Research paper

Assessing spatiotemporal eco-environmental vulnerability by Landsat data

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ABSTRACT

An indicator of quantifying eco-environmental vulnerability was established by synthesizing 12 variables, mainly retrieved from satellite data with incorporation of analytical hierarchy process (AHP). Six vulnerability levels of *potential*, *slight*, *light*, *medium*, *heavy*, and *very heavy* were graded to depict changes of vulnerability over temporal and spatial scales. The proposed approach was employed to study spatiotemporal eco-environmental vulnerability with Landsat data acquired in 1989, 2003, and 2014 for the Thua Thien – Hue Province, Vietnam. Over the time periods of 1989–2003 and 2003–2014, both *heavy* and *very heavy* vulnerability levels exhibit an increasing trend in both magnitude and spatial size: The former raised from 5.9% in 1989, to 7.9% in 2003, and 15% in 2014; and the later increased from 1.2% in 1989, to 3.2% in 2003, and 7.3% in 2014. Both levels mainly appeared on urbanized area, bare land, semi-bare land, agricultural land, and sparse forests. In contrast, there was a significant decline in *potential* vulnerability level with 36.4% in 1989, 30.9% in 2003, and 19.2% in 2014, while the remaining vulnerability levels *slight*, *light*, and *medium* fluctuated slightly, increased in 2003 and decreased in 2014. Supporting reasons for such changes include: (1) deforestation, agriculture intensification, construction of three hydro-electric projects during the period 2003–2014; and (2) significant expansion of urbanized area leading to differences in thermal signatures in urban areas as compared with rural areas. The findings demonstrate that eco-environmental vulnerability is primarily exaggerated by anthropogenic activities through land use/land cover (LULC) changes and further enhanced by natural processes including disasters in the Thua Thien – Hue Province of Vietnam. The correlation between land surface temperature (LST) and Normalized Difference Built-up Index (NDBI) is found to be positively correlated with 0.87, 0.89, and 0.84 for 1989, 2003, and 2014, respectively. In contrast, LST-Normalized Difference Vegetation Index (NDVI) is found negatively correlated with respect to the spatiotemporal trend of environmental vulnerability with -0.81 , -0.81 , and -0.76 in 1989, 2003, and 2014, respectively. In addition, areas having *potential*, *slight*, and *medium* thermal environmental levels are decreased from 1989 to 2003 to 2003–2014. At the regional scale, increased anthropogenic activities through land's modification have intensified the eco-environmental vulnerability in the study area. The currently proposed methodology is feasible for evaluating long-term eco-environmental changes processes by using remote sensing data, and valid for the other regions.

1. Introduction

Environmental changes and their causes increase the need to tackle their consequences on affecting the structural and functional ecosystem (Polsky et al., 2007; Turner et al., 2003). Natural ecosystem and eco-environmental vulnerability are sensitive to changes in land use/land cover (LULC) (Boori and Amaro, 2011; Xie et al., 2013; Hao and Ren, 2009; Adger, 2006; Valipour, 2015, 2016). Decision makers are increasingly pressured with challenges of pursuing social and economic

developments without causing detrimental impact on the environment (Hinkel, 2011; Ostendorf, 2011; Lawley et al., 2016). While there might have strong correlations among eco-environmental health, LULC, and thermal signatures (Strand et al., 2010). The thermal signature is the apparent thermal status near surface and can be characterized by land surface temperature (Xiong et al., 2012). Urban area is a complex eco-environment involving a variety of anthropogenic activities (Zhang et al., 2006). Due to changes of LULC, including distributions of urban sprawl and vegetation, urban areas often present more significant

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thermal signatures than less disturbed rural areas. Therefore, thermal signatures are considered as important eco-environmental characteristics representing evolutions in urban micrometeorology affected by LULC changes (Adger, 2000; Mallick et al., 2013; Miller and Small, 2003). Changes in LULC have been not only recognized as a key determinant factor among a broad range of land surface parameters (e.g., land surface temperature, evapotranspiration, runoff, etc.), but also considered as the most significant in terms of affecting the Earth System functioning (Lambin et al., 2003). The eco-environmental vulnerability is defined and governed by four factors: hydro-meteorology signatures, land resource, social economics (human activities), and topography condition, which can be classified into two categories: internal and external vulnerabilities. Internal vulnerability results from the structure of eco-environment itself and is less impacted by external vulnerability, which is influenced by human activities (Nguyen et al., 2016). In view of environmental vulnerability affected by significant LULC changes, there is a strong demand of using high quality geo-spatial information to visualizing how environmental vulnerability dynamics varied with LULC changes. Spatiotemporal eco-environmental vulnerability assessment aims to identify the trend and regions where tend to experience vulnerability, and answer the relevant questions: “what are the reasons for vulnerability and can we use this information to support environmental decision making”.

