Environment and Planning B: Planning and Design 2009, volume 36, pages 170 – 185

doi:10.1068/b34034

Mapping urban environmental quality using satellite data and multiple parameters

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Received 26 March 2007; in revised form 21 November 2007; published online 15 December 2008

Abstract. There have been few attempts to map or monitor urban environmental quality (UEQ) at a detailed level, or as a holistic concept comprising multiple parameters. This study examines methods and scales for integrating six parameters of UEQ, which are measured in different units and operate at different scales, into a single index for mapping UEQ differences over an urban area, the Kowloon Peninsula, Hong Kong. The parameters comprise vegetation density, heat island intensity, aerosol optical depth, building density, building height, and noise. Two approaches for spatial data integration—principal component analysis (PCA) and GIS overlay—were examined for integrating the datasets at three different levels of detail, namely electoral-district level, and raster datasets at 4 m and 64 m resolution. At all levels of detail mapped, the GIS overlay method was found to be more representative of UEQ as perceived in the field than when parameters were combined by PCA. High (4 m) spatial resolution was more representative than either 64 m resolution or UEQ mapped within electoral districts. The combined parameters vegetation density, building density, and building height gave a better index of UEQ than all six parameters combined, or any individual parameter or combination, and the best single indicator of UEQ was found to be vegetation density. Since vegetation density, building density, and building height are now relatively easy to obtain at detailed level from GIS databases or high-resolution satellite images, planning and environmental authorities may use the derived UEQ index as an objective measure of environmental quality over a whole city, for comparisons between places and cities and for monitoring changes over time.

1 Introduction

As cities become more densely built up, the environment in which people live and work becomes more stressful due to an intensifying conflict between land prices and environmental values. At any one time, urbanites may subjectively experience several environmental conditions that affect their overall comfort levels synergistically. However, there have been few attempts to measure or map these conditions as an integrated index of urban environmental quality (UEQ), perhaps because of the large degree of subjectivity involved. Traditionally, planning and environmental authorities have addressed the contributing parameters individually using technical assessments. In Hong Kong, for example, evaluations of air quality (Environmental Protection Department, 2002) and of noise, green space provision, and zoning for building density (Planning Department, 2003) are carried out separately.

Hong Kong is perhaps the world's most extreme case of modern high-density living, and controversies that have arisen recently between government and people involve a complex of environmental parameters. These include noise in high-density areas, the blocking of views, sunlight, and fresh and cool air from older residential districts by new high-rise buildings, and very high air-pollution levels exacerbated by high temperatures. Since social cohesion and environmental well-being are key factors in sustainable cities (International Center for Sustainable Cities, 2006), knowledge of problem areas would assist planners and government agencies. Indeed, Whitehead et al (2006) demonstrate that improvements to UEQ may be accompanied by increased economic activity. Until recently, environmental assessment has relied on ground-based instrumentation at fixed points or along traverse routes, both of which are spatially incomplete. This study has arisen from the recent availability of environmental data from very high resolution (VHR) satellites, which enable mapping at the detailed level of city districts, blocks, and individual streets. It evaluates methodologies for integrating different environmental parameters to map UEQ as a single index over the urban area. The mapped index is validated using an observational approach (Bonaiuto, 2004; Tzeng et al, 2002) based on the public's perceptions of UEQ in the field.

2 Background

UEQ can be considered as a complex and abstract condition that varies continuously over the urban landscape. Until recently, satellite sensors were unable to capture data in enough detail to represent the fragmented land cover of urban areas. Indeed, a comparative study of environmental quality in Hong Kong (Fung and Siu, 2001) used medium-resolution SPOT images to estimate green space at the generalized level of tertiary planning units. A similar scale study to assess the quality of life in Athens, Georgia (Lo and Faber, 1997) used the NDVI (normalized difference vegetation index) to estimate greenness as well as temperature from Landsat TM images at 30 m and 60 m resolution, and data were averaged at the census-district level. Surface temperature derived from satellite thermal sensors has been used to characterize urban heat islands (Roth et al, 1989) but thermal-image data are of low resolution [60 m for Landsat ETM and 90 m for ASTER (advanced spaceborne thermal emission and reflection radiometer)]. Therefore the majority of satellite-based studies of the urban heat island have been confined to climatological assessments of broad land-cover types at regional (city) scale (for example, Lo et al, 1997; Weng, 2001). Maps derived from these studies are at electoral-district level or administrative-district level; thus their utility for urban and environmental planning is limited because landscaping and redevelopment in cities take place at the local scale of individual buildings, blocks, or streets. Recently, a new generation of VHR satellite sensors such as IKONOS and Quickbird enabled detailed mapping of vegetation (Nichol and Lee, 2005) and detailed temperature products can be derived by the addition of land-cover information (Nichol, 1994; Nichol and Wong, 2005).

Apart from deficiencies in spatial resolution, the mapping of UEQ has been constrained by the fact that environmental quality (EQ) is a holistic concept, comprising numerous parameters that affect urbanites synergistically but are measured on different scales. Therefore, previous studies have involved the use of factor analysis to identify a relationship between one parameter (Fung and Siu, 2000; 2001) or two parameters (Lo and Faber, 1997) derived from satellite images, such as vegetation or temperature, and socioeconomic data, such as population density and income levels. For example, Fung and Siu's (2000) study of environmental quality in Hong Kong was based on the premise that the NDVI from Landsat data is closely related to other environmental indicators.

