Spatial Modeling of Environmental Quality Change Based on Geographic Information System

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Abstract. A coastal area is prone to decrease of environmental quality due to coastal land abrasion and inundation/tidal flood. Several studies have shown that the coastline of Sayung District, Demak Regency, is moving toward the mainland for 6.8 mm/year and the surrounding area is experiencing land subsidence for 5-7 cm/year. These phenomena have consequences to the environmental quality in the area. In this case, this research aims to develop a spatial model using a Geographical Information System (GIS) in describing and predicting changes of environmental quality in Sayung District, Demak Regency. Four variables in a Risk-Screening Ecological Index (RSEI) approach, namely (1) vegetation density, (2) soil moisture, (3) soil quality, and (4) built space and surface temperature were used as indicators of the environmental quality. A raster calculator and Spatial Principal Component Analysis (SPCA) were then used to calculate total value of the environmental quality. This research results that the environmental quality of the study area is decreasing which indicated by the RSEI value of 0.614 (1999), 0.4749 (2009), and 0.3933 (2019). The environmental quality in the study area is also worsened by waterbody expansion.

Keywords: tidal flooding, environmental quality, RSEI, geographic information system

1. Introduction

Sea level rise is caused by global climate change and it has consequences to environmental quality in coastal areas [1], meanwhile the coastal environments have vulnerable and dynamic characteristics [2]. The sea level which estimated by IPCC (Special Report on Emissions Scenarios of the Intergovernmental Panel on Climate Change) is 22-44 cm higher in the 21st century than that in 1990 and has been increasing for 4 mm/year [3]. Furthermore, land subsidence is also worsening the coastal environment [4,5]. The sea level increase and the land subsidence together potentially threaten the environmental quality [6].

In the case of Java Island, the northern coastline has moved 6.8 mm/year on average toward mainland [7]. Furthermore, [8,9] revealed land subsidence occurring in the northern of Java Island, mainly in Sayung District (Demak Regency), takes 5-7 cm/year. Massive developments in coastal cities intending to achieve well-being also increased the potential damage in the study area. The massive developments are exemplified by reclamation activity in Marina Beach and industrial estate development in Semarang City causing tidal flood in the coast of Demak Regency [2,10,11].

Sayung District in the Demak Regency is the most affected by the tidal flood. The National Disaster Management Agency (BNPB) of Demak Regency reported that 17 of 20 villages in Sayung District were drowned by tidal flood. Consequently, pond lands were lost and houses were damaged.
At least local people in two villages (Tambaksari and Rejosari) urgently need to be relocated [2]. Furthermore, the tidal flood has a negative impact in the field of local livelihoods [12]. However, previous studies have not assessed the environmental quality with a geographic information system in the study area. Furthermore, this research uses the geographic information system to observe changes on coastlines, mangrove distribution, and land subsidence [7,9,13].

2. Data and Methods

2.1 Data

Landsat 7 TM (1999 & 2009) and Landsat 8 OLI (2019) satellite images were downloaded freely from the website of USGS (United States Geological Survey), and were used as main data in this research. The selection of time series data is chronologically justified by the beginning of reclamation activity and tidal flood phenomenon in 1999 [14], the transformation of lands into ponds damaging local houses in 2019, and the recent condition of tidal flood in 2019. The study area in this research is Sayung Subdistrict as the most affected area by tidal flood in Demak Regency (see Figure 1). It is bordered by Semarang City in the west and by Java Sea in the north.

2.2 Methods

The satellite images were firstly cropped to the extent of study area and were processed further with raster calculator and Spatial Principal Component Analysis (SPCA) in QGIS 3.8 and ArcGIS 10.3 [15–17]. Furthermore, the Risk-Screening Ecological Index (RSEI) approach utilizing four variables, namely plant density, surface temperature, humidity or water quality, and soil quality, [16,18], is computed through equation (1)

\[
\text{RSEI} (\text{Risk - Screening Ecological Index}) = f(NDVI, NDWI, LST, NDSI) \ldots \ldots \text{(1)}
\]

A raster calculator applies mathematical operation on several satellite band channels to create a thematic raster data [19].

