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ORIGINAL ARTICLE

Integration of remote sensing, GIS, and Shannon's entropy approach to conduct trend analysis of the dynamics change in urban/built-up areas in the Upper Citarum River Basin, West Java, Indonesia

Fajar Yulianto[1] · Hana Listi Fitriana[1,2] · Kusumaning Ayu Diah Sukowati[1]

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Abstract
Spatial demand will increase when the population growth in an area. For sufficient space will occupy the surrounding land (periphery). This condition is known as urban sprawl. Urban sprawl is a complex phenomenon, as it affects social life and becomes a serious environmental problem. Environmental problems that occur because of the change in the land function of agriculture and forests into residential areas and commercial purposes. This study aims to conduct trend analysis of the spatial and temporal dynamics of urban/built-up areas during the periods 1990–2016. Integration of remote sensing, GIS, and Shannon's entropy statistical approach was used to obtain information regarding dynamics change in the areas. The results of the trend entropy value analysis show that urban/built-up development is tending to spread, with increases in entropy values based on the region's urban/built-up sub-watershed areas during the 1990–2016 periods of 1.464 and 1.597, respectively. Meanwhile, based on the radial distance from Bandung city, these are 1.511 and 1.737, respectively. The results of the relative entropy are equal to 0.151 in 1990, with an increase to 0.156 in 2016, based on the region's urban/built-up area of the sub-watershed. Meanwhile, based on the radial distance from Bandung city, the values were 0.156 in 1990 and 0.170 in 2016. This study can be used as important benchmarks for planners, policymakers, and researchers regarding spatial planning in the study area. The results could also provide important inputs for sustainable land use plans and strategies to reduce disasters and flood hazards, as well as flood disaster vulnerability analysis of residential areas.

Keywords Remote sensing · GIS · Shannon's entropy · Citarum · West Java · Indonesia

Introduction

Increasing population growth has accelerated development in various countries. Acceleration of development is characterized by urban presence. The urban system is rapidly expanding around the world and will continue to rise in the future. It is a complex phenomenon in urban growth management (Cohen 2004). The development of the city that has exceeded the use will grow the surrounding land use (Prasetyo et al. 2016). According to Sun et al. (2007), a lot of urban phenomena occurring nowadays are urban sprawl. It is a complex phenomenon that has social and environmental impacts. Social development of the city and urban sprawl led to social segregation that fosters social homogeneity (Altinok and Cengiz 2008). Meanwhile, the environmental impacts of urban growth are a change in land use (Karakayaci 2016).

Landuse/landcover is information related to socio-economic processes in terms of land development, agricultural, natural resources, and the function of ecosystems that influence global change (Munroeaic et al. 2002). The interaction between nature and humans has changed the condition of the earth's surface as an impact of land use resulting from the people's necessities of life (Betru et al. 2019). Increases in population and urban expansion have resulted in large areas of open space, forests, and agricultural land being converted for land construction due to the increasing demand for transportation facilities, and commercial and residential

✉ Fajar Yulianto
fajar.lapan.rs@gmail.com; fajar.yulianto@lapan.go.id

[1] Remote Sensing Application Center, Indonesian National Institute of Aeronautics and Space (LAPAN), Jl. Kalisari No. 8, Pekayon, Pasar Rebo, Jakarta 13710, Indonesia

[2] Department of Geography, Faculty of Mathematics and Natural Science, University of Indonesia (UI), Jl. Margonda Raya, Pondok Cina, Beji, Depok, West Java 16424, Indonesia

land. In addition, the demand for various types of agricultural products has also led to the conversion of some forest land into agricultural land (Wan et al. 2015; Deng et al. 2019). Urban/built-up expansion areas are part of landuse/land cover, which can have a positive impact in the form of progress in modernisation, industrialisation, and strengthening of economic conditions globally, leading to increased urban populations. However, urban/built-up areas existence can also have a negative impact on environmental conditions (Bhatta 2009; El Garouani et al. 2017), such as ecosystems, hydrological systems, biodiversity, and climate. These negative impacts can result in a reduction of recharge areas that function as infiltration zones in absorbing rainwater, and can also increase runoff in surface and subsurface hydrological systems in river basin environments (Wilson et al. 2003).

Remote sensing and the Geographic Information System (GIS) play important roles in providing spatial analysis and temporal archive data that can be used to monitor environmental conditions, especially developments of urban/built-up areas (e.g., Maktav et al. 2005; Gong et al. 2013; Sun et al. 2013). In addition, remote-sensing data can also cover large areas and are spatially and temporally consistent (Jat et al. 2008; Sun et al. 2013), for urban planning (Noor and Abdullah 2015; Akanbi et al. 2013), urban environmental degradation (Lu et al. 2019), Urban heat island monitoring (Chen et al. 2016), urban air quality (Yuan et al. 2018), and urban green space mapping (Chen et al. 2018). In addition, remote-sensing data can also cover large areas and are spatially and temporally consistent (Jat et al. 2008; Sun et al. 2013). Shannon's entropy statistical method is a robust statistical approach to describing the strength of the development of an urban/built-up area. According to Bhatta et al. (2010), and Nazarnia et al. (2019), Shannon's entropy is the most widely used technique for measuring urban sprawl levels, and has been proven to now be the most rigourous and reliable technique. Using entropy can measure the level of development of an area and its activities. Shannon's entropy is an equation formulated to be able to explain the degree of irregularities in the spatial phenomena. Furthermore, with remote sensing, GIS, and Shannon's entropy statistical methods, data can be integrated to provide information related to the dynamics change of urban/built-up areas (Al Mashagbah 2016; Shenbagaraj et al. 2019).

The study area is located in the Upper Citarum River Basin, West Java, Indonesia (Fig. 1), which has experienced a variety of landuse/landcover dynamic changes. The phenomenon of flooding that occurred in the study area, one of which relates to changes in landuse/landcover.