In our previous study (Nguyen et al., 2016), we proposed an assessment framework to evaluate the eco-environmental vulnerability in the Thua Thien – Hue Province, Vietnam, with involvement of 16 variables including those extracted from Landsat 8 OLI, digital maps, and *in situ* measurements. However, in view of long-term environmental monitoring across the region, it often becomes a barrier by using *in situ* measurements due to their limited spatiotemporal resolution, insufficient historical data, and infeasibility to capture both natural and man-made attributes within a given place and time. Fortunately, the time series of Landsat satellites have made a significant contribution to various fields of environmental studies, such as long-term environmental monitoring; natural and man-made disaster studies; and support of the evaluation of magnitude, dynamics, and spatiotemporal distribution of land surface parameters and eco-environmental vulnerability over timespans of multiple decades (Tehrany et al., 2013; Wilson et al., 2003).

The current work intends to further apply Landsat data to monitor eco-environmental vulnerability by proposing an improved framework over our previous version (Nguyen et al., 2016). Such improved framework is more suitable for long-term eco-environmental monitoring by advancing the illustration of spatiotemporal variability of eco-environmental vulnerability using time series of Landsat data to retrieve variables for detecting surface characteristics affecting regional eco-environment. That is, the improved framework resolves the difficulties in obtaining long-term *in situ* eco-environmental measurements that are required in the previous framework. In addition, the impacts and trends of LULC on environmental vulnerability for the past 25 years were assessed as an example to demonstrate how these remote sensing data can be used to support planners to obtain objective measurements and comparative context. In addition, this study assesses the impacts of past LULC policies on spatiotemporal eco-environmental vulnerability by: (i) evaluating eco-environmental vulnerability changes based on variables retrieved from Landsat TM, ETM, and OLI & TIRS (Thematic Mapper, Enhanced Thematic Mapper, and Operational Land Imager & Thermal Infrared Sensor); and (ii) analysing the relationship between land use changes and thermal anomaly by computing correlation coefficient between land surface temperature (LST) and Normalize Difference Built-up Index (NDBI) over the past 25 years (1989–2003–2014). Deliverable products of this study can be used to assist decision makers to deal with comparative context to answer the planning questions such as how anthropogenic processes affect the environment? Does any region of concern have less harmful impacts on the physical environment as compared with the others? Although the

Thua Thien-Hue Province was selected as our study area, the type of data and proposed framework used in the current study should be available and applicable in many moderate and large size regions.

2. Materials and methods

2.1. Materials

The present study used several data sets free of charge to examine eco-environmental vulnerability changes. Remote sensing data is the main source with meteorological data of three stations only used to compare with the results extracted from satellite data. The data used in the study are listed below:

- (1) Remotely sensed Landsat time series images from Landsat 5 TM images (acquired on 08 May 1989; 03 December 1990), Landsat 7 ETM+ images (acquired on 21 April 2003; 06 November 2000), and Landsat 8 OLI & TIRS images (acquired on 27 April 2014; 04 October 2014). Those images acquired in summer months are used to examine the LST and land cover changes with supporting seasonal vegetation features by using the images acquired in winter months.
- (2) ASTER digital elevation model (DEM) with spatial resolution of 30 m, and
- (3) Meteorological data of three stations, Hue, A Luoi, and Nam Dong used to investigate the trend of temperature (Fig. 1).
- (4) Photos of field survey used to correlate the LULC classification with ground features.

2.2. Methods

2.2.1. Image processing

Seven major steps were performed for image processing: (i) Atmospheric correction was performed for all bands by using Fast Line-of-Sight Atmospheric Analysis of Spectral Hypercubes (FLAASH) (Waner and Chen, 2001) and following the atmospheric correction, the images were geo-referenced to UTM projection, zone 48 North; (ii) Digital numbers (DNs) of thermal bands were converted to spectral radiance and then brightness temperatures are computed; (iii) Land emissivity is estimated based on NDVI method (Sobrino et al., 2008; Valor and Caselles, 1996) and brightness temperatures are converted to LST (Jimenez-Munoz et al., 2009); (iv) Visible bands of images (Landsat 5 TM image acquired on 08 May 1989; Landsat 7 ETM+ image acquired on 21 April 2003; and Landsat 8 OLI & TIRS image acquired on 27 April 2014) were selected to composite to be a single image and land cover classification is performed with Support Vector Machine (SVM) method (Cortes and Vapnik, 1995). There are nine classes of land cover types including *dense forest*, *medium forest*, *sparse forest*, *bare land*, *agricultural land*, *planted forest*, *mixed planted forest (semi-bare land, grassland, shrub, and young planted forest)*, *water*, and *urbanized area*. The accuracy assessment was also done for the classified LULC derived from Landsat images with classification accuracy, Kappa statistics coefficients being 0.84, 0.89, and 0.88 for 1989, 2003, and 2014, respectively; (v) Urban thermal field variance index (UTFVI) representing microscale temperature variation between urban and rural areas was calculated based on LST by using Eq. (1) (Liu and Zhang, 2011):