The increasing availability of digital map data representing urban infrastructure down to building level, as well as the hybrid raster-vector data handling ability of modern GIS, permit other environmental data to be stored in the same database as image data. Analysis may be done at pixel level, except for discrete data such as building density or socioeconomic data, which are measured within predetermined areal units. Three major constraints to such an integrated analysis include (i) the different units of measurement of the parameters, (ii) their different scales of operation, and (iii) the subjective nature of evaluating UEQ, which precludes absolute accuracy assessment. The objective of the present study is to investigate ways of combining six parameters of UEQ that are measured in different units, into a single integrated UEQ index, and to establish a suitable mapping scale at which these parameters operate and interact.

2.1 Methodologies for data integration

Two general approaches to the integration of different environmental parameters were demonstrated by Lo and Faber (1997) in a quality of life assessment in Athens, Georgia. These are principal component analysis (PCA) and the GIS overlay approach. Lo and Faber aggregated satellite-derived parameters at the census-district level for integration with socioeconomic data. Both methodologies result in relative UEQ indices, which are scene dependent and map UEQ on a graduated scale of lowest to highest for the census districts.

2.1.1 *PCA method*

This is a procedure for compressing multidimensional data into fewer representative dimensions. It is commonly used in remote sensing to reduce the dimensionality of a multispectral dataset by compressing the data from all wavebands into a few components that comprise most of the overall variance in the data. However, standard PCA (which uses the covariance matrix) is unsuitable for data in different measurement units (Mather, 1999) and the PCA method using a correlation matrix (which standardizes the variables) should be used.

In the case of UEQ mapping where the objective is to obtain a single representative index, if a large proportion of the variance among all parameters is found to be representated by one principal component (PC1), this may provide a single integrated UEQ index. This situation is likely, since the parameters are selected initially as indicators of UEQ, and they are expected to be correlated to some degree. However, Lo and Faber (1997) found that only 54% of the total variance was represented by PC1. According to the modifiable areal unit problem (Fotheringham and Wong, 1991), the degree of correlation between parameters is highly scale dependent (see also Openshaw and Taylor, 1979). Thus, one level of aggregation of pixel data may produce higher component loadings than another, according to the differences in synergism between parameters at each spatial scale. It is generally observed that correlations between spatial parameters increase with the size of the mapping unit (Openshaw and Taylor, 1979), but this may depend on the parameters involved as well as the nature of the study area. In the event that no resolution was able to represent a significantly large proportion of the total variability, one possible conclusion would be that PCA was not suitable for UEQ mapping in that study area because the data were uncorrelated and some parameters had low representation.

2.1.2 *GIS overlay method*

Since correlation is not involved, this method does not rely so strictly on the spatial-scale dependence between parameters. Stacked GIS layers are combined by overlay techniques, but require subjective determination of class boundaries. The range of values for each parameter may be ranked on a scale such as 1 – 10, or quantiles, and the resulting UEQ values would correspond to the sum of the data layers. An alternative approach to GIS overlay is the application of multicriteria queries to the data layers, using specific environmental thresholds, if known, or a more generic threshold such as standard deviation. The GIS overlay method can more readily accommodate data originating from different resolutions or units of measurement.

2.2 Selection of the mapping parameters

In previous UEQ mapping projects (Fung and Siu, 2001; Lo and Faber, 1997; Nichol and Wong, 2005), only vegetation and temperature have been used, due to their ready availability from satellite images. There are many affirmations of the value of vegetation in urban areas due to its ability to control and moderate temperature (Akbari et al, 1990; 2003; Gallo et al, 1993; Weng et al, 2004), air quality (Akbari et al, 1990; 2003; Dwyer et al, 1992; Klaus et al, 1999; Wagrowski and Hites, 1997), wind (Huang et al, 1990) and noise (Garcia, 2001), and for its amenity value (Dwyer et al, 1992; Jim, 2002). The undesirable effects of the urban heat island are also well documented (Akbari et al, 1990; Oke, 1988). However, in this study four additional parameters are used. These include air quality and noise due to their evident importance in public-opinion surveys (Tzeng et al, 2002). Additionally, since the presence of tall buildings is associated logically with the blocking of views, air flow, and noise, and buildings are themselves sources of heat, pollution, and noise, the two parameters building density and building height were also included. It is evident from the foregoing that these six mapped parameters should correlate to some degree. Therefore an efficient and effective UEQ index should seek to extract the maximum information while avoiding redundancy.

3 Methods

The study area is the Kowloon Peninsula, the most continuous and densely built urban area in Hong Kong (figure 1). Six environmental parameters, air quality in the form of aerosol optical depth (AOD), heat island intensity (HII), noise (N), vegetation density (VD), building height (BH), and building density (BD) were mapped over this area. VD is a measure of biomass amount rather than the total area covered (Nichol and Lee, 2005), and HII represents the air temperature difference between the urban image-derived values and a rural climatic station at the image time. Table 1 describes the sources of the parameters, their resolution, and accuracy indicators. The parameters AOD and HII represent typical distributions of aerosol and temperature, respectively, over the study area, since the data are derived from a single image time. However, since both parameters are closely related to the urban structure and activities in the urban area, they would be expected to be spatially stable at a particular time of year, which in this case was late summer. All map and questionnaire data except VD were inverted to represent high environmental quality, so that, for example, low noise and AOD levels represent high EQ.

3.1 Weighting of parameters

While parameters can be measured and mapped individually, their importance in UEQ assessment may not be equal. Since importance is subjective and may vary from city to city, and between cultures, an e-mail questionnaire was administered to two hundred Hong Kong residents, asking them to evaluate each parameter on a scale of 0 to 5. The sum of the values obtained for each parameter were then normalized over 100 (table 2) and these importance weightings were applied to the parameters input to the GIS-overlay method of data integration.