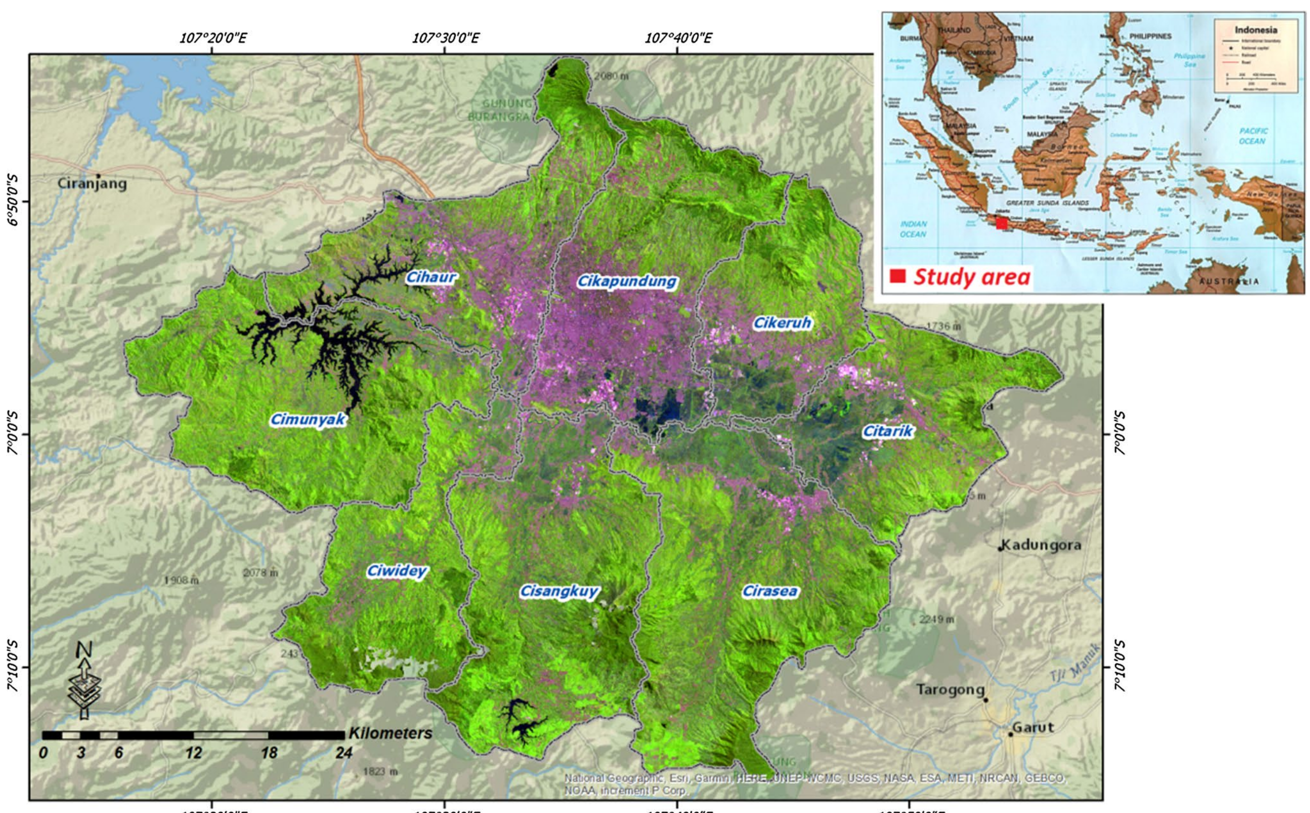

Fig. 1 Study area in the Upper Citarum River Basin, West Java, Indonesia *Source*: Landsat 8, 2016, from the Remote-Sensing Technology and Data Center, LAPAN

The increase in urban/built-up areas can reduce recharge areas, which function as infiltrations in the dynamics of the hydrological cycle. In addition, the need for the increasing number of residents to fulfil their needs, and use of agricultural land have also resulted in the conversion of land from forest to agriculture. Reduced vegetation canopies can accelerate the erosion process, which has an impact on the sedimentation and siltation of rivers in the study area Yulianto et al. (2018, 2019). The Upper Citarum River Basin has eight sub-watersheds, namely, Ciwidey, Cisangkuy, Cirasea, Citarik, Cikeruh, Cikapundung, Cihaur, and Ciminyak. To establish which sub-watersheds play a major role in contributing to flood events, especially those related to the development of urban/built-up area, Shannon's entropy statistical approach was applied.

This study aims to conduct trend analysis of the spatial and temporal dynamics of urban/built-up areas during the periods 1990–2016. Integration of remote sensing, GIS, and Shannon's entropy statistical approach was used to obtain information regarding the dynamics change of urban/built-up areas. To achieve this goal, the integrated approach was applied to eight sub-watersheds and was also based on a radius of 5 km from Bandung city for the case study related to the spatial distribution of urban/built-up areas. Furthermore, this study could be used as important benchmarks for planners, policymakers, and researchers regarding spatial planning in the study area. The results could also provide important inputs for sustainable land use plans and strategies to reduce disasters and flood hazards.

Materials and methods

Urban/built-up area information extraction

Information an urban/built-up areas from the period 1990 to 2016 was obtained based on landuse/land cover class (Fig. 2), as produced by Yulianto et al. (2018). Multi-temporal Landsat data were provided by the Remote-Sensing Technology and Data Center, LAPAN, and were used as an input for landuse/landcover classified as the maximum likelihood approach. Seven classes were produced from the study, namely, primary forests, urban/built-up areas, secondary forests and mixed gardens, plantations, wet agricultural land, dry land farming, and water bodies. Query filters were required in the GIS tools to extract information about urban/built-up area class, in accordance with the needs of the study. Furthermore, the results of the urban/built-up area extraction were used as inputs for Shannon's entropy statistical method, with the application of eight sub-watersheds within a radius of 5 km from Bandung city.

