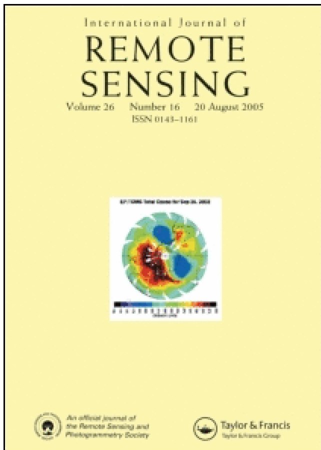

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A pixel-based method to estimate urban compactness and its preliminary application

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A pixel-based method was designed to estimate urban compactness. Remote sensing technology was used to extract urban land use, while urban pixels in the classification image were directly used to estimate urban compactness. The method was based on the assumption that an urban area in circular form was the most compact. Forty virtual circular cities with different radii were fabricated in order to derive a formula to quantify urban compactness and a curve function in the form of $y=6.9351x^{2.0039}$ can thus be derived by using two data: average radius and area. Obviously, this curve can be applied to countless virtual cities in circular form of the same compactness but with different radii. Actually, for each real city in the classification image, specific urban area and average distance can be calculated directly. For every specific data pairs being thus derived, an exclusive curve function in the general form of $y=6.9351x^{D}$ can be found. Our studies show that the value of D in the curve function could be used to quantify urban compactness.

1. Introduction

Urban compactness reflects urban morphology, which is determined by the natural environment, such as the terrain of the city and a series of human factors. In the formation of an urban spatial pattern that affects the life of the city residents in many aspects, city planners and governors play an important role. With the growth of the population in a city, the target of sustainable development that aims to meet the needs of the present without compromising the needs of future generations was suggested a long time ago. As a result, attention should be paid to urban compactness. For example, Gideon and Golany (1996) discussed the relationship between urban design morphology, including compact urban form, and the thermal performance of a city; Breheny *et al*. (1997) analysed the debate in Britain concerning the compact city; Coorey and Lau (2005) summarized urban compactness and its progress towards sustainability in the city of Hong Kong.

Quantifications of urban compactness have long been studied and some methods have already been proposed, such as the methods of circularity ratio and compactness ratio (Gibbs 1961, Richardson 1973). White and Engelen (1993) used the area within a circle and the radius of the circle to compute the convergence of some land types. Bogaert *et al*. (2000) used area-perimeter ratios for measurement of two-dimensional (2D) shape compactness of habitats. From the above methods, it

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can be found that a regular geometric shape such as a circle or a square is always used as the frame of reference in order to compute the specific value that represent the urban form (Sonka *et al.* 1993; Barnsley *et al.* 2003). After the study on the length of the coastline in Britain was initiated by Mandelbrot in 1967, the method of fractal analysis was also used to study the urban spatial distribution (Batty and Longley 1987, 1988, Weng 2003). With the development of landscape ecology, a set of landscape metrics are also proposed for the quantification of landscape pattern such as patch richness, mean patch size, patch shape and so on (Leitão and Ahern 2002, De Clercq *et al.* 2006).

From previous studies, it can be found that most of the metrics are inclined to using object size and perimeter, and few of them are based on pixels. In fact, urban land use extracted from a classification image is generally fragmental and is not in an integral form. Fractal analysis is probably suitable for describing the urban fragmentation appearing in the classification image, but definitely not suitable for deriving urban compactness. Here we attempt to derive a method to estimate urban compactness directly from remote sensing classification images and based on image pixels. It is based on the premise that the circular urban form is the most compact one. In fact, as the city is three-dimensional (3D), it would be more appropriate to take more factors such as the heights of the buildings and population density into account when defining urban compactness. However, these factors are not analysed in this letter because they are hard to acquire and difficult to associate with a classification image. The urban compactness here is mainly characterized at the level of 2D shape.

2. Principles and methodology

2.1 *Principles*

In the remote sensing classification image, the urban area was discretized as numerous non-connected urban pixels. Compactness is associated with the average distance (AD) of all urban pixels to the centre. Nevertheless the AD is not sufficient to quantify compactness because a large city may exhibit a large AD value but is actually compact. Therefore, both urban size and AD must be considered when urban compactness is to be quantified.