3.2 Accuracy assessment

It was hoped that the e-mail questionnaire, in which respondents were also asked to evaluate the EQ of named districts in the study area, could also be used to validate the UEQ mapping. However the results showed that individual respondents did not have a strong mental impression of the geography and environment over the whole study area, since similar grades were given to highly dissimilar districts. This was thought to be due to selecting e-mail recipients by place of work rather than residency in specific areas of the city. Therefore a second field-based questionnaire (appendix) was administered to eight respondents encountered at each of seventy-sixty locations, during the hot summer months of July and August 2006. No preference was shown according to age, sex, or social group and it was assumed all respondents were Hong Kong residents carrying out their daily activities in the area. The locations were selected by

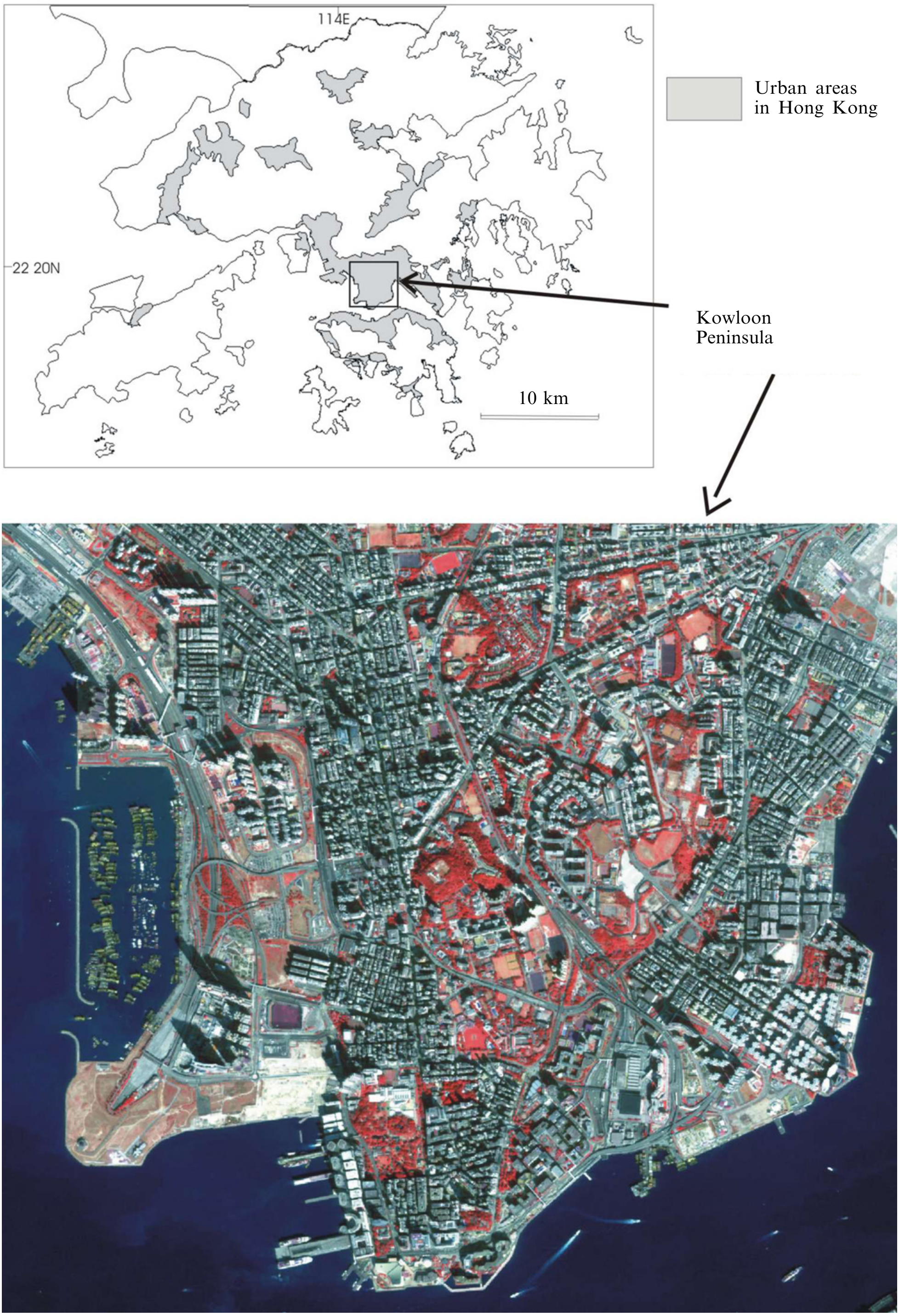

Figure 1. [In colour online, see http://dx.doi.org/10.1068/b34034] Quickbird image showing the densely built nature of the Kowloon Peninsula, and its relationship to other urban areas in Hong Kong.

Table 1. Data sources and estimated accuracy.