$$UTFVI = \frac{T_s}{T_s - T_{mean}} \quad (1)$$

where UTFVI is the urban thermal field variance index; T_s is the LST of certain pixel in degree Celsius (°C); and T_{mean} is the mean LST of the whole study area in degree Celsius. To classify thermal field variance index into different levels, histograms are used to reveal the statistical distribution of calculated thermal field variance values from grid cells; (vi) Calculated Normalized Difference Built-up Index (NDBI), Normalized Difference Vegetation Index (NDVI), Normalized Difference Water

Fig. 1. Vietnam and sea level rise stations (a); and Thua Thien-Hue Province (b). The development of the Hue city from Landsat time series (c); and Landsat time series images over the Thua Thien-Hue Province (d). (Red areas in images captured on 27 April 2014 show constructions of 3 hydro-electric projects). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 2. Long-term eco-environmental vulnerability assessment framework.

Index (IDWI), and Normalized Difference Moisture Index (NDMI) (details of these calculations, refer to [Nguyen et al. \(2016\)](#)); and (vii) Investigated the relationship between LST and NDBI and NDVI.

2.2.2.2. Assessment framework

Two concerned issues of evaluating eco-environmental vulnerability involved in our previous study ([Nguyen et al., 2016](#)) were: (i) some indices were generated from *in-situ* measurement data, especially

Table 1

Weightings of group variables and variables used for the calculation of eco-environmental vulnerability for the Thua Thien-Hue Province in 1989, 2003, and 2014. Consistency ratio (CR) of four group determinant factors is 0.023 (modified and adapted from [Nguyen et al., 2016](#)).

Group variables/Factors (B_i)	Global weight (W_i)	Variables/Factors (C_i)	Local weight (w_i)
B_1 . Hydrometeorology	0.200	C_1 NDMI	0.095
		C_2 NDWI	0.161
		C_3 LST	0.593
		C_4 Distances from hydrological network	0.265
B_2 . Society-economics	0.329	C_5 Distances from urbanized area	0.164
		C_6 NDBI	0.297
		C_7 UFTVI	0.539
B_3 . Land resources	0.142	C_8 LULC	0.667
		C_9 NDVI	0.333
B_4 . Topography	0.329	C_{10} DEM	0.611
		C_{11} Slope angle	0.347
		C_{12} Slope aspect	0.134

meteorological indices such as precipitation, which have certain limited capabilities of reflecting spatial variation of eco-environmental vulnerability due to insufficient spatial resolutions and (ii) thus applicability of previous framework were limited by resolution of station measurement and interpolation technique applied. Therefore, this paper presents a modified framework improved upon the former framework proposed by [Nguyen et al. \(2016\)](#) in order to examine spatiotemporal eco-environmental vulnerability changes over the Thua Thien-Hue Province in 1989, 2003, and 2014. The modified framework aims to effectively use the variables from Landsat data to combat the difficulties associated with historical data missing. Accordingly, spatiotemporal eco-environmental vulnerability maps are generated with consideration of both natural and made attributes then presented this information with unique indices and synthesis maps. Importantly, the improved framework is able to consider the effect of anthropogenic activities as LULC changes on regional eco-environment ([Fig. 2](#)). The assessment was evaluated by 12 variables with nine of them constructed from Landsat data and the reminding three variables extracted from DEM. Twelve variables were divided into four group determinant factors consisting of hydrometeorology (B_1), socioeconomics (B_2), land re-

sources (B_3), and topography (B_4). B_1 includes four variables: (C_1) Normalized Difference Moisture Index (NDMI), (C_2) NDWI, (C_3) LST, and (C_4) Distance from hydrological network extracted from land cover classification. B_2 includes three variables: (C_5) Distance from urbanized area extracted from land cover classification, (C_6) NDBI, and (C_7) UFTVI. B_3 includes two variables (C_8) LULC and (C_9) NDVI. B_4 includes 3 variables: (C_{10}) DEM, (C_{11}) slope angle, and (C_{12}) slope aspect.

