymbol{\varepsilon_{10}}$= Surface Emissivity

$\boldsymbol{B_{10}(T_s)}$= Radiance of the black body at same Temperature of $\boldsymbol{T_s}$.

$\boldsymbol{T_s}$= Land Surface Temperature

Therefore, the real **LST** is calculated by using following equations;

$$\boldsymbol{LST} = \boldsymbol{K2}/\boldsymbol{ln}\left(\frac{\boldsymbol{K1}}{\boldsymbol{B_{10}(T_s)}} + \mathbf{1}\right) \quad (7)$$

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Where **K1** and **K2** are the coefficient that can be obtained from the metadata of the images [2].

According to [9] **Ɛ** is calculated by finding it relationship with NDVI. When the NDVI value is between 0.157 and 0.727, the empirical relationship of **ε** and NDVI is expressed as below;

$$\boldsymbol{\varepsilon = 1.009 + 0.047\ ln\ NDVI} \quad (8)$$

When NDVI <0, ε is 1 (the emissivity of water body is close to 1).

When NDVI is 0–0.157, the vegetation coverage is very low, and ε is 0.92. When NDVI>0.727, ε is 1 [2].

The Normalized difference soil index (**NDBSI**) is calculated as in the equations below;

$$\boldsymbol{NDBSI = (SI + IBI)/2} \quad (9)$$

Where **SI** is the Soil Index and **IBI** is the Index-based Built- up Index respectively.

The Soil Index (**SI**) is calculated as below;

$$\boldsymbol{SI = \frac{[(\rho_{SWIR1} + \rho_{Red}) - (\rho_{Blue} + \rho_{NIR})]}{[(\rho_{SWIR1} + \rho_{Red}) + (\rho_{Blue} + \rho_{NIR})]}} \quad (10)$$

$$\boldsymbol{IBI = \frac{\{\frac{2\rho_{SWIR1}}{(\rho_{SWIR1}+\rho_{NIR})} - \left[\frac{\rho_{NIR}}{(\rho_{NIR}+\rho_{Red})} + \frac{\rho_{Green}}{(\rho_{Green}+\rho_{SWIR1})}\right]\}}{\{\frac{2\rho_{SWIR1}}{(\rho_{SWIR1}+\rho_{NIR})} + \left[\frac{\rho_{NIR}}{(\rho_{NIR}+\rho_{Red})} + \frac{\rho_{Green}}{(\rho_{Green}+\rho_{SWIR1})}\right]\}}} \quad (11)$$

Where *ρBlue, ρGreen, ρRed, ρNIR, and ρSWIR1* are the corresponding bands of Blue, Green, Red, NIR, and SWIR1 in the Landsat5 TM and Landsat8 OLI sensors, respectively for equation 9 & 10.

The Principal Component Analysis (PCA) was used to integrate all the four indicators rather than the conventional weighted approach. Since each index has different unit and numerical range, the values of the four indicators were normalized between [0, 1]. The normalized indexes were used (integrated) to perform the Principal Component Transformation as in equation (12), and the result is the ecological condition/situation of the study area (RSEI model). RSEI model was later obtained by normalizing the values of the $RSEI_0$ within [0, 1]. When the value of RSEI is closer to 1, the ecological environment quality is healthier (better). On the hand, when the value of RSEI is closer to 0, the ecological environment quality is poor [2].

$$\boldsymbol{RSEI_0} = \boldsymbol{f}(\boldsymbol{NDVI}, \boldsymbol{WET}, \boldsymbol{LST}, \boldsymbol{NDSI}) \qquad (12)$$