Shannon's entropy statistical method

Shannon's entropy is a statistical measurement method to ascertain the degree of spatial concentration of a geographical variable, and was developed by Yeh and Li (2001). According to Yeh and Li (2001) and Nazarnia, Harding, and Jaeger (2019), the value of entropy is between 0 and $\log(n)$ and can be calculated by Eqs. (1) and (2). The relative entropy that can be used to scale entropy to a value between 0 and 1 is calculated by Eq. (3). If urban/built-up areas have a relative entropy value low or close to (0), this indicates that the degree of urban sprawl is zero, or can be concentrated in one zone. On the other hand, high values (maximum 1) of relative entropy indicate higher levels of urban sprawl:

$$E_n = \sum_i^n P_i \log \frac{1}{P_i} \tag{1}$$

$$P_i = \frac{x_i}{\sum_j^n xj} \tag{2}$$

$$E_n^{'} = \sum_i^n P_i \log \frac{1}{P_i} / \log(n), \tag{3}$$

where E_n is Shannon's entropy value; P_i is the proportion of urban/built-up areas in the i zone $\left(P_i = \frac{x_i}{\sum_j^n xj}\right)$; n is the number of zones; x_i is the observed value of the phenomenon in the i zone; and $E_n^{'}$ is the relative entropy that can be used to scale entropy.

Results

Urban/built-up area information extraction

The results of the multi-temporal query filters for urban/built-up area classes from years 1990, 1996, 2000, 2003, 2009, and 2016 in the eight sub-watershed locations, within a radius of 5 km from Bandung city, are presented in Fig. 3. The total area of the urban/built-up areas, based on the eight sub-watersheds, is shown in Table 1. In addition, the total area of the urban/built-up areas based on the radius of 5 km from Bandung city is presented in Table 2, with detailed calculations, as shown in "Appendix" Tables 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, and 18.

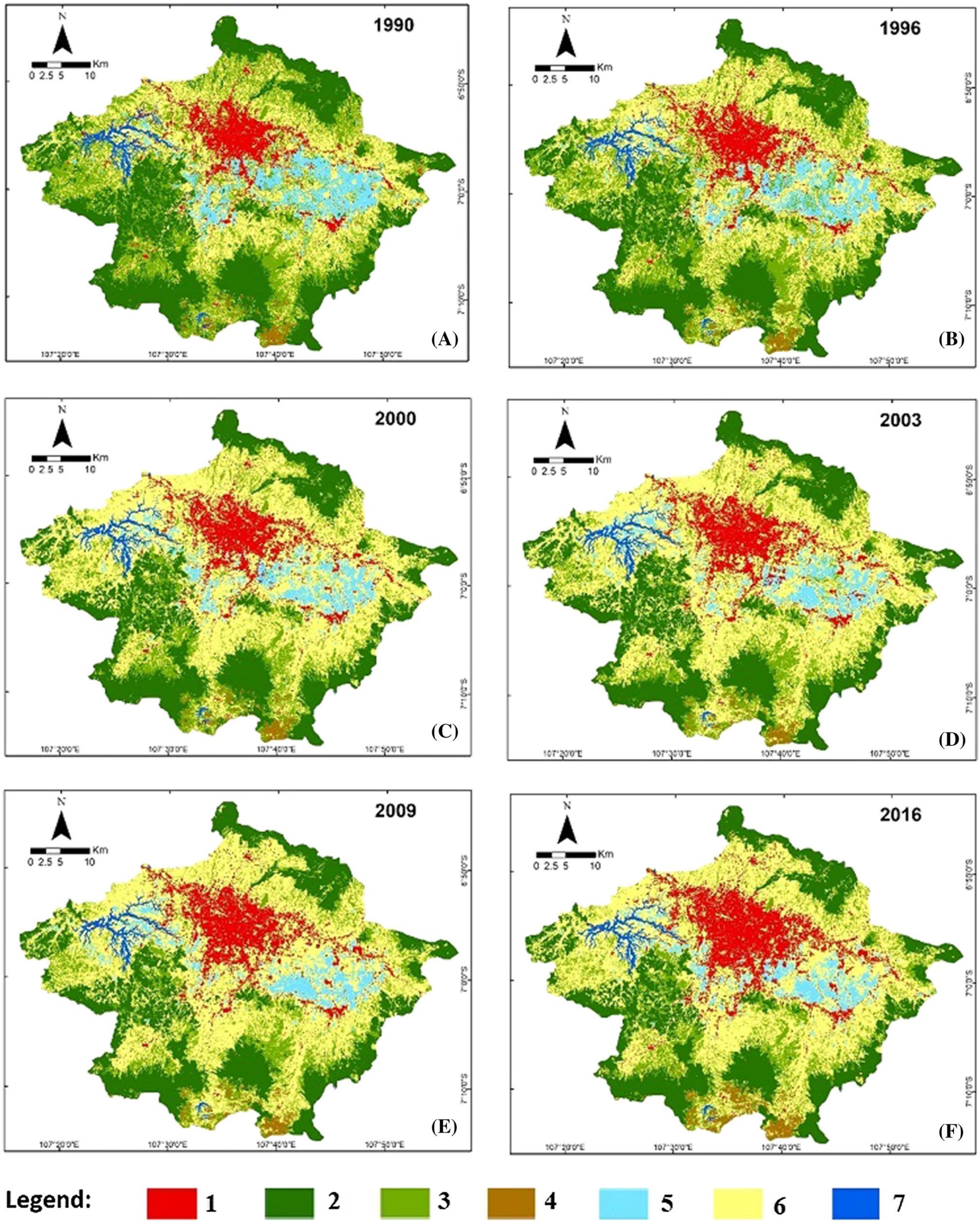

Fig. 2 Landuse/land cover class information from the periods 1990 to 2016, as produced by Yulianto et al. (2018). **a** in 1990, **b** in 1993, **c** in 2000, **d** 2003, **e** 2009, **f** 2016. Legend class ID 1: urban/built-up areas, 2: primary forest, 3: secondary forest and mixed garden, 4: plantation, 5: wet agricultural land, 6: dryland farming, 7: water body