Parameter	Source	Source resolution	Method of accuracy testing, and level of accuracy
Aerosol optical depth (AOD).	Landsat ETM+ image of 17 September 2001 using contrast reduction method (Retalis et al, 1999).	150 m.	Correlation of 19 AOD image pixels with PATH air quality model data at 500 m resolution for different air quality parameters. Significant at 5% confidence level for 2.5 parts per million, VOC, O_3, NO, NO_2, NO_x.
Heat island intensity (HII) based on air temperature difference from a reference rural station at image time.	Landsat ETM+ image of 17 September 2001 and Ikonos satellite image of 23 November 2000. Difference between rural and urban stations at image time.	4 m. Emissivity correction of Landsat thermal image by land-cover type from 4 m resolution Ikonos satellite image (Nichol, 1994).	Noise-equivalent temperature difference for Landsat ETM+ is 0.3°C. Conversion from surface to air temperature was done using a regression equation based on 338 paired points of surface and air temperatures with an R value of 0.9 (Nichol, 2005).
Noise (N).	Modelled using predictor software from traffic-flow data and building locations.	10 m.	Noise levels in the study area range from 40–90 dB, and most within 50–80 dB. Noise was measured at 320 random locations, for which 75% were within 5 dB of modeled map.
Vegetation density (VD) as a measure of biomass.	Ikonos satellite image of 23 Novemer 2000 using method of Nichol and Lee (2005).	4 m.	Correlation coefficient of 0.90 between image data and 41 sample field plots.
Building height (BH).	Land Information Centre of Hong Kong digital map data at 1 : 1000 scale.	Rasterized 4 m.	All buildings recorded in digital map database: lowest accuracy level 1.5 m.
Building density (BD) per electoral district.	Land Information Centre of Hong Kong digital map data at 1 : 1000 scale.	By electoral district.	All buildings recorded in digital map database: lowest accuracy level 1.5 m.

stratified random sampling to ensure there were at least two points within each of the thirty-seven electoral subdistricts. At each point respondents were asked to give a percentage mark for each of the six EQ parameters at the place where they were standing and its surroundings up to a 50 m radius. In order to obtain well-considered answers, reference photographs of local places with extremely low and high values for each parameter were shown. A similar method is described by Wong and Domroes (2005). The last question (Q7) asked respondents to give a percentage grade for the overall EQ at the location. This question was used as the reference for validation of the UEQ mapping, and the first six questions were used for insight into how each of the six parameters contribute to the overall UEQ values allocated in Q7. The e-mail questionnaire and the field questionnaire were administered to laypersons, as opposed

Table 2. Importance weightings of UEQ (urban environmental quality) parameters derived from e-mail questionnaires sent to two hundred Hong Kong residents.

Parameter	Importance (weight) normalized over 100
Air quality (aerosol optical depth)	26.1
Heat island intensity	14.0
Noise	18.2
Vegetation density	17.9
Building height	9.3
Building density	14.6

to experts, because the environmental parameters being evaluated were easily understandable to nonexperts, and could be evaluated at any field location. This also justifies the assumption that cities are for the people who inhabit them and that their perceptions will ultimately govern the city's vigour and sustainability.

3.3 Techniques of data integration

The methods and procedures used for data integration and the production of UEQ maps are summarized in figure 2.

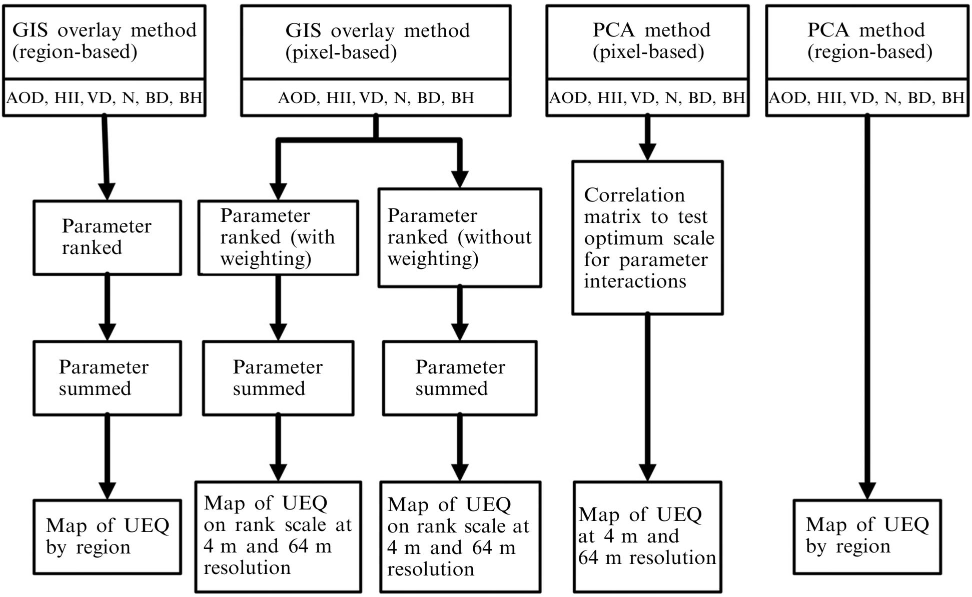

Figure 2. Methods and procedures for data integration and the production of urban environmental quality maps. PCA = principal component analysis; UEQ = urban environmental quality; for other abbreviations see parameters in table 1.

3.3.1 *Pixel-based PCA*

PCA was performed based on the correlation matrix, which converts the variables measured on different scales to standard scores. In order to discover the optimum scale at which a single index, PC1, could most represent the combined parameters, resampling in increments of 4 m, from 4 m to 80 m was performed. However, since it was found that no resolution contained more than 66% of the variance, and in order to utilize the highest resolution of 4 m while maximizing the data variability, the first three PCs were combined into a single index, PCs 1 – 3. This was done by normalization, followed by weighting by their respective eigenvalues. The final maps were produced at two resolutions, the highest resolution of 4 m, and that at which the highest variance was obtained by PC1 (64 m).

3.3.2 *Region-based PCA*
The data for all parameters were averaged for the thirty-seven electoral subdistricts prior to PCA and, as for pixel-based PCA, maps were produced from PC1 and PCs 1 – 3.

3.3.3 *Region-based GIS overlay of ranked parameters*
As with region-based PCA, the data were averaged by electoral subdistrict, but then ranked by separation into ten equal classes, with the higher values representing the most desirable environmental quality. The UEQ value for each subdistrict was obtained by summing the ranked scores for each variable, giving possible values from 6 to 60.