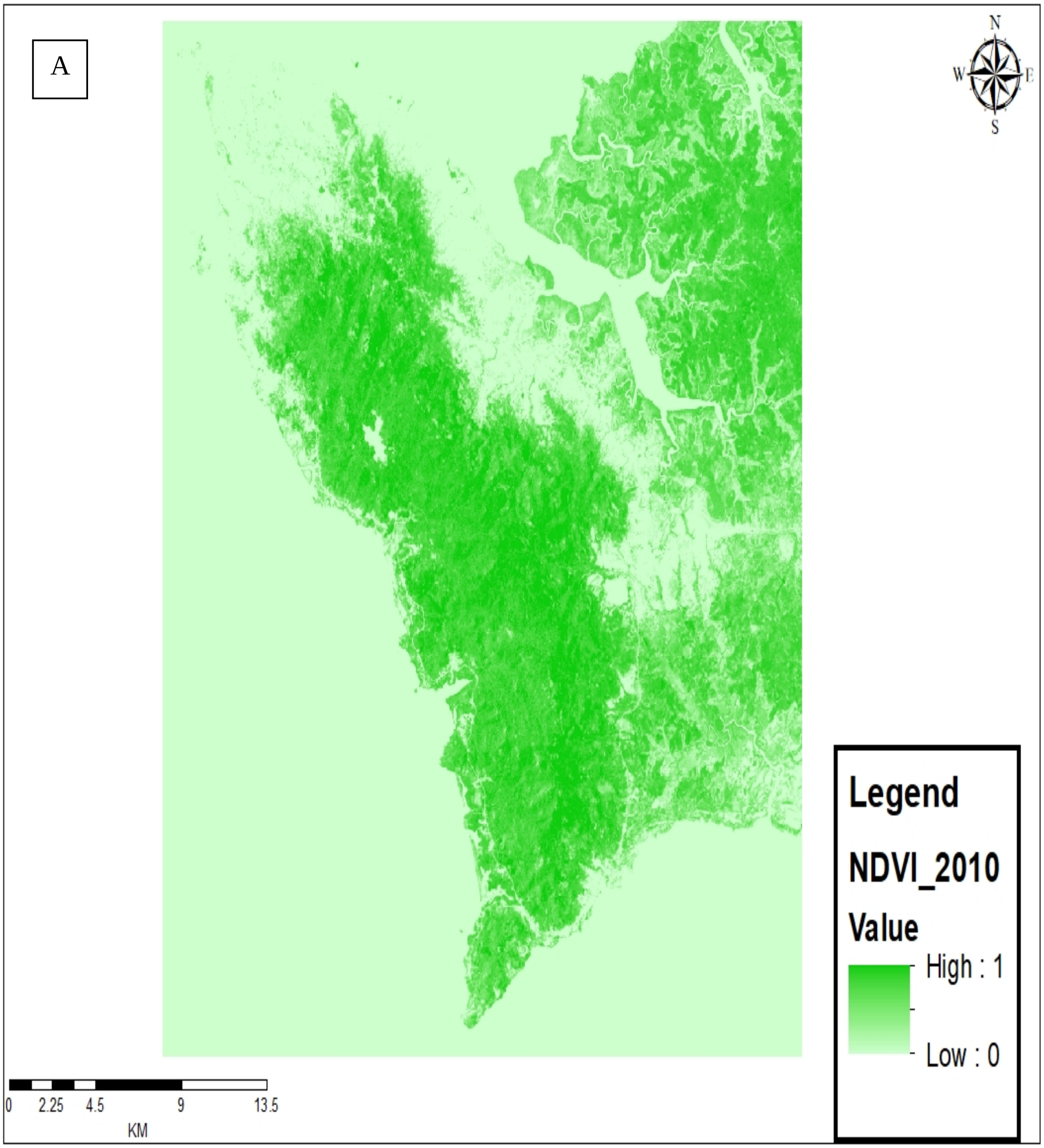
3. Results and Discussion

3.1 RSEI Indicators

RSEI included four essential indicators (greenness, humidity, heat, and dryness) that are closely linked to human survival among several ecologically relevant natural factors. Those indicators are NDVI represented by greenness, WET represented by humidity or wetness, LST represented by heat, and NDSI represented by dryness. These indicators are discussed below.

3.1.1 Normalized Difference Vegetation Index (NDVI)

Vegetation change is an important reflection parameter in the change of ecological environment [4,6]. The NDVI is widely used in the world today for the study of changes in vegetation. The NDVI ranges between -1 to +1. For the purpose of this research, these values are normalized between 0 to 1. A higher value reflects dense vegetation, and the lower value reflects sparse or no vegetation. From the map (Figure 3 A & B) and the statistics computed, it is observed that, the vegetation reduced from 2010 to 2018 (Table 2(PC1)). This reduction in relation to surface water is not good, as it will prone to direct sunrays and hence increase the rate of evaporation or evapotranspiration. Overall, NDVI contribute positively to the RSEI model.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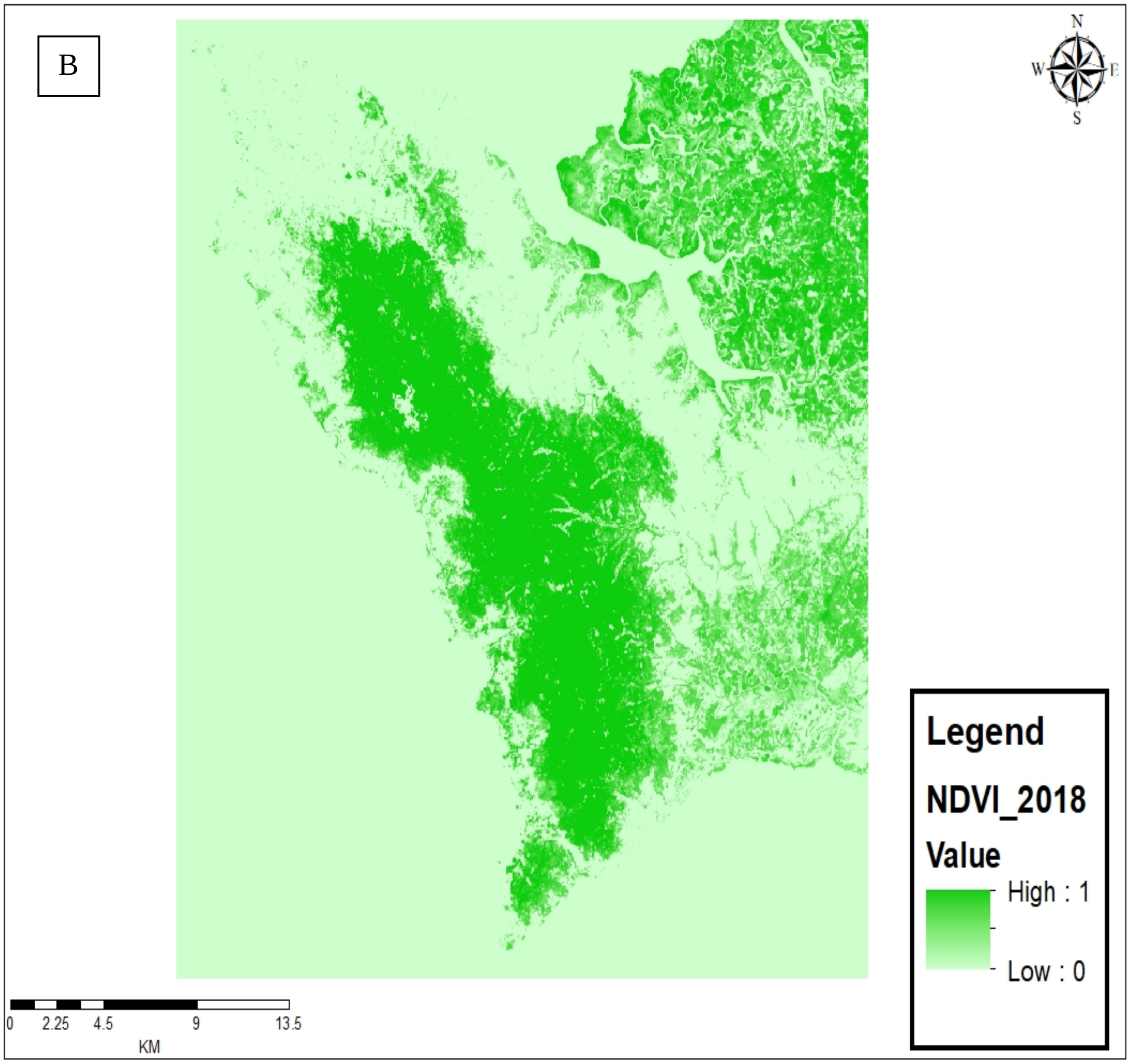
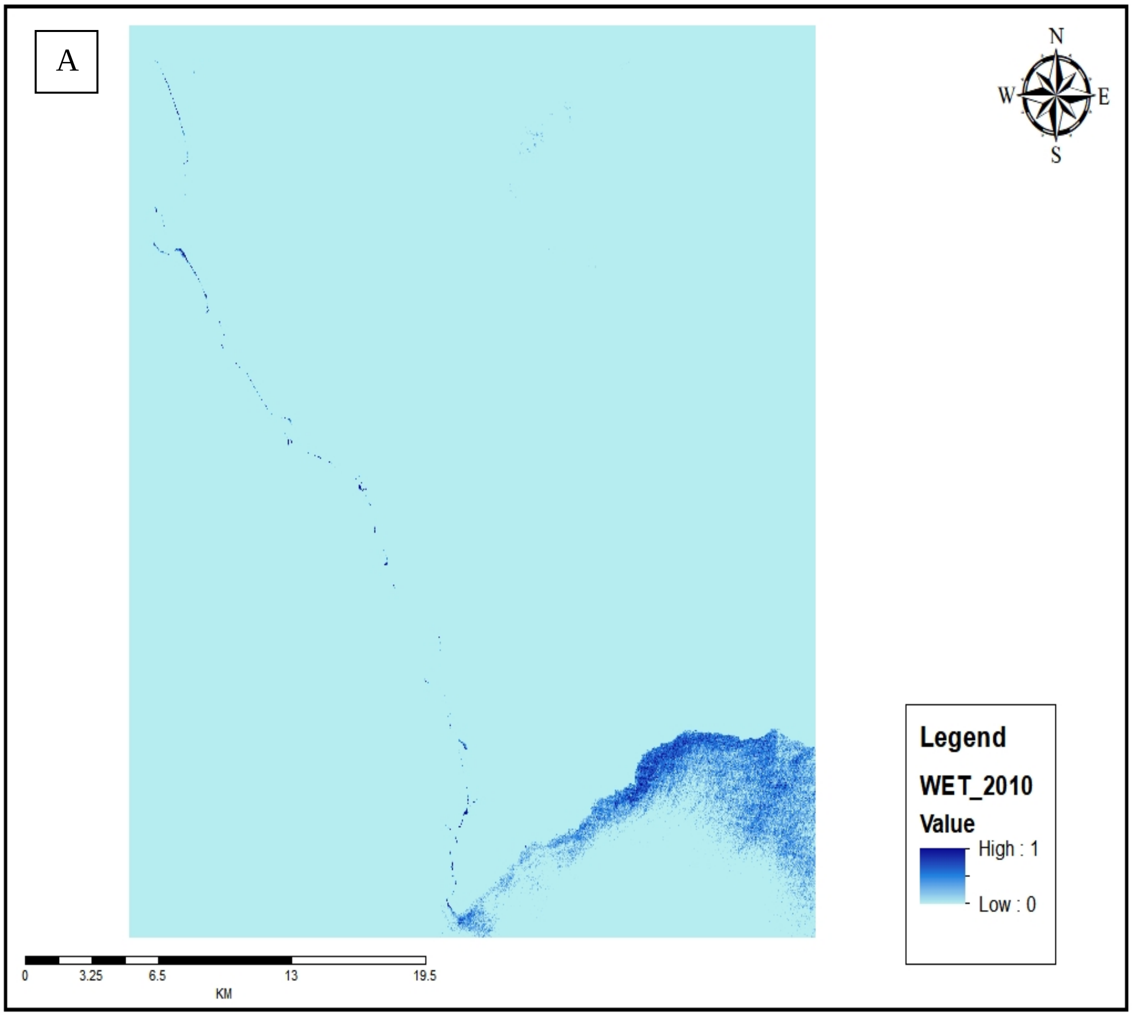