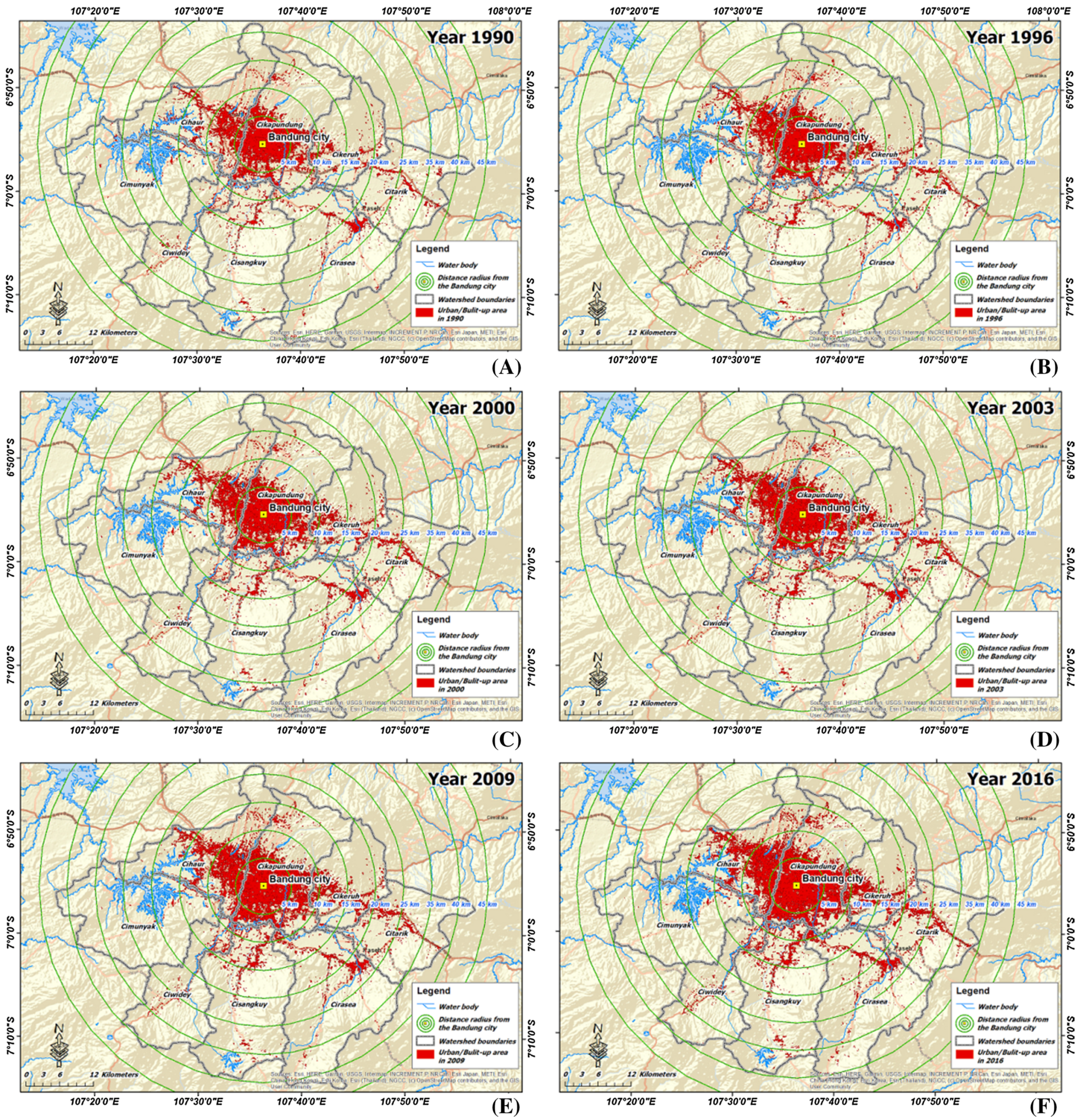

Fig. 3 Urban/built-up area information from years 1990 to 2016 with in a radial distance of 5 km from Bandung city: **a** urban/built-up area in 1990; **b** urban/built-up area in 1996; **c** urban/built-up area in 2000; **d** urban/built-up area in 2003; **e** urban/built-up area in 2009; **f** urban/built-up area in 2016

Shannon's entropy statistical method

The results of Shannon's entropy calculations for the periods 1990–2016, based on the region's urban/built-up area, sub-watersheds, and radial distance from Bandung city, are presented in Table 3. In addition, the results of the relative Shannon's entropy calculations for the same period are shown in Table 4.