Forty virtual cities with different urban sizes and AD but the same compactness were simulated (figure 1). The AD and urban area for each virtual city were computed and form 40 coordinates points illustrated in figure. 2. Regression analysis shows that all the coordinate points for the cities are basically located on one curve expressed by the function of $y = 6.9351x^{2.0039}$, where y is the urban area and x stands for the AD (figure 2). Here the function was different from the formula of circle area

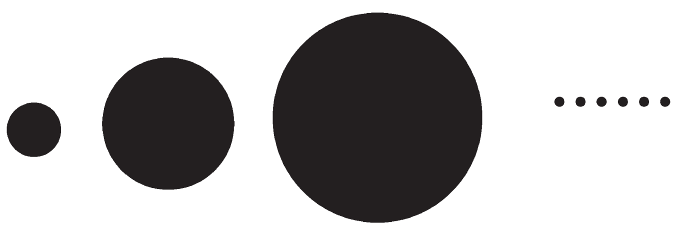

Figure 1. Virtual circular cities with different area and AD values (six small dots are suspension points).

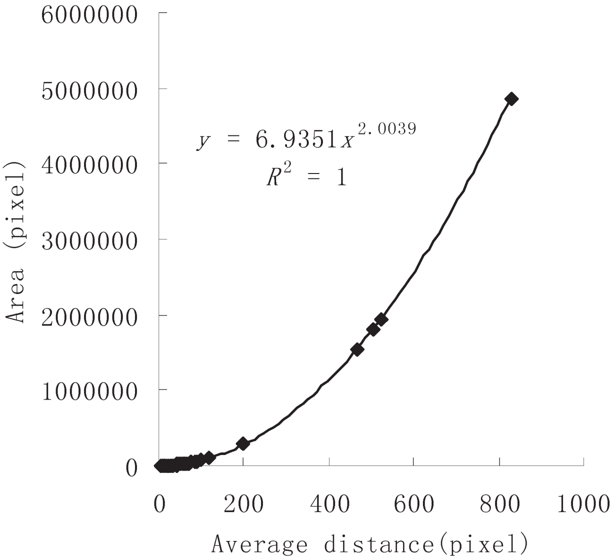

Figure 2. Relationship between AD and urban area.

(area=pi × radius × radius), because the average radius was used here and also the borderline of virtual city is not smooth because of the effects of discretizing over a raster image.

Based on some algebraic knowledge, the curve for the function y=6.9351x^D is determined only by the coefficient of D and demonstrates the following two characteristics in the first quadrant of Descartesian coordinates (figure 3): (1) The value of y increases as x increases on the condition that the value of D is larger than zero; (2) If y_1=6.9351x^{D1}, y_2=6.9351x^{D2} and $D1>D2$, then $y_1>y_2$ on the condition that the value of x is larger than one. If x is considered as the AD and y as the urban area, the point (x, y) must be located in the first quadrant of Descartesian

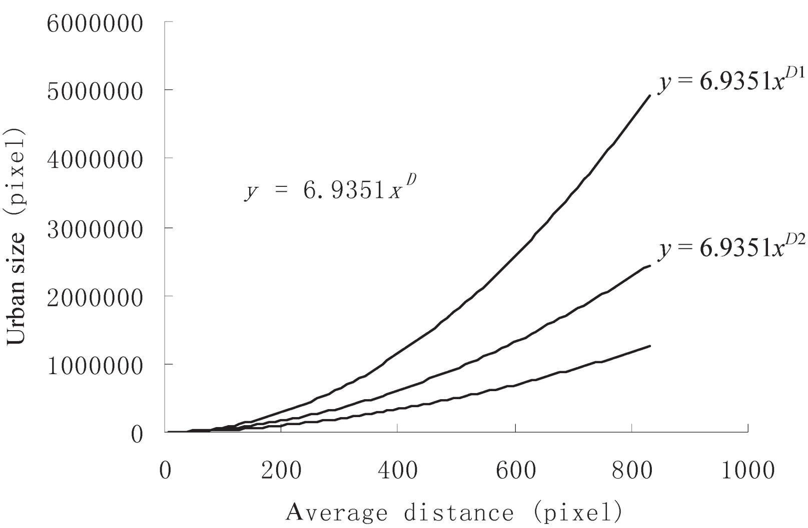

Figure 3. Curves for the function y=6.9351x^D.