Figure 3. Normalized Difference Vegetation Index (NDVI) for 2010 (A) & 2018 (B).

3.1.2 WET

Wetness has a significant effect on the study area's ecological environment. Therefore, more attention should be paid to protecting surface water area, especially limiting engineering activities of paving and construction around the surface waters. Wetness increased from 2010 to 2018 (Table 2(PC1)). This index contributes positively to the RSEI model. The increment could be probably due to variations in precipitation between the research periods.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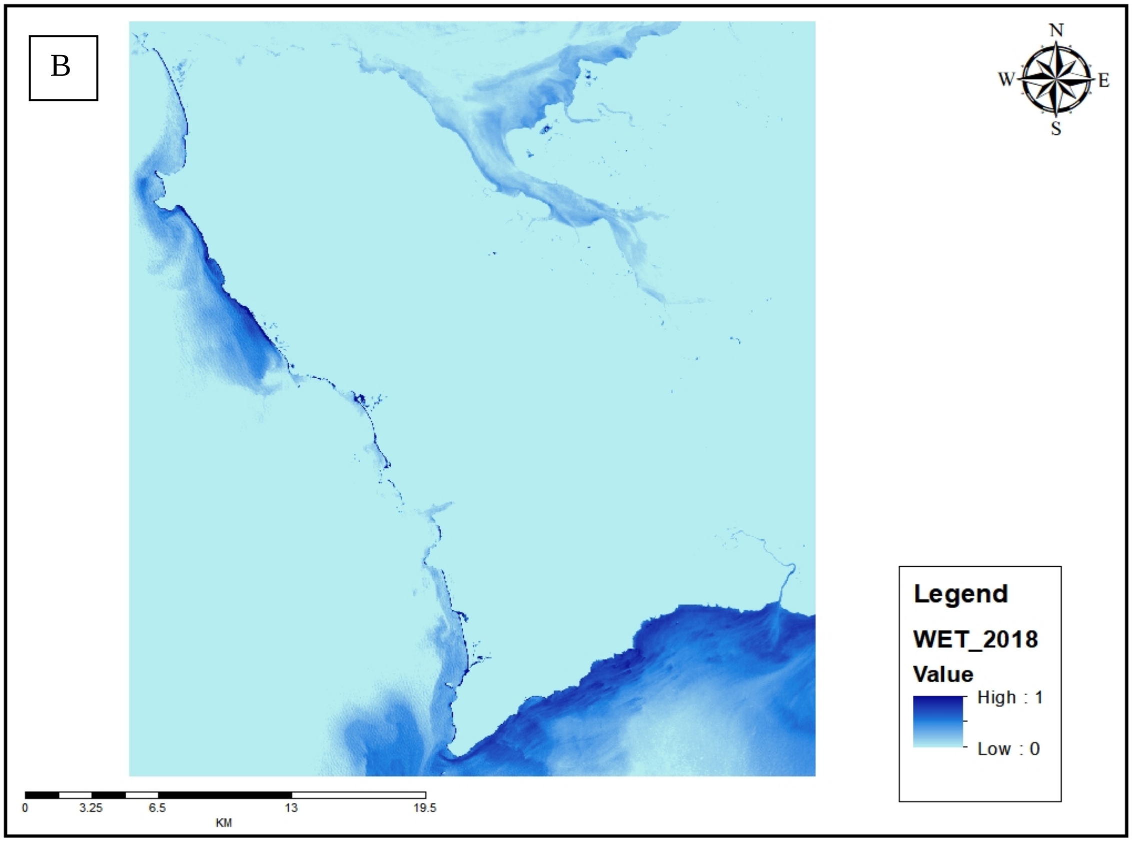

Figure 4. Wetness (WET) or Humidity for 2010 (A) & 2018 (B).