Table 1 Urban/built-up area based on the eight sub-watersheds

Sub-watershed	Area (in hectares)					
	1990	1996	2000	2003	2009	2016
Cihaur	3409.7	3936.7	3986.2	4505.2	5367.4	6486.6
Cikapundung	8414.6	8965.7	9222.3	9702.7	10,451.0	12,311.6
Cikeruh	1115.7	1481.2	1635.0	1751.1	1961.8	2793.9
Ciminyak	207.1	210.3	218.8	292.9	422.2	435.3
Cirasea	1019.8	1022.3	1194.9	1257.6	1373.7	1788.1
Cisangkuy	808.3	858.7	944.5	1111.6	1318.9	1692.9
Citarik	720.9	872.8	1073.5	1129.3	1135.6	1454.2
Ciwidey	391.9	392.8	405.1	459.9	586.6	753.9
Total	16,088.0	17,740.5	18,680.3	20,210.3	22,617.2	27,716.5

Table 2 Urban/built-up area based on the radius of 5 km from Bandung city

Distance (in km)	Area (in hectares)					
	1990	1996	2000	2003	2009	2016
< 5 km	5904.1	6037.9	6084.1	6114.1	6419.6	6892.8
5–10 km	5255.6	6056.6	6294.6	7339.2	8346.4	10,577.2
10–15 km	2077.1	2534.2	2782.6	3070.2	3820.8	5133.1
15–20 km	1111.9	1275.0	1426.6	1526.8	1779.6	2351.8
20–25 km	1170.8	1230.3	1424.0	1447.9	1492.1	1761.2
25–30 km	431.6	468.2	489.6	497.3	498.3	714.8
> 30 km	137.0	138.3	178.8	214.8	260.5	285.6
Total	16,088.0	17,740.5	18,680.3	20,210.3	22,617.2	27,716.5

Table 3 Results of Shannon's entropy calculations for periods 1990–2016, based on the region's urban/built-up area, sub-watersheds and radial distance from Bandung city

Urban/built-up area	1990	1996	2000	2003	2009	2016
	E_n	E_n	E_n	E_n	E_n	E_n
Sub-watersheds	1.464	1.482	1.517	1.540	1.565	1.597
Radial Distance	1.511	1.568	1.624	1.647	1.687	1.737

Table 4 Results of relative Shannon's entropy calculations for periods 1990–2016 based on the region's urban/built-up area, sub-watersheds and radial distance from Bandung city

Urban/built-up area	1990	1996	2000	2003	2009	2016
	E_n'	E_n'	E_n'	E_n'	E_n'	E_n'
Sub-watersheds	0.151	0.152	0.154	0.155	0.156	0.156
Radial distance	0.156	0.160	0.165	0.166	0.170	0.179

Discussion

Spatio-temporal analysis of urban/built-up area from 1990 to 2016

The availability of satellite data plays an important role in providing multi-temporal urban/built-up area development information (Bhatta et al. 2010; Nazarnia et al. 2019). Analysis of changes in land use/land cover spatially and temporally is an effective way of assessing the environmental status of an area. This is an important aspect in detecting environmental changes caused by the influence of one class on the landuse/land cover. The dynamics of change in urban/built-up areas is one aspect that can affect environmental quality (El Garouani et al. 2017). In this study, urban/built-up area information extraction was conducted based on multi-temporal query filters for such areas from years 1990, 1996, 2000, 2003, 2009, and 2016, based on the results of research by Yulianto et al. (2018). Table 1 shows the urban/built-up area based on the eight sub-watersheds. It can be seen that the Cikapundung sub-watershed, with an area of 30,571.6 ha, has the highest urban/built-up area distribution. In 1990, the percentage of the urban/built-up area was 27.5%, which continued to rise until 2016 when it comprised 40.3% of the total area of the Cikapundung sub-watershed. Cihaur sub-watershed is the second largest, with an area of 30,571.6 ha, and which had a 12.6% urban/built-up area in 1990, rising to 23.9% of the total area in 2016. The Cikeruh sub-watershed ranks third, with a percentage of 6.2% in 1990 and 15.4% in 2016. The lowest urban/built-up sub-watersheds in the study area were Ciminyak, Ciwidey, Cisangkuy, Cisarea, and Citarik. With regard to the sub-watersheds, they have played an important role in the development of urban/built-up areas; the Cikapundung sub-watershed has made the most influential contribution to the increase in runoff in the study area, which means that the location in 2016 only leaves around 59.7%, which has the potential to become a water catchment area during the rainy season. The results of a study conducted by Sutrisna et al. (2010) show that the level of soil damage in the Cikapundung sub-watershed was quite high, having reached more than 75% of the lost layers and erosion, resulting in a decrease in land productivity. Furthermore, water quality degradation also occurs, according to the results of research by Rahayu et al. (2018). The Cikapundung sub-watershed in the dry season in 2015 was classified as heavily polluted, but in the wet season in 2016 was classified as mildly polluted. Table 2 shows the urban/built-up area based on the radial distance of 5 km from Bandung city. The highest level of development of urban/built-up areas is at a distance of 5–10 km. It can be seen that such development reached 5321.6 Ha, or 204.7 Ha/year, during the periods 1990–2016. The second highest level of development is at 10–15 km, at 3.056 Ha or 117.53 Ha/year, during the periods 1990–2016. The third highest is within a radius of < 5 km, with a development rate of 988.7 Ha, or 38.1 Ha/year.

Shannon's entropy statistical analysis for periods 1990–2016

Shannon's entropy and Shannon's relative entropy were calculated based on the region's urban/built-up area, sub-watersheds, and radial distance from Bandung city, as shown in Tables 3 and 4. The entropy value obtained in 1990 was 1.464, which increased to 1.597 in 2016, based on the urban/built-up area in the sub-watersheds. With regard to the radial distance from Bandung city, the figure was 1.511 in 1990, rising to 1.737 in 2016. The results of the relative entropy were 0.151 in 1990, with an increase to 0.156 in 2016, based on the urban/built-up area of the sub-watershed. In addition, based on the radial distance from Bandung city, the value was 0.156 in 1990 and 0.170 in 2016. Based on the entropy value calculations, the use of radial distance from Bandung city is more sensitive in describing changes in entropy trends and relative entropy. In general, the trend of development and change in entropy and relative entropy from 1990 spread, and tended to continue to increase up to 2016. Urban/built-up areas extend in all directions, with greater development leading to areas with relatively flat topographical access roads.