3.3.4 *Pixel-based overlay of ranked parameters*
The pixel data at resolutions of 4 m and 64 m were ranked as for region-based GIS overlay (above), and the ranked scores summed. The 4 m and 64 m resolutions were selected in order to retain the maximum detail (4 m) as well as to represent the scale at which the parameters operate and interact (64 m), which was derived from the PCA analysis described above.

4 Results
4.1 Questionnaire
Analysis of the e-mail questionnaire data (table 2) indicated support for the findings of Tzeng et al (2002) in which Taipei residents rated air quality and noise as the two most important considerations, with air quality significantly more important than noise. For the field questionnaire (appendix), if the six parameters used in this study were the only considerations of people's perceptions of UEQ and they were equally important, then the response for Q7 should be highly correlated with the sum of the other six questions. In fact the R value of 0.76 is lower than expected, but higher when importance weightings from the e-mail questionnaire (table 2) are applied. This suggests that people do not actually perceive all parameters to be of equal importance, and weighting of the parameters would be required for mapping UEQ. Furthermore, since the overall UEQ values (Q7) appear more related to VD than to any other parameter (table 3, column 5), people may first of all associate high UEQ with a large amount of greenery.

4.2 Methods for data integration
4.2.1 *Pixel-based PCA*
Figure 3 shows that the resolution at which PC1 holds the largest percentage of the variance occurs at 64 m, with 66% of the variance, while at 4 m resolution, PC1 contains only 27% of the variance. However, PCs 1 – 3 together contained 61% and 91% of the total variability for 4 m and 64 m resolution, respectively. In view of the low variance on PC1, as well as the dominance of PC1 by VD and HII, with N and AOD almost absent (for both 4 m and 64 m resolutions) the eigenvalue-weighted sum of PCs 1 – 3 was used. By comparison with Q7, only the 4 m resolution map based on PCs 1 – 3 was significant at the 1% level ($R = 0.46$) (table 4).

4.2.2 *Region-based PCA*
Although high correlation (and thus high factor loadings) are usually obtained between parameters for large mapping units, this was not observed for the large regions (electoral districts) in this study, and is thought to be due to the irrelevance of the administrative boundaries to environmental factors. In fact only 41% of the variability

Table 3. Field questionnaire on environmental quality at seventy-six locations in Hong Kong: overall mean value, and mean SD (standard deviation) among respondents at each place, for each parameter, and correlation of UEQ (urban environmental quality) parameters, with overall judgment of UEQ (Q7).

Question[a]	Parameter	Mean value (%) (n = 608)	Mean SD of 8 responses at each site	Correlation with Q7 (R) (n = 608)
Q1	Air quality (aerosol optical depth)	63.3	16.1	0.68
Q2	Heat island intensity	73.3	15.5	0.38
Q3	Noise	62.7	18.0	0.67
Q4	Vegetation density	63.2	16.1	0.76
Q5	Building height	52.8	18.2	0.32
Q6	Building density	56.6	16.8	0.60
	All 6 parameters			0.76
	All 6 parameters weighted		0.81	
Q7	Overall UEQ	55.6	14.1	

[a] See appendix.

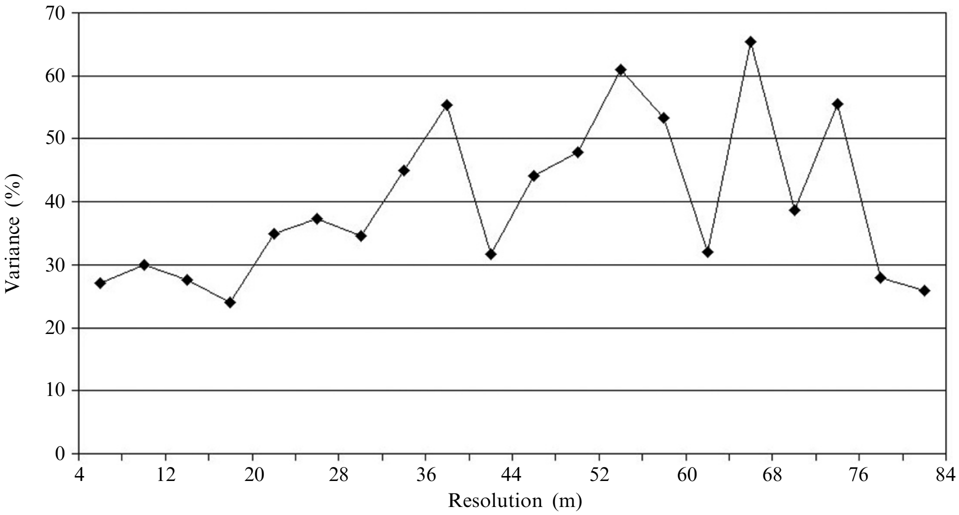

Figure 3. Percentage loading of parameters on principal component 1 (PC1) at different resolutions.

was represented on PC1. Like the pixel-based PCA, PC1 was represented mainly by VD and HII, with N and AOD almost absent. However, a map produced from PCs 1–3 (which account for 85% of the overall variance in the data) had a higher correlation (R = 0.59) with the field data, than that produced from PC1 alone (R = 0.49) (table 4).

4.2.3 *Region-based overlay of ranked parameters*

The map produced from region-based overlay has a range of UEQ values from 18 to 47, and is shown as figure 4. When compared with Q7, an R value of 0.53 was obtained. However, a lower R value of 0.51 was obtained when the parameters were weighted using importance values (table 2).

Table 4. Comparison of urban environmental quality mapping methods with respondent evaluations (Q7).