After deriving the 12 variables of interest, eco-environmental vulnerability evaluation was performed for the years 1989, 2003, and 2014 with the aid of an analytical hierarchy process (AHP) and geographical information system (GIS) by using Eqs. (2), (3):

$$EVA = \sum_{i=1}^4 B_i * W_i \quad (2)$$

$$B_i = \sum_{j=1}^{nB_i} C_j * w_j \quad (3)$$

where EVA denotes the eco-environmental vulnerability, B_i is the i th group determinant factor W_i is the weight of the i th group determinant factors, C_j is the j th variable, w_j is the weight of the j th variable, and nB_i is the number of variables in group determinant factor B_i introduced in [Table 1](#).

To classify vulnerability intensity, the EVA was standardized and compared. In this study, we used histograms to reveal the statistical distribution corresponding to values of grid cells of eco-environmental vulnerabilities raster to classify EVA into six categories, namely *potential* (1–2.0), *slight* (2.0–2.6), *light* (2.6–2.9), *medium* (2.9–3.0), *heavy* (3.0–3.5), and *very heavy* (3.5–4.0).

3. Results and discussion

3.1. Spatiotemporal distribution pattern of eco-environmental vulnerability levels

[Fig. 3](#) presents eco-environment vulnerability patterns in the Thua Thien-Hue Province during the period of timeframes 1989–2003, and 2003–2014 generated from four determinant factors including hydrometeorology, land resources, topography, and social economics as seen in the Appendices ([Figs. A1–A4](#)). An overall perspective of the eco-environmental vulnerability exhibited an increasing trend and the vulnerability is heavy in the north, along the coastline and in the center, while it is relatively light in the south. The contribution of

Fig. 3. The map of eco-environmental vulnerability in the Thua Thien-Hue Province in 1989, 2003, and 2014.

Table 2

Results of statistical analysis and the proportion of each eco-environmental vulnerability level in the Thua Thien – Hue Province in the years 1989, 2003, and 2014.

Vulnerability levels	1989				2003				2014			
	Grid number	%	Mean EVA	SDT	Grid number	%	Mean EVA	SDT	Grid number	%	Mean EVA	SDT
Potential	161363	36.4	2.28	0.57	137814	30.9	2.58	0.75	85602	19.2	2.90	0.65
Slight	115584	26.1			96736	21.7			110964	24.9		
Light	87654	19.8			94261	21.2			84591	19.0		
Medium	46804	10.6			67220	15.1			64998	14.6		
Heavy	26368	6.0			35234	7.9			66953	15.0		
Very heavy	5300	1.2			14076	3.2			32460	7.3

Fig. 4. Spatial distribution of eco-environmental vulnerability in the Thua Thien–Hue Province in 1989, 2003, and 2014 according to elevation and districts.

heavy, and *very heavy* vulnerability levels shows evolving patterns (from 5.9% in 1989–7.9% in 2003 and 15% in 2014 for *heavy* vulnerability level; from 1.2% in 1989, to 3.2% in 2003, and 7.3% in 2014 for *very heavy* vulnerability level). In contrast, there was a significant decline in *potential* vulnerability level (36.4% in 1989, 30.9% in 2003, and 19.2% in 2014). The remaining vulnerability levels include *slight*, *light*, *medium* fluctuating slightly by increasing in 2003 and decreasing in 2014. Table 2 presents the mean values of EVA of the whole study area and statistical computation of each vulnerability level in 1989, 2003, and 2014. In general, eco-environmental vulnerability during 1989–2003–2014 have an upward trend with mean EVA values of 2.28 in 1989, 2.58 in 2003, and 2.89 in 2014. Note that higher EVA values represent more serious eco-environmental vulnerability.

Fig. 4 indicates that eco-environmental vulnerability in *medium*, *heavy*, and *very heavy* levels occurred mainly in Phong Dien, Quang Dien, Nam Dong, and A Luoi districts, showing an evolving trend in

their physical size and magnitude. The contributing factors for an upward trend in *medium*, *heavy*, and *very heavy* levels are due to the fact that part of natural forest has been converted to plantation forest, water (due to construction of 3 reservoir hydro-electric dams between 2003 and 2014), and that expansion of urbanized area appears in Quang Dien, Phong Dien, and Nam Dong districts showing sprawl in human settlement. Another supporting reason to explain this trend is that agricultural land in low elevation belt has been invasively converted to urbanized area and agricultural intensification activities continue to explore and practice in higher land so that disturbance of human activities stepping from low to high lands. In addition, higher intensification of *medium*, *heavy*, and *very heavy* levels located in low elevation belt from 0 m to 80 m and climbed to higher land from 80 m to 350 m in 2014, mainly lying on urbanized area, bare land, semi-bare land, agricultural land, and poor and recovery forests as seen in Fig. 5.