3.1.3 Normalized Differential Build-up and bare Soil Index (NDBSI)

NDBSI's selection to reflect dryness is because the index can enhance soil features as well as built-up soil features that cause dry land surfaces. Infrastructural development reduces more vegetation and surface water, making the soil dry and impervious and hence an overall decrease in the natural landscape. Therefore, an important obstacle for achieving sustainable urban growth in Freetown is how to enhance the ecological environment while increasing urban development. The process of urbanization has accelerated since 2010, and the effect of urbanization on the ecological environment will become ever more important in the near future. From the maps below (Figure 5 A & B), the imperviousness or dryness increased slightly from -0.077140 in 2010 to -0.422110 in 2018 (Table 2(PC1)). Both the highest values for the two years are closer to 0 than to 1, indicating that it has a negative effect (bad) to the ecological environment.

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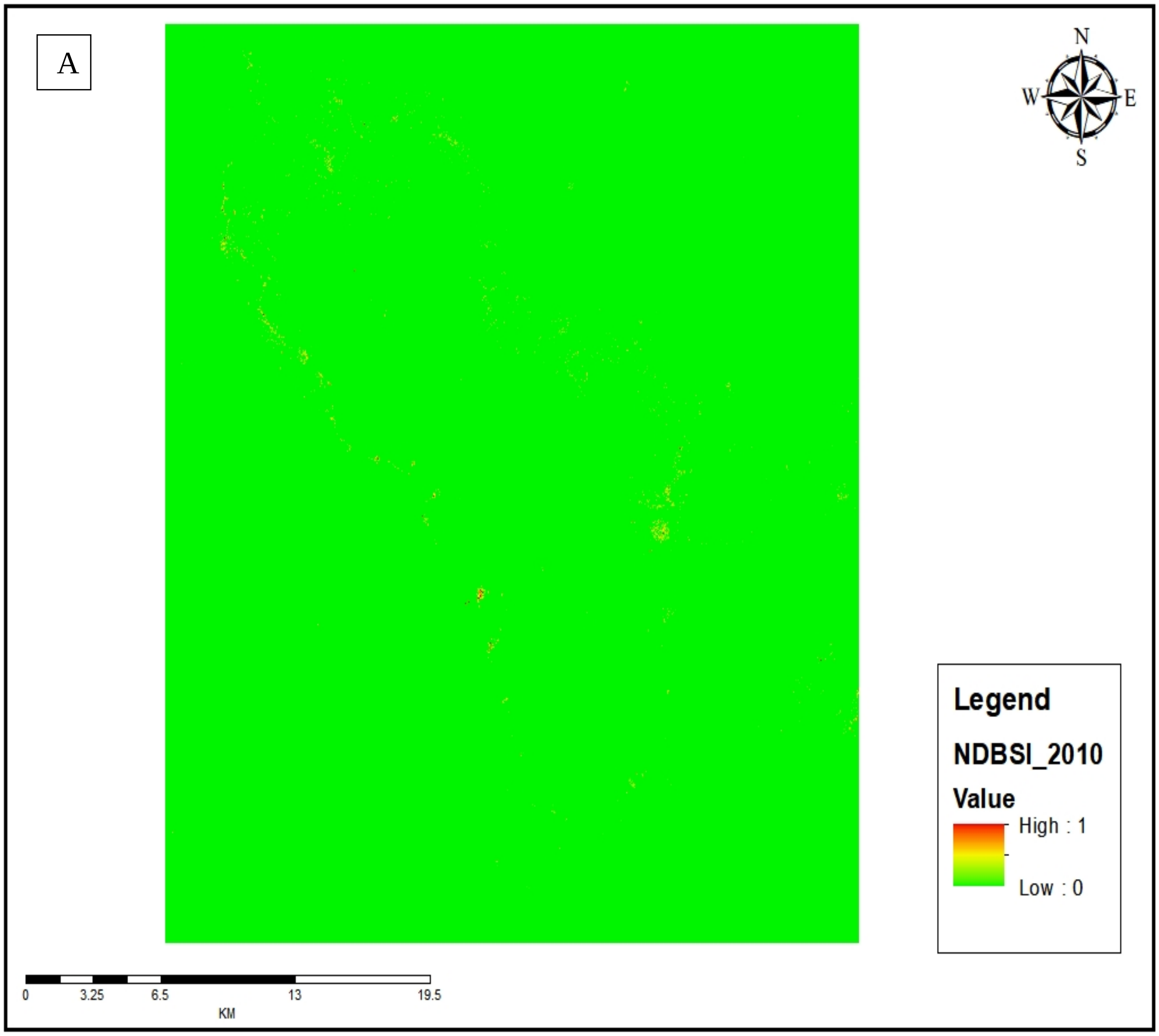