Mapping method	R (n = 76)
Region PCA (PC1)	0.49
Region PCA (PCs 1–3)	5.90
Pixel PCA 4 m (PC1)	0.01*
Pixel PCA 4 m (PCs 1–3)	0.46
Pixel PCA 64 m (PC1)	0.07*
Pixel PCA 64 m (PCs 1–3)	0.24*
Region overlay	0.53
Region overlay with weighting	0.51
Pixel overlay 4 m	0.62
Pixel overlay 64 m	0.55
Pixel overlay with weighting 4 m	0.61
Pixel overlay with weighting 64 m	0.54

* Not significant at 1% level.
PCA = principal component analysis; PC = principal component.

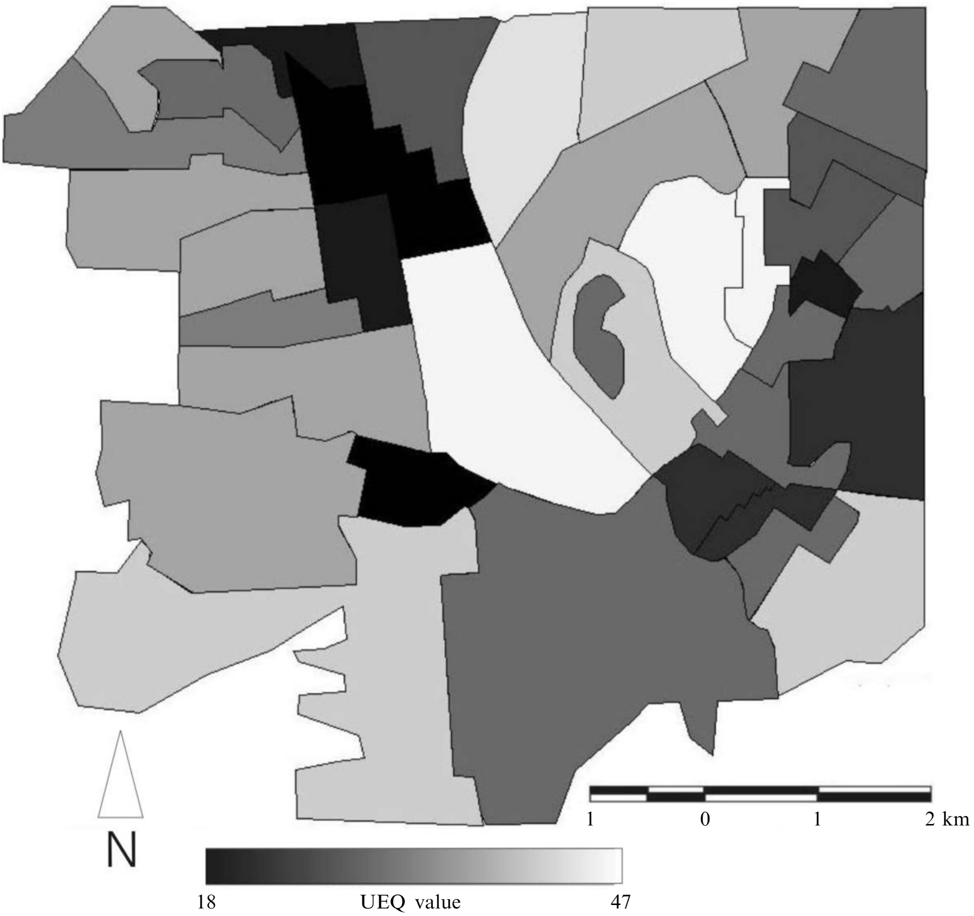

Figure 4. Map of UEQ (urban environmental quality) within electoral districts of Kowloon Peninsula, Hong Kong, from region-based overlay of the parameters vegetation density, building density, and building height.

4.2.4 *Pixel-based overlay of ranked parameters*
The summation of all six ranked parameters at the base mapping resolution of 4 m gave a range of UEQ values from 14 to 53 (figure 5), and at 64 m resolution a smaller range of 18 to 51 was obtained (figure 6), due to the spatial averaging process. When compared with Q7, R values of 0.55 for 4 m and 0.50 for 64 m resolutions were obtained (table 5). After weighting, the corresponding R values were somewhat lower, at 0.46 and 0.40 for the 4 m and 64 m resolutions, respectively. However, all these are significant at the 1% level.