Fig. 5. Spatial distribution of eco-environmental vulnerability in the Thua Thien–Hue Province in 1989, 2003, and 2014 according to land cover types.

3.2. Discussion of influential factors

3.2.1. Land use/land cover changes

In terms of LULC changes, the driving factors of eco-environmental vulnerability were increased in *heavy* and *very heavy* levels and declined in *potential* levels throughout the periods 1989–2003, and 2003–2014 mainly caused by expansion of urbanized area, cultivation development, and natural forest land narrowing, which can be seen from Figs. 5–7, in the land cover changes analysis.

Figs. 5–7 show the increase in the physical size of urbanized area with expansion of LST over decades (Fig. 8). There was a dramatic increase in urbanized area and decrease in agricultural land and forest land. Urbanized area had greatest changes during different time periods, from 166.12 km² in 1989, 256 km² in 2003, to 530.93 km² in 2014. There was a significant decrease in agricultural land from 357.25 km² in 1989, through 228.94 km² in 2003, to 240.88 km² in 2014. Changes in urbanized area mainly occurred in urban and surrounding areas where cropland was replaced by concrete (buildings,

roads, ...etc.) and the reduction of forest land mainly appeared in rural and low mountainous areas where a part of natural forest area was gradually replaced by planted forest and cropland and building. Regarding the reasons for such changes, they can be interpreted as such (i) before 1954, the communities mainly relied on the nature by shifting cultivation and hunting, but in this timeframe the disturbances of humans on the forest were insignificant possible due to low population and long fallow period; (ii) In the period 1967–1973, the forest was destroyed by the wars. The human disturbance becomes a crucial concern since 1975 when the Vietnamese government implemented the New Economic Zone (NEZ) program, which encouraged people to settle in the highland. In this period, the new settlers were lack of proper training and knowledge of sustainable long-term use of abundant land. As a result, the upland forests were heavily abstracted since there was no official regulation to properly govern the forestland management. In addition, humans were free to exploit the forestland for any purposes; (iii) Between 1994 and 2000, the Watershed Management Boards organized the planting of a major part of the hill land.

Fig. 6. Dynamic of land cover from 1989, 2003, to 2014 derived from Landsat images, (classification accuracy, Kappa coefficients are 0.84, 0.89, and 0.88 for 1989, 2003, and 2014, respectively).

Fig. 7. Land cover changes in past decades 1989–2014 in the Thua Thien-Hue Province.

Fig. 8. Spatiotemporal LST distribution over Thua Thien-Hue Province derived from thermal bands of Landsat (Mean LSTs and Standard deviations (STDs) are 23.9 °C (STD 2.1); 24.6 °C (STD 2.4); and 26.1 °C (STD 2.7) for 1989, 2003, and 2014, respectively).

Agricultural production has been gradually transferred from the hill slope to the river valleys. Consequently, the planted forests have been vastly redistributed; and (iv) between 2005 and 2008, the Vietnamese government and the Thua Thien-Hue Province strictly enforced the forest protection law, and implemented forest reclassification and

zoning, especially in the up-stream protected forest areas (Tran et al., 2010; TTHPPC, 2005). However, it always takes time for the planted forest to grow and the quality of planted forest is incomparable with natural forest, not to mention the fact that the population is high nowadays. Impressively, there was a significant change in water bodies

Table 3
Changes in LSTs of nine districts over decades.

No	District names	Area (km ²)	08 May 1989		21 April 2003		27 April 2014	
			Mean	Std	Mean	Std	Mean	Std
1	Hue (urban)	71.9	25.7	1.4	26.5	1.6	27.6	2.1
2	Phu Vang (urban)	277.2	24.9	2.2	26.5	2.7	26.7	3.5
3	Quang Dien (urban)	162.7	25.1	2.7	26.1	3.0	26.1	3.4
4	Phu Loc	705.8	24.1	1.8	25.8	2.5	27.7	2.8
5	Huong Tra	518.2	24.7	1.3	24.8	1.4	26.4	1.9
6	Huong Thuy	455.9	24.6	1.7	25.3	2.0	27.3	2.0
7	A Luoi	1105.7	22.5	1.2	22.9	1.1	24.4	1.7
8	Nam Dong	643.7	22.8	1.1	24.0	1.4	26.6	2.3
9	Phong Dien	947.1	24.8	2.6	24.3	3.1	26.4	3.2

Fig. 9. Annual measured air temperature at 3 stations (Hue, A Luoi, and Nam Dong).