NDVI (Normalized difference Vegetation Index) reflects vegetation coverage, biomass and leaf in an area [15] which is calculated through equation (2).
\[ \text{NDVI} = \frac{(\rho_{NIR} - \rho_{red})}{(\rho_{NIR} + \rho_{red})} \]  \hspace{1cm} (2)

WET (Wetness) index commonly used to model humidity level and surface water quality [18]. In contrast to Normalized Difference Water Index (NDWI) detecting only surface water, the WET index has more complex calculation combining the moisture of surface water, soil and vegetation [20]. The WET index is computed through equation (3) for Landsat TM and equation (4) for Landsat OLI.

\[
\begin{align*}
WET_{TM} &= 0.0315 \rho_{blue} + 0.2021 \rho_{green} + 0.3102 \rho_{red} + 0.1594 \rho_{NIR} - 0.6806 \rho_{SWIR1} - 0.6109 \rho_{SWIR2} \hspace{1cm} (3) \\
WET_{OLI} &= 0.1511 \rho_{blue} + 0.1972 \rho_{green} + 0.3293 \rho_{red} + 0.3407 \rho_{NIR} - 0.7117 \rho_{SWIR1} - 0.4559 \rho_{SWIR2} \hspace{1cm} (4)
\end{align*}
\]

LST (Land Surface Temperature) describes the condition of surface temperature and is computed through equation (5) [16].

\[ \text{LST} = \frac{K_2}{\ln \left( \frac{eK_1}{L_P} \right) + 1} \]  \hspace{1cm} (5)

NDBSI (Normalized difference Built-up & Soil Index) is combining built-up land index (IBI) and soil index (SI) generating a map of bare land or built-up [21,22] through equation (6). The original formulas for SI and IBI are shown in equation (7) and equation (8) respectively.

\[
\begin{align*}
\text{NDBSI} &= \frac{(SI + IBI)}{2} \hspace{1cm} (6) \\
SI &= \frac{[\rho_{SWIR1} + \rho_{red}] - (\rho_{blue} + \rho_{NIR})}{[\rho_{SWIR1} + \rho_{red}] + (\rho_{blue} + \rho_{NIR})} \hspace{1cm} (7) \\
IBI &= \frac{\rho_{SWIR1} + \rho_{red}}{\rho_{SWIR1} + \rho_{NIR}} \hspace{1cm} (8)
\end{align*}
\]

Spatial Principal Component Analysis Method (SPCA) is employed to summarize four variables of environmental quality having different measurement units into a single main component (PC) [18]. SPCA is fundamentally similar to weighted overlay, but SPCA is also able to analyze correlations between variables [23]. A normalization process is firstly needed to simplify and standardize each environmental variable in the SPCA method. The normalization is computed through equation (9).

\[ NI = \frac{I - I_{\text{min}}}{I_{\text{max}} - I_{\text{min}}} \]  \hspace{1cm} (9)

The normalized four variables are then computed in equation (10) resulting an SPCA value. The SPCA value is once more normalized to generate a value of 0 to 1 representing the environmental quality [16,18].

\[ \text{RSEI} = sPCA \{f(\text{NDVI}, \text{NDWI}, \text{LST}, \text{NDBSI}) \} \]  \hspace{1cm} (10)

3. Results and Discussion

3.1 Variables in the Spatial Principal Component Analysis (SPCA)

The key to assessing environmental quality is measuring the index value of the combination of the four existing variables, namely NDVI, WET, NDBSI and LST. In this study, the combination was carried out using Spatial Principal Component Analysis (SPCA). This is because the index of the four
variables has different measurement units, so that it will be difficult to combine if using ordinary weights. Before carrying out PCA, normalization was carried out on the four variables in order to obtain the same unit / parameter, namely (0, 1). This parameter illustrates that the closer to number 1, the better the quality, while closer to number 0, the quality is getting worse [16,22] After that, PCA results are obtained as can be seen in Table 1.

**Table 1. Results of the Spatial Principle Component (SPCA)**

| Year | Variables | PC1  | PC2  | PC3  | PC4  |
|------|-----------|------|------|------|------|
| 1999 | LST       | 0.27719 | 0.29763 | 0.91178 | -0.05692 |
|      | NDBI      | 0.15197 | 0.81658 | -0.28281 | 0.47971 |
|      | NDVI      | 0.88243 | -0.36563 | -0.13239 | 0.26478 |
|      | WET       | -0.3484 | -0.33307 | 0.26674 | 0.83458 |
|      | Eigen value | 0.0271 | 0.00865 | 0.00092 | 0.00017 |
|      | Percent Eigen value | 73.5664 | 23.4763 | 2.4966 | 0.4607 |
| 2009 | LST       | 0.21112 | 0.29914 | 0.92964 | 0.0414 |
|      | NDBI      | 0.20255 | 0.80973 | -0.32631 | 0.44365 |
|      | NDVI      | 0.91764 | -0.35326 | -0.10145 | 0.15119 |
|      | WET       | -0.26897 | -0.36063 | 0.13783 | 0.88238 |
|      | Eigen value | 0.0277 | 0.00805 | 0.00079 | 0.00019 |
|      | Percent Eigen value | 75.3973 | 21.9114 | 2.1628 | 0.5285 |
| 2019 | LST       | 0.30518 | 0.5945  | 0.73857 | -0.08913 |
|      | NDBI      | -0.13457 | 0.68866 | -0.43018 | 0.56796 |
|      | NDVI      | 0.93131 | -0.15578 | -0.23113 | 0.23448 |
|      | WET       | -0.14637 | -0.38477 | 0.4648 | 0.7839 |
|      | Eigen value | 0.03882 | 0.00941 | 0.00182 | 0.0001 |
|      | Percent Eigen value | 77.4053 | 18.7687 | 3.6308 | 0.1951 |