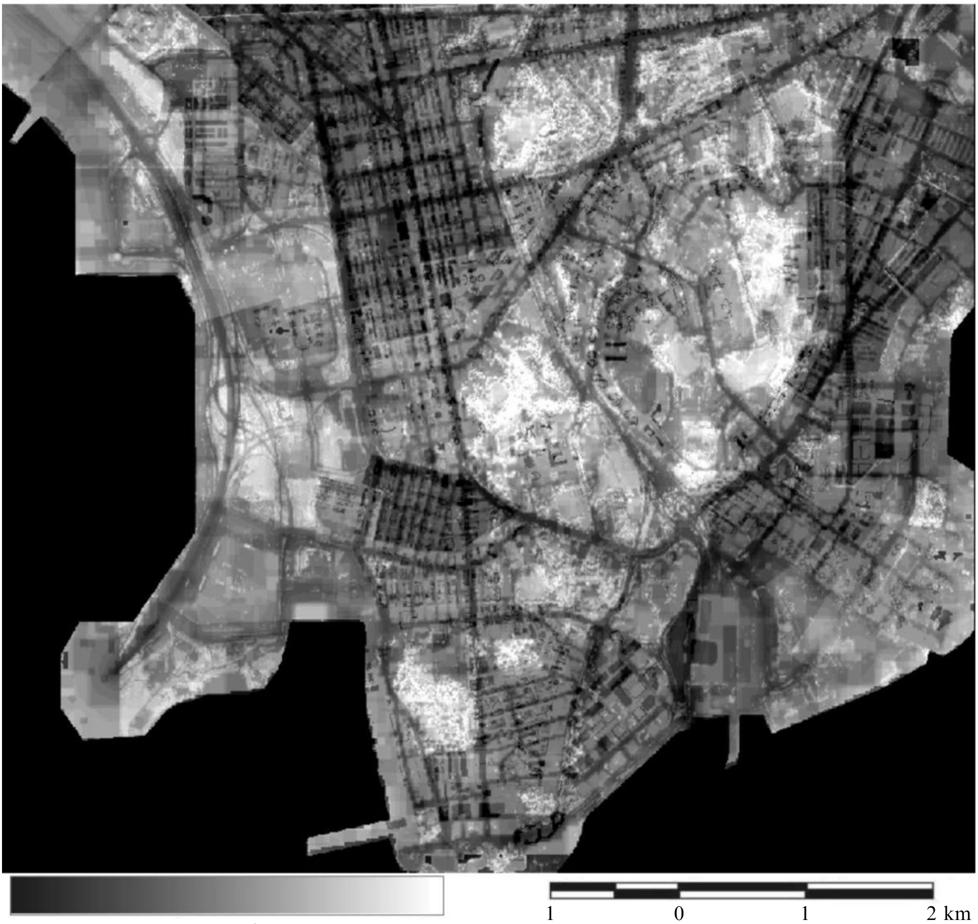

Figure 5. Map of UEQ (urban environmental quality) of Kowloon Peninsula, Hong Kong, from pixel-based overlay of the parameters vegetation density, building density, and building height, at 4 m resolution.

Table 5 also shows the correlation values obtained from individual parameters, and from combinations of five, four, or three parameters. Except for the individual parameters, only R values above 0.50 are shown. Of the individual parameters, VD obtained the highest correlation ($R = 0.53$) at 4 m, and BD at 64 m, respectively. For the combined parameters the highest correlations were obtained using only the three parameters VD, BH, and BD for both 4 m and 64 m resolutions, and the overall highest correlation (0.62) was for 4 m resolution with no weighting applied.

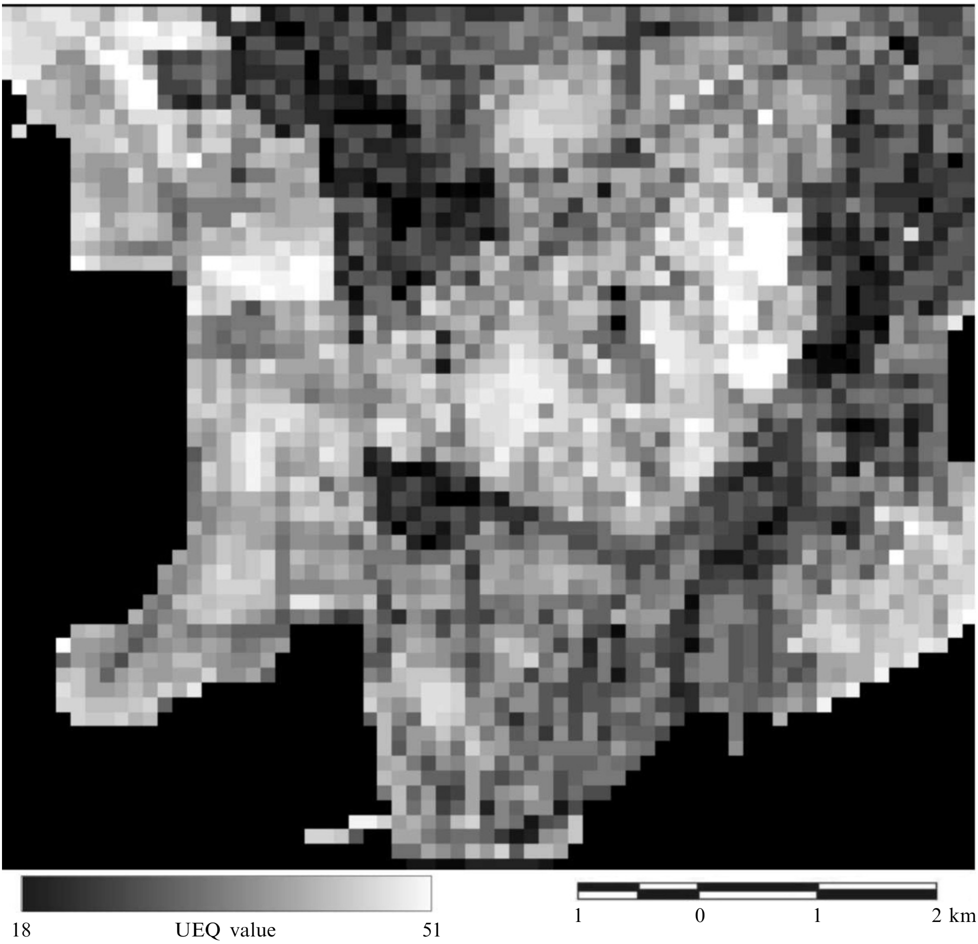

Figure 6. Map of UEQ (urban environmental quality) of Kowloon Peninsula, Hong Kong, from pixel-based overlay of the parameters vegetation density, building density, and building height, at 64 m resolution.