Limitations and potential applications

There are several limitations in describing the condition of urban/built-up areas in the study area. Descriptions related to such conditions are used to support information on a mapping scale of 1: 25,000–1: 50,000. More detailed mapping scale information at 1: 10,000 is needed in the future, and can be used to obtain more detailed information, using satellite image inputs such as SPOT 6/7, Pleiades and Worldview, amongst others. Several supporting factors, such as population and economic growth, in describing the development of urban/built-up areas have not been included in this study. These could be input for further research in completing information on the development of urban/built-up areas in the study area to support environmentally sustainable development. One potential application is to predict the entropy and relative entropy values for the coming years, it is assumed that changes occur linearly. In addition, the results of this study could also be used for flood disaster vulnerability analysis of residential areas in the study area, both multi-temporally and in the future.

Figure 4 shows the trends of entropy and relative entropy during the periods 1990–2016, which can be obtained by the equation of the relationship between the entropy value and time (in years). The equation for entropy value based on the calculation from the eight sub-watersheds is $y = 0.0054(x) - 9.2179$. On the basis of the calculation of radial distance within a range of 5 km from Bandung city, $y = 0.0087(x) - 15.758$, where y is the entropy value and x is the time in years. Entropy values for 2020–2100 are predicted and are presented in Table 5. The equation for relative entropy based on the calculation from the eight sub-watersheds is $y = 0.0003(x) - 0.3976$. The calculation of radial distance radius within 5 km of Bandung city is $0.0009(x) - 1.5503$, where y is the relative entropy value and x is time in years. The predicted results of relative entropy for 2020–2100 are presented in Table 6.

Conclusion

This study aimed to conduct trend analysis of the spatial and temporal dynamics of urban/built-up areas during the periods 1990–2016. Remote sensing and GIS have been

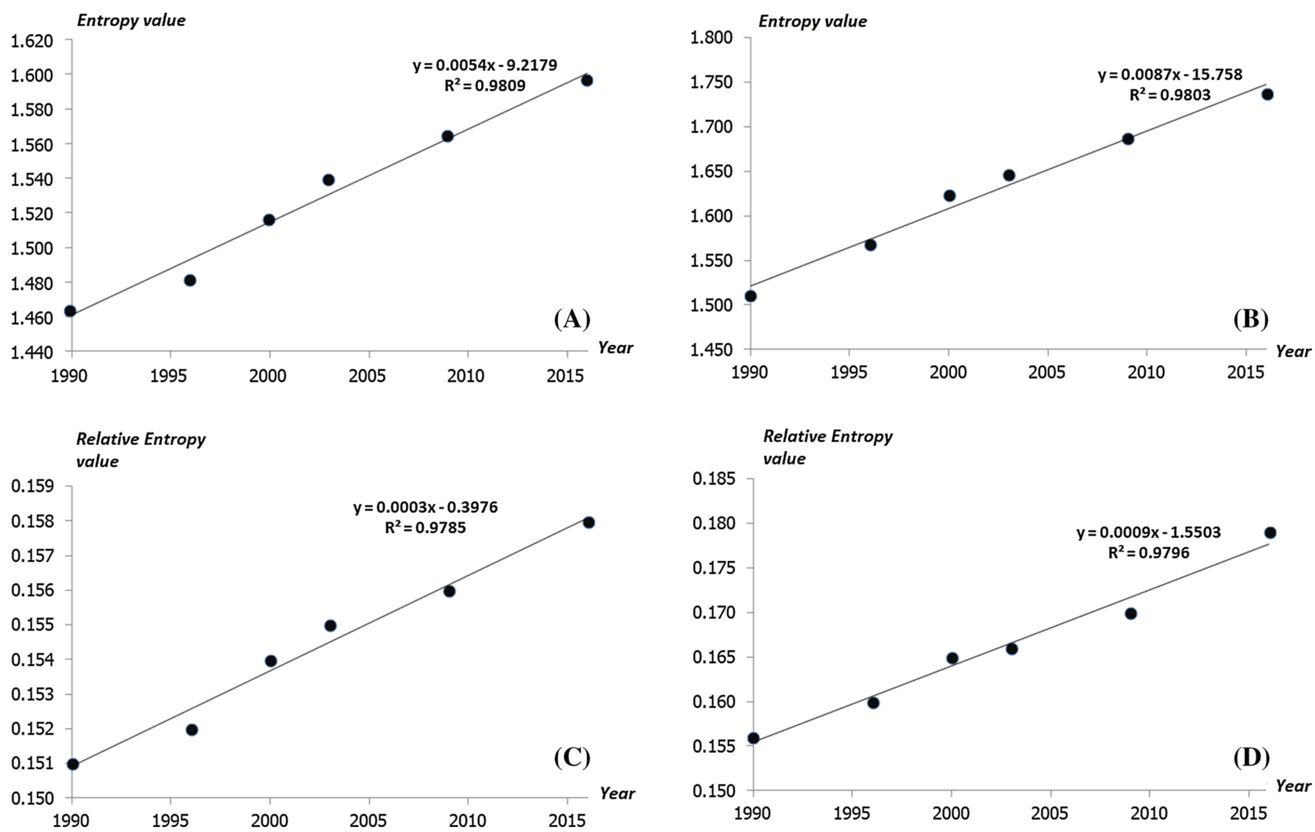

Fig. 4 Trend of entropy and relative entropy values over the periods 1990–2016 in the study area: **a** entropy value and **c** relative entropy value, based on the calculations from the eight sub-watersheds; **b** entropy value and **d** relative entropy values, based on the calculations of radial distance of 5 km from Bandung city

Table 5 Results of the prediction of Shannon's entropy calculation for years 2020–2100, based on the region's urban/built-up area, sub-watersheds, and radial distance from Bandung city