**Table 2. Correlation Results Between RSEI Variables**

| Year | Variables | LST  | NDBI  | NDVI  | WET  |
|------|-----------|------|-------|-------|------|
| 1999 | LST       | 1.00000 | 0.61912 | 0.62114 | -0.81429 |
|      | NDBI      | 0.61912 | 1.00000 | 0.09205 | -0.70551 |
|      | NDVI      | 0.62114 | 0.09205 | 1.00000 | -0.73181 |
|      | WET       | -0.81429 | -0.70551 | -0.73181 | 1.00000 |
|      | Mean Correlation | 0.68485 | 0.47222 | 0.48166 | 0.75053 |
| 2009 | LST       | 1.00000 | 0.69705 | 0.55389 | -0.80003 |
|      | NDBI      | 0.69705 | 1.00000 | 0.22872 | -0.83286 |
|      | NDVI      | 0.55389 | 0.22872 | 1.00000 | -0.65502 |
|      | WET       | -0.80003 | -0.83286 | -0.65502 | 1.00000 |
|      | Mean Correlation | 0.68366 | 0.58621 | 0.47921 | 0.76263 |
| 2019 | LST       | 1.00000 | 0.25285 | 0.59955 | -0.70898 |
|      | NDBI      | 0.25285 | 1.00000 | -0.41409 | -0.53237 |
|      | NDVI      | 0.59955 | -0.41409 | 1.00000 | -0.51398 |
|      | WET       | -0.70898 | -0.53237 | -0.51398 | 1.00000 |
|      | Mean Correlation | 0.52046 | 0.12371 | 0.23314 | 0.58511 |
Based on the table, it can be seen that the contribution rate of each variable reaches 73.5664%, 75.3973% and 77.4053% (1999, 2009, and 2019) on PC1 which shows a stability of an average increase of around 2%. Meanwhile, the values of the other main components (PC2, PC3 and PC 4) show relatively unstable numbers, so it is difficult to explain the results of the environmental quality assessment. Based on these results, the formulation of RSEI is based on a combination of the four variables on PC1. Furthermore, on PC1 the variables LST, NDBI and NDVI showed positive values in 1999 and 2009, which means these three variables have a positive role in assessing environmental quality. Meanwhile, the WET variable shows a negative value for three periods which indicates that WET has a negative role in assessing environmental quality in the study area. This shows the difference from research conducted by [16,18] that variables from NDBSI and LST play a negative role in environmental quality assessment, while NDVI and WET play a positive role in quality assessment.

Furthermore, to examine comprehensively the RSEI results, the researcher analyzed the correlation results between the four variables through the PCA results which can be seen in Table 2. As can be seen in the table below, between LST, NDBI and NDVI have a positive relationship, while the WET variables with LST, NDBI and NDVI have a negative relationship. If you follow the Pearson correlation parameter, the variable that has a strong relationship with a value above 0.8 is the relationship between LST and WET. The results of the correlation are carried out only to see the relationship between variables and not to assess the relationship with the RSEI results.

### 3.2 Risk-Screening Ecological Index Classification (RSEI)

The classification of the RSEI results is carried out to make it easier to analyze environmental quality. The classification is done by dividing into seven levels, level 1 and 2 represent water bodies, while levels 3-7 present very bad, bad, moderate, good, and very good in each year to show changes in environmental quality in more detail [18] as seen in Figure 2. Furthermore, it is necessary to calculate the average RSEI value and four variables (Table 3) to determine the development of environmental quality values in the study area.