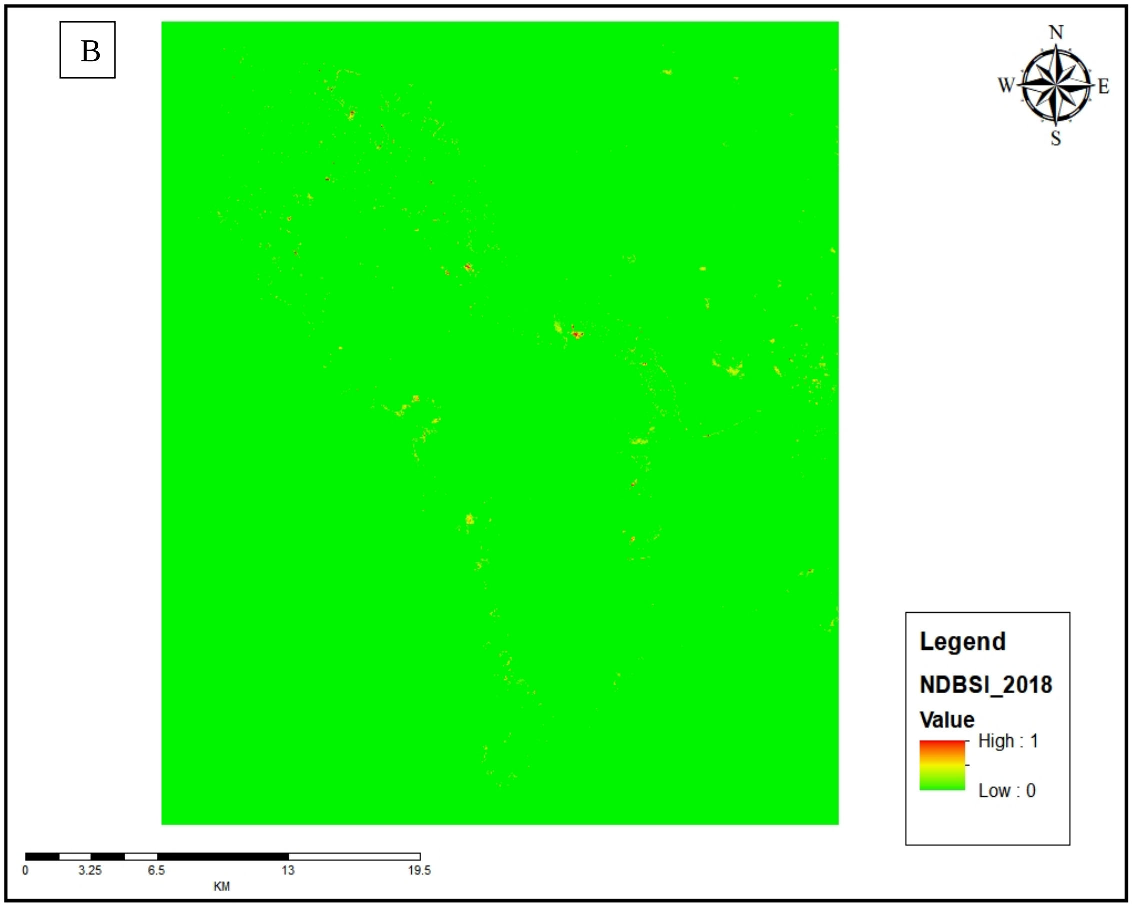


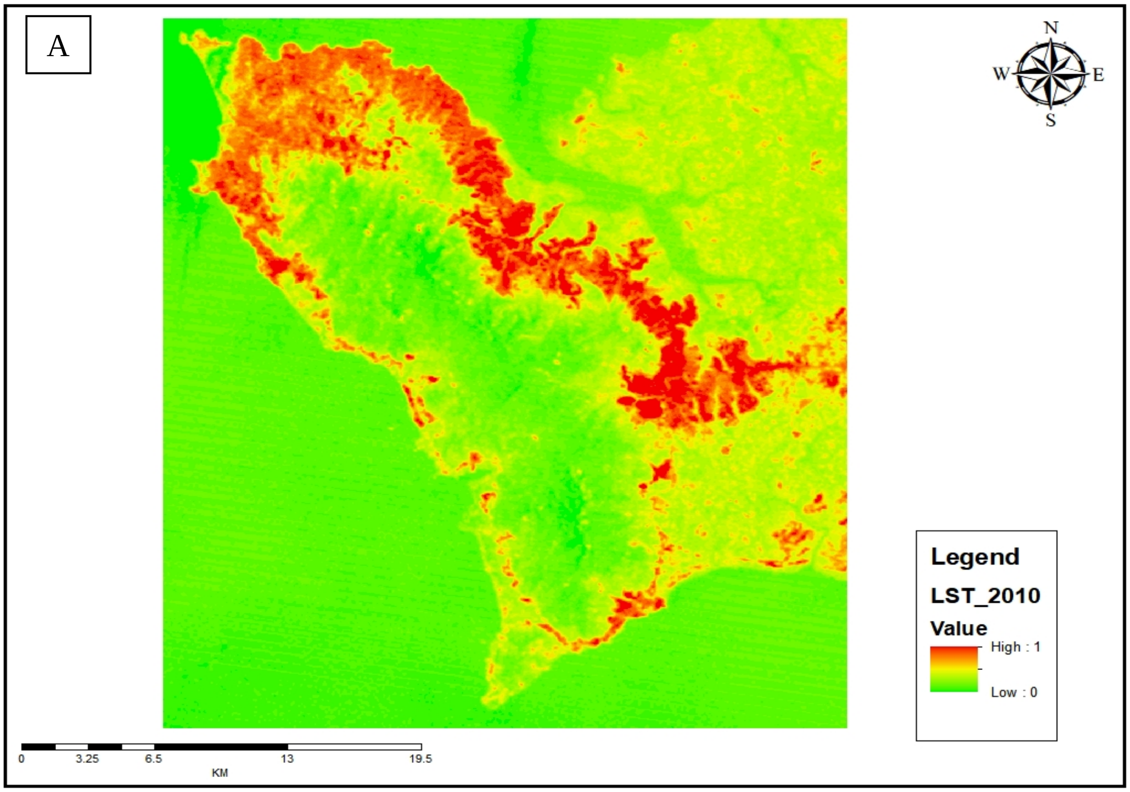
Figure 2. Normalized Difference Building-Soil Index (NDBSI) for 2010 (A) & 2018 (B).

3.1.4 Land Surface Temperature (LST)

[10] defined Land surface temperature (LST) as the temperature sensed when the land surface is touched with the hands or the skin temperature of the ground. Throughout several fields of study, LST is an important factor, such as global climate change, hydrological and agricultural processes and urban land use / land cover. It is necessary to measure LST from remote sensed images because it is an important factor affecting most of the Earth's physical, chemical and biological processes, which is also captured by the research conducted by [11].

The LST in degree Celsius (Figure 7 A & B) increased (Low) from 17.93 ^{0}C (2010) to 23.32 ^{0}C (2018), and increased (High) from 35.26 ^{0}C (2010) to 42.91 ^{0}C (2018). This increases the dryness and hence ameliorates the rate of evaporation and evapotranspiration, posing negative effect to surface water ecology. The normalized LST in relation to ecological quality (Table 2

(PC1)) indicates that the temperature increased from -0.042611 in 2010 to -0.111302 in 2018 respectively. From the maps, it is also observed that, the highly built up areas has the highest temperature.