Fig. 10. Distribution of population in Thua Thien-Hue Province in 1989, 2003, and 2014.

due to the appearance of 3 reservoir hydro-electric dams constructed after 2010. At the regional scale, the increase of urbanized area, and decrease of cropland and woodland may affect local climate and environmental degradation. Since more people live in the city (Figs. 6, 10), there is an increase in human demands. Fig. 6 shows a significant increase in total population in the Thua Thien-Hue Province throughout the periods from 1989 to 2014. However, the urban population is dramatically increased, while the rural population is significantly declined.

3.2.2. Land surface temperature (LST)

The LSTs in urban and rural areas were investigated by estimating mean and standard deviation for each district in the Thua Thien-Hue Province (Table 3). The LSTs in 1989, 2003, and 2014 are shown in Fig. 8. There was an increasing trend in LST in both urban and rural areas (mean LST was increased by 0.7 °C and 1.5 °C between the 1989–2003 period and 2003–2014 period, respectively), and the difference in the mean LST between urban and rural areas fluctuated from 0.9 °C to 2.9 °C. The Fig. 8 shows the evolving patterns of LST from urban to rural areas in 1989, 2003, and 2014, and indicates that each district has a different spatiotemporal pattern of LST. There is an increasing trend for LST from urban to rural areas from 1989 to 2014.

There is no record of precipitation from ground measurement at the time when satellite pass. Therefore, in this study, precipitation is not considered. Annual air temperature from *in situ* measurement at 3 stations (Hue, A Luoi, and Nam Dong) shows a good agreement with an increasing trend of LST derived from thermal bands of Landsat sensors (Fig. 9). The measured air temperature increased by around 0.5 °C, 1.0 °C, and 0.9 °C at the Hue, A Luoi, and Nam Dong stations, respectively, throughout the period from 1989 to 2014. The difference in LST from 1989 to 2014 is larger than that in the corresponding measured air temperature. This is possibly due to the larger variation of LST associated with complexity of land cover types as compared to less variability of the air temperature generally measured at height of 2 m. Therefore, difference in LST is higher than those in monthly and annually measured air temperatures.

3.2.3. The correlation analysis between land surface thermal anomalies and land cover change and its association with eco-environmental vulnerability changes

To investigate the relationship between land cover changes and LST variation, several sampling points were randomly taken over the Thua Thien-Hue Province and LST, NDBI, and NDVI values were extracted from the raster data to compute correlation coefficients. The LST-NDBI correlation coefficients (i.e., 0.87, 0.89, and 0.84 for 1989, 2003, and 2014, respectively) indicate a positive influence of built-up land on urban temperature, implying that the built-up land can intensify the thermal environment in the Thua Thien-Hue Province. In contrast, negative LST-NDVI correlations (i.e., −0.81, −0.81, −0.76 in the same period) demonstrate that vegetation can weaken thermal intensity (Fig. 11).

3.2.4. Remarks for eco-environmental management

In terms of solutions for short- and long-run visions, we may have a broader view about interaction between natural and human systems to adjust eco-environment in the context of rapid economic development and lessen the negative processes to alert ongoing development plans in a positive way. Understanding the underlying factors that facilitate and inhibit collaboration in eco-environmental settings is an important step towards improvement of public participation in environment (citizen observatories) and resource policy decision making (Selin and Chavez, 1995). Two important issues are always concerned in environmental monitoring and management: (i) defining the problem; and (ii) proposing the solutions. In this study, eco-environmental vulnerability and influential factors are associated with the view of human practice on land's transformation and LULC changes can be attributed to different ways by various applications and contexts (Malczewski, 2003). Agricultural experts, urban planners, and economic experts would have different perceptions: Agricultural experts tend to develop farming activities from low to high land, from inland to coastal zone; Economic experts take advantages of natural resources for exploration; Urban planners develop and expand from urban to sub-urban and rural areas, and implement construction. Ultimately, it is important to make

Fig. 11. Correlation coefficients between LST, NDVI, and NDBI in Thua Thien-Hue Province for 1989, 2003, and 2014.

an agreement between development and environmental protection for sustainable ecological development. A persistent and troubling gap between implementation and planning solution requires that the managers must find a new way to enforce proposed solution effectively (Tran et al., 2010). Thus, we suggest that environmentalists, planners, and officials of administrative units simultaneously and closely cooperate to implement what have been proposed in the scientific community. Society and village meeting with representatives of those who involved in the assistance to the planners, and local authorities must resolve the problems by taking into account of people's point of view. Environmental scientists, planners, and local authorities should well inform the people, farmers, and other land users the consequences of the way people use the land. Also, planning should be prepared as early as possible, and land users must be well kept informed of the progress. After all, the more the people willing to involve implementation, the higher the proposed solution can succeed. Although eco-environmental management may be addressed beautifully, its implementation faces a big challenge to achieve a balance between sustainable development and economic boost in the real world.