Based on the Table 3, the average RSEI value in the 1999, 2009 and 2019 study areas has decreased with a value of 0.614; 0.4749; and 0.3933. This shows a downward trend, which indicates that the environmental quality is decreasing in the study area. The greenness variable (NDVI) and surface temperature (LST) also show a downward trend from each period. The humidity variable (WET) decreased by 0.03 initially, which then increased at the end of 0.14. The built-up land and soil (NDBSI) variables increased in the initial period by 0.07 which then decreased by 0.12 at the end. This shows a decrease in the value of the three RSEI variables, namely NDVI, LST and NDBSI, while there is an increase in the value of the WET variable. This is in line with the findings of the SPCA analysis where the NDVI, LST and NDBSI variables have a positive role and WET has a negative role in RSEI. Thus, the decreasing NDVI, LST and WET results in decreasing RSEI results and exacerbated by increasing WET also causes RSEI results to decrease.

There was a wide change in environmental quality based on the RSEI level in the study area between 1999,2009 and 2019 (Table 3). The proportion of RSEI for combined very bad, bad and moderate in 1999, 2009 and 2019 were 27.74%, 48.80% and 39.12%, respectively. This shows an increase in 1999-2009 by 21.05% and then a decrease in 2009-2019 of 9.68%. Meanwhile, the combined proportions were very good and good in 1999,2009 and 2019, respectively 54.34%, 18.39%, and 18.68 percent. These figures indicate a downward trend.

Apart from the five levels of the RSEI, there are findings that there is a significant upward trend in water bodies in the study area. Based on the table above, the proportion of the body of water increased by 14.9% in the first period and then an increase of 9.39% in the second period. The higher sea level and the depth of land subsidence also caused several administrative areas in Sayung District to sink. The villages most affected are Bedono and Sidogemah villages [2,8]. Then, the community chose to move from a sinking location to a safer location.

Furthermore, spatially poor and very bad RSEI levels are found along the coast of the study area from 1999, 2009 and 2019 (Figure 2). However, there is no previous research that shows changes in
environmental quality comprehensively in the study area. However, if you look at the research conducted by Asiyah et al. [10] which only focuses on changes in the quality of settlements in the study area, it shows that there has been a decrease in the quality of the settlement environment that occurs in the form of slum settlements. The change in the quality of the residential environment was due to an increase in sea level and a decrease in land level which triggered tidal flooding so that the land was lost / submerged and some houses were damaged.

Table 3. Average Value of RSEI and RSEI Variables

| Year | WET  | NDVI | LST  | NDBSI | RSEI  |
|------|------|------|------|-------|-------|
| 1999 | 0.7505 | 0.5002 | 0.5657 | 0.5022 | 0.6141 |
| 2009 | 0.7211 | 0.4340 | 0.5400 | 0.5791 | 0.4749 |
| 2019 | 0.8630 | 0.3908 | 0.3985 | 0.4577 | 0.3933 |

Figure 2. RSEI Classification in Sayung District 1999, 2009 dan 2019
Table 4. Area of Environmental Quality Change in Sayung District

| Level    | 1999 Area (ha) | 1999 %  | 2009 Area (ha) | 2009 %  | 2019 Area (ha) | 2019 %  |
|----------|----------------|---------|----------------|---------|----------------|---------|
| High     | 840.59         | 10.67   | 113.18         | 1.44    | 236.75         | 3.00    |
| Good     | 3,441.24       | 43.67   | 1,335.57       | 16.95   | 1,235.21       | 15.68   |
| Moderate | 1,062.08       | 13.48   | 2,184.54       | 27.72   | 1,018.84       | 12.93   |
| Poor     | 443.47         | 5.63    | 1,064.39       | 13.51   | 994.27         | 12.62   |
| Bad      | 680.67         | 8.64    | 596.38         | 7.57    | 1,069.35       | 13.57   |
| Water Body | 1,411.94    | 17.92   | 2,585.93       | 32.82   | 3,325.59       | 42.20   |
| Total    | 7,880          |         | 7,880          |         | 7,880          |         |

3.3 **Environmental Quality Change Rate**

The level of change in environmental quality is an assessment carried out to see changes in the combined results of environmental quality classifications in 1999, 2009, and 2019. The results of this assessment produce 9 classification levels which are then divided into 3 classes through the equation

\[
RSEI_{\text{changed}} = (RSEI_{y2} - RSEI_{y1}) + (RSEI_{y3} - RSEI_{y2})
\]

[24]. Levels consist of numbers -4 to 4, where negative numbers indicate environmental degradation, numbers 0 indicate that environmental quality has not changed, and positive numbers indicate an increase in environmental quality. The results of the analysis of the level of change in environmental quality can be seen in Table 5.