Urban/built-up area	2020	2040	2060	2080	2100
	E_n	E_n	E_n	E_n	E_n
Sub-watersheds	1.690	1.798	1.906	2.014	2.122
Radial distance	1.816	1.990	2.164	2.338	2.512

Table 6 Results of prediction of relative Shannon's entropy calculation for years 2020–2100, based on the region's urban/built-up area, sub-watersheds, and radial distance from Bandung city

Urban/built-up area	2020	2040	2060	2080	2100
	E'_n	E'_n	E'_n	E'_n	E'_n
Sub-watershed	0.208	0.214	0.220	0.226	0.232
Radial distance	0.268	0.286	0.304	0.322	0.339

successfully used to map these areas spatially and temporally. Shannon's entropy approach was also used to analyze development trends and changes in urban/built-up areas, as indicators to recognize and measure their spatial expansion, both at regional and local levels. The results of the trend analysis of the radial distance from Bandung city show an increase in entropy values that are more sensitive than urban/built-up areas that was applied to 8 (eight) sub-watersheds, which change for entropy value is 0.226 and also for relative entropy value is 0.014 from years 1990 to 2016 that has pattern is tending to spread. The Cikapundung sub-watershed has played a large role in the development of urban/built-up areas and made the most influential contribution to the increase in runoff in the study area. In 2016, the location had a 40.3% urban/built-up area, so only leaving 59.7% with the potential to become a water catchment area during the rainy season. This shows that there is a fairly high growth rate and that effective management is needed to achieve sustainable development. In addition, there are other driving factors, such as increasing population, economic growth, and implementation of land use planning, which are not effective and will lead to the possibility of a serious impact on the surrounding environment. This study could be used as important benchmarks for planners, policy makers, and researchers regarding spatial planning in the study area. The results could also provide important inputs for sustainable land use plans and strategies to reduce disasters and flood hazards.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Appendix

See Tables 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, and 18.

Table 7 Results of Shannon’s entropy statistical method calculation (1990) based on the eight sub-watersheds

Sub-Watershed	n	P_i	$\log \frac{1}{P_i}$	$P_i * \log \frac{1}{P_i}$	E_n	E'_n
Cihaur	3409.7	0.212	− 1.551	− 0.329	1.464	0.151
Cikapundung	8414.6	0.523	− 0.648	− 0.339		
Cikeruh	1115.7	0.069	− 2.669	− 0.185		
Ciminyak	207.1	0.013	− 4.353	− 0.056		
Cirasea	1019.8	0.063	− 2.758	− 0.175		
Cisangkuy	808.3	0.050	− 2.991	− 0.150		
Citarik	720.9	0.045	− 3.105	− 0.139		
Ciwidey	391.9	0.024	− 3.715	− 0.090		
Total	16,088.0					

Table 8 Results of Shannon’s entropy statistical method calculation (1996) based on the eight sub-watersheds

Sub-watershed	n	P_i	$\log \frac{1}{P_i}$	$P_i * \log \frac{1}{P_i}$	E_n	E'_n
Cihaur	3936.7	0.222	− 1.506	− 0.334	1.482	0.152
Cikapundung	8965.7	0.505	− 0.682	− 0.345		
Cikeruh	1481.2	0.083	− 2.483	− 0.207		
Ciminyak	210.3	0.012	− 4.435	− 0.053		
Cirasea	1022.3	0.058	− 2.854	− 0.164		
Cisangkuy	858.7	0.048	− 3.028	− 0.147		
Citarik	872.8	0.049	− 3.012	− 0.148		
Ciwidey	392.8	0.022	− 3.810	− 0.084		
Total	17,740.5					

Table 9 Results of Shannon’s entropy statistical method calculation (2000) based on the eight sub-watersheds

Sub-watershed	n	P_i	$\log \frac{1}{P_i}$	$P_i * \log \frac{1}{P_i}$	E_n	E'_n
Cihaur	3986.2	0.213	− 1.545	− 0.330	1.517	0.154
Cikapundung	9222.3	0.494	− 0.706	− 0.348		
Cikeruh	1635.0	0.088	− 2.436	− 0.213		
Ciminyak	218.8	0.012	− 4.447	− 0.052		
Cirasea	1194.9	0.064	− 2.749	− 0.176		
Cisangkuy	944.5	0.051	− 2.985	− 0.151		
Citarik	1073.5	0.057	− 2.857	− 0.164		
Ciwidey	405.1	0.022	− 3.831	− 0.083		
Total	18,680.3					

Table 10 Results of Shannon's entropy statistical method calculation (2003) based on the eight sub-watersheds

Sub-watershed	n	P_i	$\log \frac{1}{P_i}$	$P_i * \log \frac{1}{P_i}$	E_n	E_n'
Cihaur	4505.2	0.223	−1.501	−0.335	1.540	0.155
Cikapundung	9702.7	0.480	−0.734	−0.352		
Cikeruh	1751.1	0.087	−2.446	−0.212		
Ciminyak	292.9	0.014	−4.234	−0.061		
Cirasea	1257.6	0.062	−2.777	−0.173		
Cisangkuy	1111.6	0.055	−2.900	−0.160		
Citarik	1129.3	0.056	−2.885	−0.161		
Ciwidey	459.9	0.023	−3.783	−0.086		
Total	20,210.3					

Table 11 Results of Shannon's entropy statistical method calculation (2009) based on the eight sub-watersheds