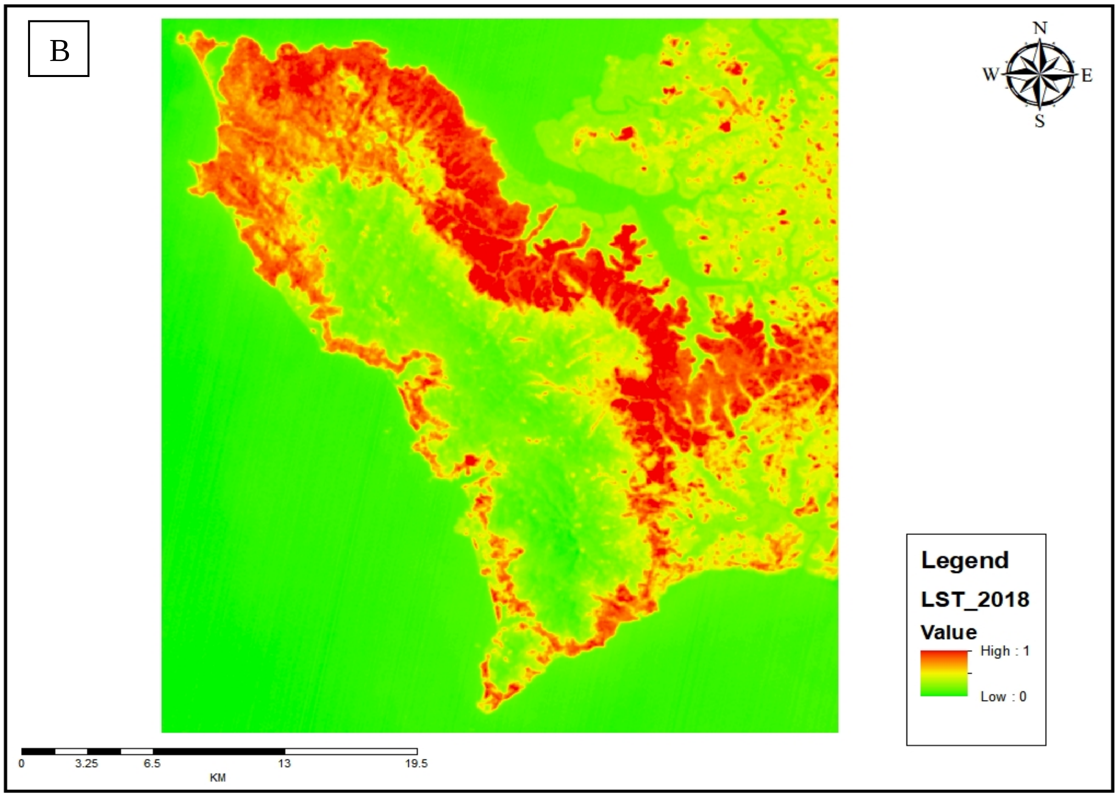


Figure 3. Normalized Land Surface Temperature in Relation to Ecological Quality for 2010 (A) & 2018 (B).

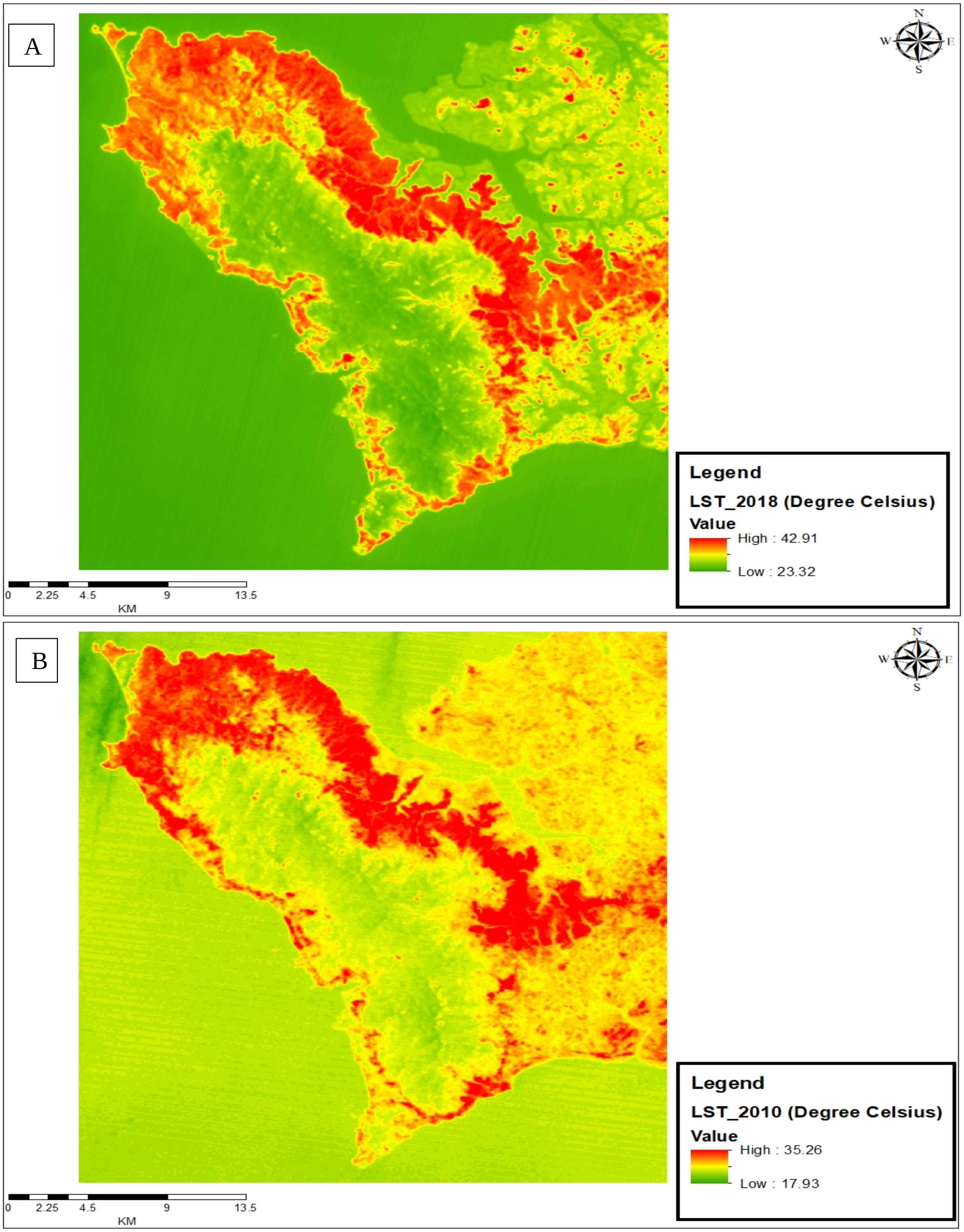


Figure 4. Land Surface Temperature (LST) in Degree Celsius for 2010 (A) & 2018 (B).