The results if viewed temporally by comparing changes in environmental quality in 1999, 2009, and 2019, namely environmental degradation of 5,112.31 hectares (64.88% of the total area). Changes in water bodies are included in environmental degradation, this is because changes in water bodies (tidal flooding) affect environmental damage in the study area. Meanwhile, the land area that did not change was 2,390.09 hectares (30.33% of the total area) and there was an increase in environmental quality in the study area, although it was not significant at 377.6 hectares (4.79% of the total study area). In conclusion, changes in environmental quality show a fairly large trend of degradation compared to the increase in environmental quality.

From a spatial perspective that can be seen in Figure 3, the degradation that occurs in the study area is not only in the coastal area but also occurs on the southern side of the study area which is not in direct contact with the sea. This shows that it is not only the tidal flood factor that affects environmental quality degradation. Administratively, it can be seen in attachment 1 that the villages of Sidogemah, Pilangsari and Purvosari have a percentage of environmental degradation of 95.6%, 92.9% and 91.5%, respectively, compared to their area. This was followed by Loireng and Timbulsloko Villages with environmental degradation percentages of 82.7% and 85.6%, respectively. Meanwhile, the villages of Bulusari, Dombo, Gemulak, Frampelan, and Sidorejo have a percentage between 70-80%. This shows that administratively almost the entire Sayung sub-district is experiencing environmental degradation, including 16 out of 20 villages experiencing environmental degradation with a percentage above 50%.

Unlike the other villages, Srunulan and Jetaksari Villages had a larger percentage of the area that did not change, namely 59.2% and 58.3% of their area, respectively. Furthermore, Banjarsari Village and Tugu Village had a greater percentage of improvement in environmental quality compared to other villages, namely 14% and 13.6% respectively of their total area. In addition, it can be seen spatially that there is an increase in the quality of the environment in the coastal areas of Sayung District, to be precise in Bedono, Surodadi and Banjarsari villages, which illustrates that there are activities that affect the improvement of the environmental quality. This is in line with the research conducted [13,25] in the village, that there are mangrove planting activities and a protected area.
designated for mangrove forests to prevent tidal flooding that is getting bigger in the coastal area of the Sayung District.

Table 5. The Level of Environmental Quality Change in Sayung District

| Class       | Level | Area (Ha) | Change Area (Ha) | %     |
|-------------|-------|-----------|------------------|-------|
| Degenerated | -4    | 8.03      | 5,112.31         | 64.88 |
|             | -3    | 205.93    |                   |       |
|             | -2    | 1,748.63  |                   |       |
|             | -1    | 3,149.72  |                   |       |
| Unchanged   | 0     | 2,390.09  | 2,390.09          | 30.33 |
| Improved    | 1     | 315.28    | 377.60            | 4.79  |
|             | 2     | 39.06     |                   |       |
|             | 3     | 15.48     |                   |       |
|             | 4     | 7.78      |                   |       |

Figure 3. Environmental Quality Changes in Sayung District (1999,2009,2019)

4. Conclusion

Based on the results of the study, it was found that the environmental quality in Sayung District in 1999, 2019 and 2019 was of poor quality, especially in coastal areas. In addition, the research results show that there is a large environmental degradation with a total area of 5,112.31 hectares or 64.8% of the total area of Sayung District. The result of environmental degradation is also the result of the increase in water body area by 1,913.65 hectares or 37.43% of the total area of environmental degradation. This results in variable soil moisture which can detect changes in water bodies to have a big role in environmental changes.

The results of the average index value of the four variables show that the humidity variable has a greater impact on environmental quality assessment. This can be seen in the average value, where the
humidity variable value has a greater value and has an increasing trend. The impact of the humidity variable on environmental quality assessment shows that the value of the humidity variable greatly affects the quality of the environment in Sayung District, Demak Regency. Furthermore, the four environmental quality variables have positive and negative roles in environmental quality assessment. Based on the results of the study, it was found that the variables of greenness, buildings and soil, as well as surface temperature had a positive role in environmental quality, while the humidity variable had a negative role in assessing environmental quality. The positive role in question is that if the variable experiences an increase in value, the quality of the environment will get better and vice versa, the negative role in the variable.

This study has research limitations, it cannot be denied that there are other variables that also influence environmental quality assessment. In addition, there are weaknesses related to research results. The modeling in this study is classified as a regional model, so that the results of its accuracy and accuracy cannot reach smaller administrative areas. So that the results of this study still need to be studied in more depth regarding changes in environmental quality. On the other hand, although this study focuses on remote sensing approaches and is regional in nature, field validation is needed to see the accuracy of the findings. This research was constrained in field validation due to the corona virus pandemic which forced research to be based only online and through a remote sensing approach.

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