4. Conclusions

This study explored the spatiotemporal eco-environmental vulnerability in the Thua Thien-Hue Province for both time periods of 1989–2003 and 2003–2014 by using variables retrieved from Landsat time series data to investigate evolution of both natural processes and anthropogenic activities. From the results, we draw the following conclusions:

1. In general, time series maps of eco-environmental vulnerability in the Thua Thien-Hue Province in 1989, 2003, and 2014 show an evolving pattern of urban thermal anomalies highly associated with sprawl of urbanized area. Also, they are closely correlated with higher eco-environmental vulnerable levels, namely *medium*, *heavy*, and *very heavy* over the period of interest as the *heavy* vulnerability level raised from 5.9% in 1989, to 7.9% in 2003, and 15% in 2014; and the *very heavy* vulnerability level increased from 1.2% in 1989, to 3.2% in 2003, and 7.3% in 2014.
2. Analysis of eco-environmental vulnerabilities associated with LULC changes in recent 25 years indicates that evolving distributions of *heavy* and *very heavy* vulnerability levels mainly occurred on *urbanized area*, *bare land*, *semi bare land*, *agricultural land*, and *sparse forests*. In contrast, there is a significant decline in *potential* vulnerability level (36.4% in 1989, 30.9% in 2003, and 19.2% in 2014). The remaining vulnerability levels *slight*, *light*, *medium* fluctuated slightly by increasing in 2003 and decreasing in 2014.
3. Supporting reasons for the observed changes are possibly due to: (1) deforestation, agriculture intensification, and construction of three hydro-electric projects during 2003–2014; and (2) significant expansion of urbanized area leading to differences in thermal signatures in urban areas as compared with rural areas. It is readily aware of that intensification and expansion of human activities from lowland to highland have amplified the vulnerability of eco-environment in the Thua Thien-Hue Province.
4. The successful assessment framework proposed and practiced in this study can be applied to the other regions by adjusting factors relevant to the concerned variables required. Also, it is necessary to conduct eco-environmental vulnerability assessments for neighbor-

ing regions of the Thua Thien-Hue Province to further evaluate regional eco-environmental vulnerability in the central Vietnam associated with severe disaster and anthropogenic disturbances.

Additionally, in this study there is not much analysis between eco-environmental vulnerability and disaster events, which can become a crucial topic for future investigations. Besides, the study area only focuses on the Thua Thien-Hue Province so that there exists still a big gap for future exploitation to expand the study side and study eco-mechanism of eco-environmental vulnerability, not only based on LULC changes, but also considering climate changes and characteristic of disaster events in the region of concern.

Author contributions

Anh Kim Nguyen came up with research idea through discussion

Appendix A

A1. The pair-wise comparison matrix, class weights, and consistency ratio (CR)

Tables A1–A4 present the detail of assigning the weights for the AHP process including hydro-meteorology, social-economics, land resources, and topography.

Table A1
The hydro-meteorology (B_1).

Factors/Variables	LST	Dis. Hyd. network	NDWI	NDMI			
LST	1	3	4	5			
Dis. Hyd. network	1/3	1	2	3			
NDWI	1/4	1/2	1	2			
NDMI	1/5	1/3	1/2	1			
Column Sum	1.783	4.833	7.500	7.500			
Normalization	LST	Dis. Hyd. network	NDWI	NDMI	Weight/ Row average	Row totals	Row totals/average
LST	0.561	0.621	0.533	0.667	0.595	2.511	4.217
Dis. Hyd. network	0.187	0.207	0.267	0.400	0.265	1.071	4.041
NDWI	0.140	0.103	0.133	0.267	0.161	0.633	3.933
NDMI	0.112	0.069	0.067	0.133	0.095	0.383	4.022
Column Sum	1.000	1.000	1.000	1.000	1.000		

$\lambda_{\max} = 4.053$; Consistency index (CI) = 0.020; Consistency ratio (CR) = 0.016; Random index (RI) = 0.890; and $n = 4$; Dis. Hyd. network is distance from hydrological network.

Table A2
The social-economics (B_2).