coordinates and an exclusive curve with function like $y=6.9351x^D$ will pass through the point. Obviously, this function curve shows the two characteristics as described above. Different AD or area will be located on different curves, hence the curve passing through the point for the city is exclusive, and that is to say, a different city will own a unique value of D. Here, both average distance and urban area are taken into account for the establishment of this exclusive curve. Therefore, it can be used to quantify urban compactness.

2.2 *Method*

In the classification image, each class was endowed with a specific value in byte data type and each pixel was fixed by its row and column coordinates. Based on the coordinates for each urban pixel, the urban geometry centre can be calculated following the equations as listed below

$$CentreX=\frac{1}{n}\sum_{i=1}^{n}(x_i-0) \tag{1}$$

$$CentreY=\frac{1}{n}\sum_{i=1}^{n}(y_i-0) \tag{2}$$

where *CentreX* and *CentreY* stand for the abscissa and ordinate of the urban geometry centre respectively; n is the number of urban pixels; x and y stand for the row and column numbers respectively. Here it should be pointed out that the urban centre could also be named manually using a pair of specific urban pixel row and column. In the above equations, coordinate of (0, 0) is used as the origin of the image. After the urban centre is determined, the AD can be computed according to the following equation:

$$AD=\frac{1}{n}\sum_{i=1}^{n}\sqrt{(x_i-CentreX)^2+(y_i-CentreY)^2} \tag{3}$$

where AD is the average distance; x and y are urban pixel row and column number respectively. After the AD and the urban area are computed, the D value can be computed. By converting the form of function $y=6.9351x^D$ to equations (4) and equation (5), the value of D can be figured out easily using the urban area and AD.

$$\ln(y)=\ln(6.9351)+D^*\ln(x) \tag{4}$$

$$D=(\ln(y)-\ln(6.9351))/\ln(x) \tag{5}$$

Here D is the urban compactness, y is the urban size expressed by number of urban pixels, and x is AD.

3. Application

The method was applied to Dongguan City located in the Pearl River Delta, China. Landsat Thematic Mapper (TM) data for the year 1990, and Landsat Enhanced Thematic Mapper Plus (ETM+) data for the year 2003 were used for classification and extraction of the urban land use. Firstly, the ETM+ data for 2003 were registered to the TM data for 1990 by a map-to-map method with root mean square

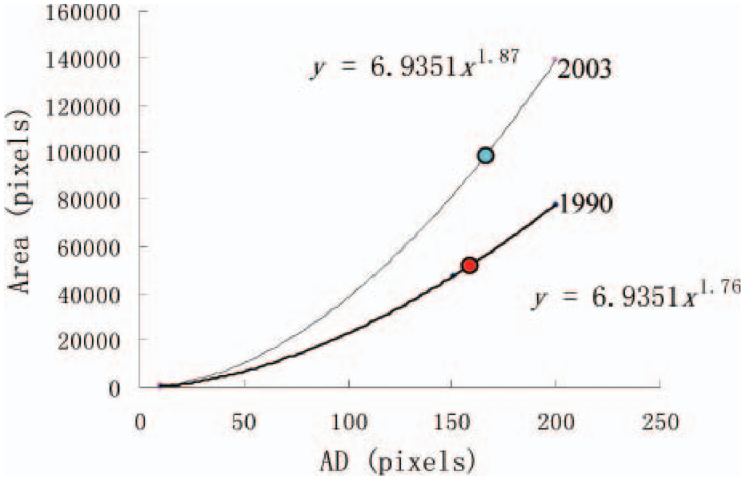

Figure 4. Points of Dongguan in the plot coordinate system and the curves passing through them.

error (RSME) of less than 0.5 pixels. In this study, supervised classification with the maximum likelihood algorithm was performed on the Landsat images by using all bands except Band 6. According to the equations listed above [equation (1), equation (2)], the urban centre was found to be at (283, 321) in 1990 but at (342, 289) in 2003. The average distance was 150.58 pixels for the year 1990 and 167.53 pixels for the year 2003. The urban area was 47 898 pixels for the year 1990 but 101 240 pixels for the year 2003. So the plot coordinates for 1990 and 2003 are (150.58, 47898) and (167.53, 101240) respectively (figure 4).