3.2 RSEI Model Analysis

RSEI is obtained by Normalizing the values of each NDVI, WET, NDBSI and LST indices within [0, 1], and integrating them for environmental comparison. According to [2,7], when the RSEI value is closer to 1 the quality of the ecological system is higher or better. On the other hand, when the RSEI value is nearer to 0, the quality of the ecological environment is low or poor. This research model shows a great agreement to the above statement as shown in figure 8.

The normalized indexes were used (integrated) to perform the Principal Component Transformation as in equation (12), and the result is the ecological condition/situation of the study area (RSEI model). As shown in Table 2, in the first main variable (PC1), the contribution rate of each index was 87.29760 percent and 89.25508 percent respectively, within the two periods (2010 and 2018). Each index was comparatively stable and suggested that most of the characteristics of the four indexes had been accumulated by the first main variable (PC1).The NDVI and the WET are positive in the first principal component (PC1), suggesting that they play a positive role in the quality of the environment in a synergistic way. Both LST and NDSI are negative and suggest negative environmental effects. The other principal components figures (PC2, PC3, and PC4) are unstable and inconsistent, making justification of ecological phenomena difficult. Thus, RSEI is formulated through the integration of the four indicators in the first principal component (PC1).

Table 2. Principal Components Analysis Results.

Year	Indicators	PC1	PC2	PC3	PC4
2010	NDVI	0.897321	0.067122	-0.022171	-0.20027
	WET	0.201631	0.326199	0.553126	0.81001
	NDBSI	-0.077140	0.302548	0.663212	-0.58892

	LST	-0.042611	0.86643	-0.29564	0.052369
	Eigenvalue	0.330422	0.036594	0.024455	0.003564
	Percent Eigenvalue	87.29760	9.033564	0.400325	0.99235
2018	NDVI	0.762136	0.035640	0.324847	0.004589
	WET	0.267133	0.456824	-0.356842	0.35684
	NDBSI	-0.422110	0.623154	0.603254	-0.35897
	LST	-0.111301	-0.668980	0.365849	-0.86954
	Eigenvalue	0.307100	0.015892	0.005684	0.23659
	Percent Eigenvalue	89.25508	6.235849	6.01235	4.03215

Four Levels are ranked for the RSEI; Bad (0-0.25), Good (0.2-0.50), Very good (0.50-0.75) and Excellent (0.75-1.0)

Table 3. RSEI score and Interpretation.

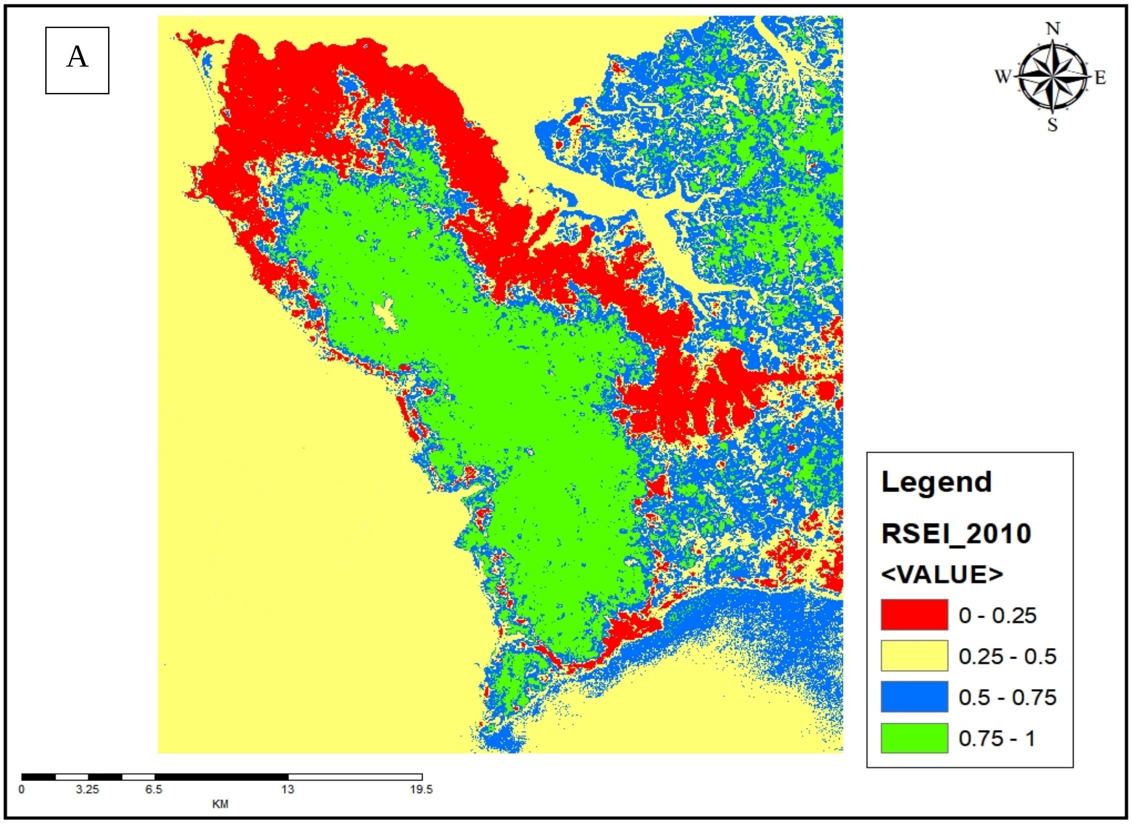
Value Range	Interpretation
0 – 0.25	Bad
0.25 – 0.50	Good
0.50 - 0.75	Very Good
0.75 – 1.0	Excellent

The NDVI and the WET ecological scores are closer to 1 and are positive, indicating that they play a positive role in the ecological environment quality in a synergistic way. Both LST and

NDBSI are negative (PC1) implying negative environmental effects because their highest ecological scores are closer to 0. In terms of the RSEI indicators, the most suitable ecological conditions should have increased vegetation density, higher vegetation-soil moisture (wetness), less dryness, and lower temperature [3].