Factors/Variables	Dis. Dev. Land	Built- up index	UFTVI			
Dis. Dev. Land	1	1/2	1/3			
Built-up index	2	1	1/2			
UFTVI	3	2	1			
Column Sum	6.000	3.500	1.833			
Normalization	Dis. Dev. Land	Built- up index	UFTVI	Weight/ Row average	Row totals	Row totals/ average
Dis. Dev. Land	0.167	0.143	0.182	0.164	0.492	3.004
NDBI	0.333	0.286	0.273	0.297	0.894	3.008
UFTVI	0.500	0.571	0.545	0.539	1.625	3.015
Column Sum	1.000	1.000	1.000	1.000		

$\lambda_{\max} = 3.009$; Consistency index (CI) = 0.005; Consistency ratio (CR) = 0.009; Random index (RI) = 0.520; and $n = 3$; Dis. Dev. Land is distance from urbanized area; UFTVI is urban field thermal variance index.

with Yuei-An Liou. She conducted data collection, data processing, and result analysis. The manuscript draft was prepared by Anh Kim Nguyen and enriched by Yuei-An Liou and Ming-Hsu Li. Yuei-An Liou finalized the manuscript.

Conflicts of interest

The authors declare no conflicts of interest.

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Table A3The land resources (B_3).

Factors/Variables	NDVI	LULC			
NDVI	1	1/2			
LULC	2	1			
Column Sum	3.000	1.500			
Normalization	NDVI	LULC	Weight/Row average	Row totals	Row totals/average
NDVI	0.333	0.333	0.333	0.667	2.000
LULC	0.667	0.667	0.667	1.333	2.000
Column Sum	1.000	1.000			

 $\lambda_{\max} = 2.000$; Consistency index (CI) = 2.000; Consistency ratio (CR) = 0.000; Random index (RI) = 0.000; and $n = 2$.
Table A4The topography (B_4).

Factors/Variables	Terrain elevation	Slope angle	Slope aspect			
Terrain elevation	1	2	4			
Slope angle	1/2	1	3			
Slope aspect	1/4	1/3	1			
Column Sum	1.500	3.000	8.000			
Normalization	Terrain elevation	Slope angle	Slope aspect	Weight/Row average	Row totals	Row totals/average
Terrain elevation	0.667	0.667	0.500	0.611	1.843	3.015
Slope angle	0.333	0.333	0.375	0.347	1.056	3.040
Slope aspect	0.167	0.111	0.125	0.134	0.403	3.000
Column Sum	1.000	1.000	1.000	1.000		

 $\lambda_{\max} = 3.018$; Consistency index (CI) = 0.009; Consistency ratio (CR) = 0.018; Random index (RI) = 0.520; and $n = 3$.

A2. Variable/factor description

A2.1. Hydro-meteorology

Fig. A1 presents the hydro-meteorology over the Thua Thien-Hue Province in 1989, 2003, and 2014. To evaluate the role of hydro-meteorology

Fig. A1. The map of hydro-meteorological impacts in Thua Thien-Hue Province in 1989, 2003, and 2014.

on the environment, four variables are selected consisting of LST, NDWI, NDMI, and distance from hydrological network retrieved from Landsat data image. Distances are computed by using ArcGIS tools.

These four variables were classified and weighted using AHP as shown in Table A1 and converted into a grid map with $100 \text{ m} \times 100 \text{ m}$ spatial resolution. The Natural Interval Classification method (de Smith et al., 2015) is applied to classify hydro-meteorology map into six levels (*potential, slight, light, medium, heavy, and very heavy*).

A2.2. Land resource

Fig. A2 presents land resource impact on the study region in 1989, 2003, and 2014. This map is generated from two variables consisting of NDVI

Fig. A2. The map of land resource impacts in Thua Thien-Hue Province in 1989, 2003, and 2014.

Fig. A3. The map of social-economic impacts in Thua Thien-Hue Province in 1989, 2003, and 2014.

and LULC. AHP method is applied to assign weights for variables as shown in Table A2.

A2.3. Land resource

Fig. A3 provides socioeconomic impact in 1989, 2003, and 2014. Land resource map is generated from three variables including distance from urbanized area, NDBI, and, UTFVI (Fig. A4).

A2.4. Topography

Terrain elevation, slope angle, and slope aspect are selected to evaluate topographical impact on environment. Variation of elevation is an important influential factor for regulating evapotranspiration, soil erosion, flood, and landslide, and other processes that could impact environmental vulnerability (Nguyen et al., 2016). Three variables are weighted by using AHP method that is described in Table A4.

Fig. A4. The map of topographical impacts in Thua Thien-Hue Province in 1989, 2003, and 2014.

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