Sub-watershed	n	P_i	$\log \frac{1}{P_i}$	$P_i * \log \frac{1}{P_i}$	E_n	E_n'
Cihaur	5367.4	0.237	−1.438	−0.341	1.565	0.156
Cikapundung	10,451.0	0.462	−0.772	−0.357		
Cikeruh	1961.8	0.087	−2.445	−0.212		
Ciminyak	422.2	0.019	−3.981	−0.074		
Cirasea	1373.7	0.061	−2.801	−0.170		
Cisangkuy	1318.9	0.058	−2.842	−0.166		
Citarik	1135.6	0.050	−2.992	−0.150		
Ciwidey	586.6	0.026	−3.652	−0.095		
Total	22,617.2					

Table 12 Results of Shannon's entropy statistical method calculation (2016) based on the eight sub-watersheds

Sub-watershed	n	P_i	$\log \frac{1}{P_i}$	$P_i * \log \frac{1}{P_i}$	E_n	E_n'
Cihaur	6486.6	0.234	−1.452	−0.340	1.597	0.158
Cikapundung	12,311.6	0.444	−0.811	−0.360		
Cikeruh	2793.9	0.101	−2.295	−0.231		
Ciminyak	435.3	0.016	−4.154	−0.065		
Cirasea	1788.1	0.065	−2.741	−0.177		
Cisangkuy	1692.9	0.061	−2.796	−0.171		
Citarik	1454.2	0.052	−2.948	−0.155		
Ciwidey	753.9	0.027	−3.605	−0.098		
Total	27,716.5					

Table 13 Results of Shannon's entropy statistical method calculation (1990) based on the radial distance with a range of 5 km from Bandung city

Radial distance	n	P_i	$\log \frac{1}{P_i}$	$P_i * \log \frac{1}{P_i}$	E_n	E_n'
< 5 km	5904.1	0.367	−1.002	−0.368	1.511	0.156
5–10 km	5255.6	0.327	−1.119	−0.365		
10–15 km	2077.1	0.129	−2.047	−0.264		
15–20 km	1111.9	0.069	−2.672	−0.185		
20–25 km	1170.8	0.073	−2.620	−0.191		
25–30 km	431.6	0.027	−3.618	−0.097		
> 30 km	137.0	0.009	−4.766	−0.041		
Total	16,088.0					

Table 14 Results of Shannon's entropy statistical method calculation (1996) based on the radial distance with a range of 5 km from Bandung city

Radial distance	n	P_i	$\log \frac{1}{P_i}$	$P_i * \log \frac{1}{P_i}$	E_n	E_n'
< 5 km	6037.9	0.375	−0.980	−0.368	1.568	0.160
5–10 km	6056.6	0.376	−0.977	−0.368		
10–15 km	2534.2	0.158	−1.848	−0.291		
15–20 km	1275.0	0.079	−2.535	−0.201		
20–25 km	1230.3	0.076	−2.571	−0.197		
25–30 km	468.2	0.029	−3.537	−0.103		
> 30 km	138.3	0.009	−4.756	−0.041		
Total	17,740.5					

Table 15 Results of Shannon's entropy statistical method calculation (2000) based on the radial distance with a range of 5 km from Bandung city

Radial distance	n	P_i	$\log \frac{1}{P_i}$	$P_i * \log \frac{1}{P_i}$	E_n	E_n'
< 5 km	6084.1	0.378	−0.972	−0.368	1.624	0.165
5–10 km	6294.6	0.391	−0.938	−0.367		
10–15 km	2782.6	0.173	−1.755	−0.303		
15–20 km	1426.6	0.089	−2.423	−0.215		
20–25 km	1424.0	0.089	−2.425	−0.215		
25–30 km	489.6	0.030	−3.492	−0.106		
> 30 km	178.8	0.011	−4.499	−0.050		
Total	18,680.3					

Table 16 Results of Shannon's entropy statistical method calculation (2003) based on the radial distance with a range of 5 km from Bandung city

Radial distance	n	P_i	$\log \frac{1}{P_i}$	$P_i * \log \frac{1}{P_i}$	E_n	E_n'
< 5 km	6114.1	0.380	−0.967	−0.368	1.647	0.166
5–10 km	7339.2	0.456	−0.785	−0.358		
10–15 km	3070.2	0.191	−1.656	−0.316		
15–20 km	1526.8	0.095	−2.355	−0.223		
20–25 km	1447.9	0.090	−2.408	−0.217		
25–30 km	497.3	0.031	−3.477	−0.107		
> 30 km	214.8	0.013	−4.316	−0.058		
Total	20,210.3					

Table 17 Results of Shannon's entropy statistical method calculation (2009) based on the radial distance with a range of 5 km from Bandung city

Radial distance	n	P_i	$\log \frac{1}{P_i}$	$P_i * \log \frac{1}{P_i}$	E_n	E_n'
< 5 km	6419.6	0.399	−0.919	−0.367	1.687	0.170
5–10 km	8346.4	0.519	−0.656	−0.340		
10–15 km	3820.8	0.237	−1.438	−0.341		
15–20 km	1779.6	0.111	−2.202	−0.244		
20–25 km	1492.1	0.093	−2.378	−0.221		
25–30 km	498.3	0.031	−3.475	−0.108		
> 30 km	260.5	0.016	−4.123	−0.067		
Total	22,617.2					

Table 18 Results of Shannon's entropy statistical method calculation (2016) based on the radial distance with a range of 5 km from Bandung city

Radial distance	n	P_i	$\log \frac{1}{P_i}$	$P_i * \log \frac{1}{P_i}$	E_n	E_n'
< 5 km	6892.8	0.428	− 0.848	− 0.363	1.737	0.179
5–10 km	10,577.2	0.657	− 0.419	− 0.276		
10–15 km	5133.1	0.319	− 1.142	− 0.364		
15–20 km	2351.8	0.146	− 1.923	− 0.281		
20–25 km	1761.2	0.109	− 2.212	− 0.242		
25–30 km	714.8	0.044	− 3.114	− 0.138		
> 30 km	285.6	0.018	− 4.031	− 0.072		
Total	27,716.5					

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