Two different curves describing the compactness of Dongguang City in the years of 1990 and 2003 were simulated (figure 4). As clearly shown from figure 4, the two curves pass through two points separately. The value of D for 1990 is 1.76 but becomes 1.87 for 2003, which demonstrates that the compactness was greatly increased from 1990 to 2003. The change in compactness can also be found from the classification image. Figure 5 is the urban land use information that was extracted

(*a*) (*b*)

Figure 5. Urban-used land of Dongguan in 1990 and 2003. (*a*) Urban-used land in 1990; (*b*) urban-used land in 2003.

Figure 6. Four typical urban forms with different urban compactness values. (*a*) $D=1.67$; (*b*) $D=1.77$; (*c*) $D=1.88$; (*d*) $D=1.96$.

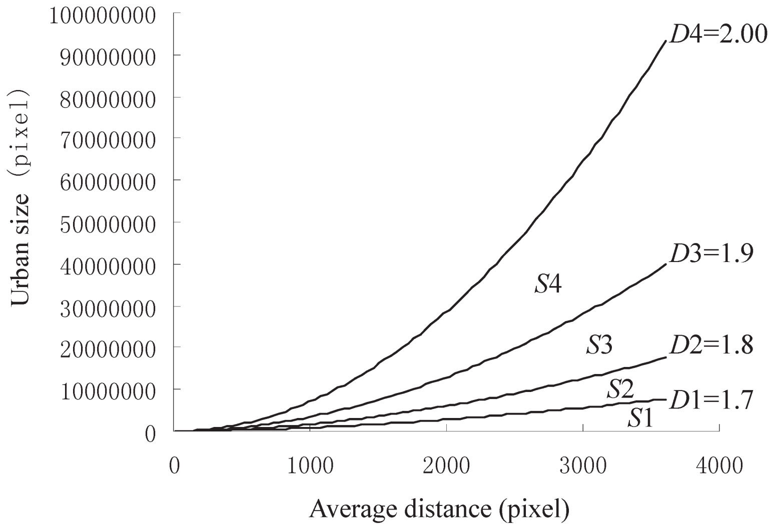

Figure 7. Scales of compactness shown by the curves.

from the classification image. It can be seen clearly that the compactness is much larger in 2003 than in 1990.

4. Conclusion

In the present paper, urban compactness was discussed and a pixel-based method was derived for the purpose of its calculation directly from a classification image. Thirty cities located in the Pearl River Delta region were chosen for compactness computation by using the method detailed above. Figure 6 shows four typical urban forms. According to our study, four scales were computed, which are: (1) dispersed, with D ranging from 1.0~1.7; (2) intermediately dispersed, with D ranging from 1.7~1.8; (3) intermediately compact, with D ranging from 1.8~1.9; and (4) compact with D ranging from 1.9~2.0. Here D values of 1.7, 1.8, 1.9 and 2.0039 can be used as the thresholds to partition the compactness scales into four parts, namely, *S*1, *S*2, *S*3 and *S*4 (figure 7). If the point of one city is located in Part *S*1, it implies that the compactness is smaller than 1.7 and the urban form is quite dispersed.

The compactness of a city may be expressed with different methods, which reflect the different aspects of a city. In the current study, the compactness study was mainly focused on the urban spatial pattern and the layout of the urban land use. Compared with other methods, the peculiarity of this method is based on pixels and calculated directly from a classification image. Since the urban pixels in the classification image are discrete and treated as independent, this method seems appropriate.

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