The four RSEI indicators act in concert to provide a quantitative response signal to ecological stressors, making RSEI more holistic than their individual metrics [3]. In this research, the ecological quality of the study area improved slightly from 87.3% in 2010 to 89.3% in 2018. Overall, the ecological quality could be termed very good. In the study area, the bad region (RED in the map) is largely located in developed and bare land areas, possibly causing extreme soil erosion due to drought, so the ecological condition is poor or bad.

The secret to improving the natural condition of Freetown's Surface Water is therefore to avoid and stop deforestation across the catchment areas. Vegetation diminishes the detrimental effects of water heat (Evaporation) and other adverse effects of climate change. Vegetation can therefore minimize heat, dryness, and increase wetness, all of which favors sustainable surface water presence.



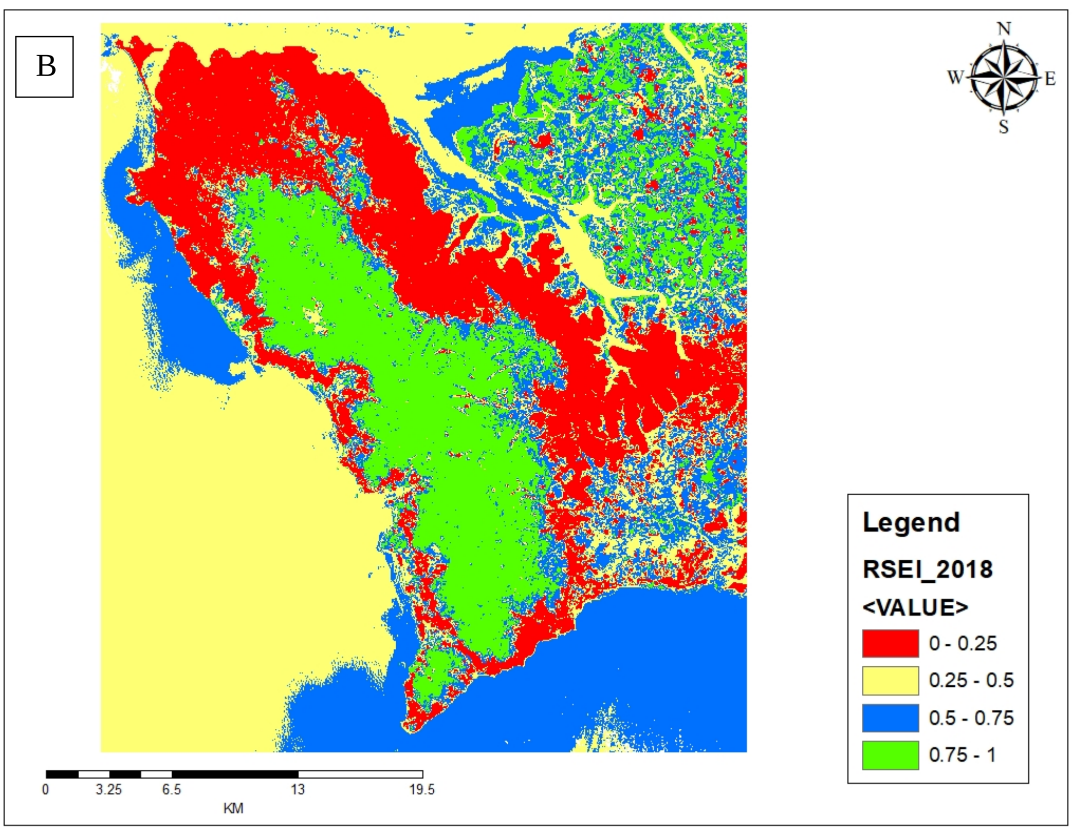


Figure 5. RSEI model Map for 2010 (A) and 2018 (B).

The mean values of RSEI in 2010 and 2018 are 0.3314 and 0.3319 respectively. This indicates a steady/slight upward trend; an indicator of the consistency of the study area's ecological environment/ecosystem is improving. Looking at the means of the individual indicators, Wetness increases from 0.0278 to 0.0323, Greenness made a slight decrease from 0.2935 to 0.2569, Heat decreases from 0.7391 to 0.6990 and Dryness increases from 0.0018 to 0.0031. The mean values (relating to ecological environment quality) show more or less a balanced developmental Trend. The Standard Deviations are also computed as in the table below (Table 4).

Table 4. The mean & Standard Deviation (S.D) values of the indicators and remote sensing ecological index (RSEI).

YEAR		INDICATORS				RSEI
		WET	NDVI	LST	NDBSI	
2010	MEAN	0.0278	0.2935	0.7391	0.0018	0.3314
	S.D	0.0167	0.3621	0.2829	0.0301	0.0988
2018	MEAN	0.0323	0.2569	0.699	0.0031	0.3319
	S.D	0.0811	0.3869	0.3167	0.0447	0.1043

3 Conclusions

Remote Sensing Ecological Index (RSEI) model was built using the 2010 Landsat 5 Thematic Mapper (TM) and 2018 Landsat 8 Operational Land Imager (OLI). This period (2010-2018) is chosen because it was the period massive infrastructural development and an increased rate of deforestation and water shortage took place in Freetown. RSEI model, based on remote sensing technology integrated the normalized NDVI, WET, LST and NDBSI to assess the Greenness, Wetness (Humidity), Heat and Dryness (Imperviousness) respectively using the Principal Component Analysis (PCA) approach and measuring the ecological environment objectively, qualitatively and quantitatively. They better represent the evolving ecological conditions in relation to surface Water over the years. The Greenness and Wetness have positive effect on the ecological environment quality, whilst Heat and Dryness have negative effect. It is therefore unraveled that, the ecological condition improved slightly from 87.3% in 2010 to 89.3% in 2018. Overall, the ecological condition of the study area is not bad, but could be termed as good; the bad ecological condition trends towards 0 (0%) or < 50% and the good ecological condition trends towards 1 (100%) or > 50%. However, if the trend of deforestation, urbanization, imperviousness (Dryness), land surface temperature (Heat) continues to increase, the ecological condition to surface water will reduce.

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