5 Discussion

The objective of using PCA in this study was firstly to examine whether the multivariate data could be compressed into one representative dimension as a single index, and secondly to test if the resulting single index could represent people's perceptions of UEQ. Even if sufficient compression could be achieved, if the corresponding scale does not accord with the scale of people's perceptions of UEQ, the method will be unsuitable. Furthermore, since importance weightings cannot be incorporated, the PCA depends on assumptions made in section 2.2 that the six parameters used in this study are valid indicators or UEQ and of equal weight. Since correlation between parameters at high resolution (4 m) was minimal, a significant degree of data compression could not be achieved. On the other hand, at 64 m resolution, although the data were successfully represented by PC1 and PCs 1 – 3, the scale did not accord with people's perceptions of UEQ. Thus, overall, the pixel-based PCA bore no, or only moderate, relationship to UEQ as perceived by field respondents. Although region-based PCA was more able to represent the data due to higher correlation between parameters at the coarse level of aggregation, and was also significantly related to field observations,

Table 5. Pixel overlay at 4 m and 64 m: correlation of single and combined parameters with respondents' evaluations (Q7) at 76 points in Kowloon Peninsula, Hong Kong. Except for single parameters, only R values of 0.50 and over are given.

Parameter	4 m resolution		64 m resolution	
	not weighted	weighted	not weighted	weighted
Sum of 6 parameters	0.55	0.50	0.46	0.40
Air quality (aerosol optical depth)	**0.21**		**0.18**	
Heat island intensity	0.38		0.34	
Noise	**0.07**		**0.05**	
Vegetation density	0.53		0.40	
Building height	0.51		0.27	
Building density	0.48		0.46	
Omit vegetation density	0.55	0.56		
Omit heat island intensity	0.55	0.52		
Omit noise	**0.57**		0.50	
Omit aerosol optical depth	**0.58**			
Omit building height, noise	0.54			
Omit building height, aerosol optical depth	0.54			
Omit vegetation density, noise	0.55		0.50	
Omit vegetation density, aerosol optical depth	0.56	0.53		
Omit vegetation density, heat island intensity		0.60		0.53
Omit vegetation density, building height		0.56		
Omit vegetation density, building density		0.52		
Omit heat island intensity, building height	0.50	0.51		
Omit heat island intensity, noise	0.57		0.50	
Omit heat island intensity, aerosol optical depth	0.58	0.50		
Omit noise, aerosol optical depth	**0.61**		**0.54**	
Only vegetation density, building density, building height	0.62	0.61	0.55	0.54

Note: figures in bold type indicate low correlation for air quality (aerosol optical depth) and noise individually, or high correlation when these parameters are omitted.

the practical applications derived from mapping UEQ at this general level may be limited.

The GIS overlay method was better able to represent UEQ, than PCA. However, the incorporation of importance weightings resulted in lower correlations between most of the output maps and field questionnaire data (table 5). This may be surprising since the weightings derived from the e-mail questionnaire, which gave greatest importance to the two parameters AOD and N (table 3), are in agreement with previous studies (Tzeng et al, 2002). Their apparent lesser importance in this study has two possible explanations. Firstly, the field survey was conducted in the hottest summer months, so feelings of thermal discomfort may have been more influential than for the e-mail questionnaire which gave AOD and N the highest weightings. Secondly, not only is the highest weighted parameter AOD the most difficult to map at the high resolution of 150 m, but if significant background AOD from long-distance sources were present at the image time, local variations due to local factors such as traffic volume and air-flow corridors, may be submerged in the overall AOD signal.

The contrast-reduction method was successfully used for AOD mapping in Athens, Greece (Retalis et al, 1999) where pollution sources are more local. Although the AOD image was verified against nineteen point locations over the whole of Hong Kong using (SARMAP air quality) model data (table 1), the urban area may be less accurate. In the case of noise, since Hong Kong is a noisy city (Morris, 1997) people are accustomed to noise on streets and in public places where the survey was carried out, and its undesirability may be associated more with the home environment. The bold text in table 5 indicates that individual maps of the highest weighted parameters AOD and N are unrelated to UEQ as perceived by field respondents, and if they are omitted from the GIS overlay maps, higher correlations are obtained.

Overall, the best UEQ index was provided by GIS overlay of the three combined parameters VD, BD, and BH at 4 m resolution. VD was the best single index of UEQ and almost as effective as all the parameters summed. This appears to support the observations of Bonaiuto et al (1999) that green space was better able to explain people's satisfaction with their place of residence than any one of ten other concepts of their residential neighbourhood, and Emmanuel (1997) observed that vegetational change was closely linked to social change in Detroit.

6 Conclusion

The questionnaire results suggest that the UEQ parameters used in this study are relevant, but that some form of value judgments, or intuitive weightings, are applied when people consider the overall UEQ of a location. These judgments may differ for different seasons of the year if the survey is conducted in the field. It is evident from the questionnaire data that people perceive UEQ locally, since all 4 m maps were better correlated with field data than the 64 m or region-based maps. However, at all levels of detail mapping, the PCA approach was found to be less useful than GIS overlay because even though a large proportion of the overall variance in the data could be represented at 64 m by PC1 or PCs 1 – 3, the resulting UEQ index was not representative of the reference UEQ, that is, the field evaluations. Conversely, at 4 m resolution, which would be expected to be more representative of people's local perceptions, the PCs were unable to represent the data variability, due to low interparameter correlations (therefore low factor loadings) at high resolution.

A further disadvantage of the PCA approach is that it depends strongly on the initial assumption of the equal importance of the six selected parameters, whereas with the GIS overlay approach weightings can be applied easily. Although the weightings did not prove effective in this study, the GIS overlay approach was found to better represent UEQ. The method is simpler and potentially more interactive, since weightings based on human perceptions can be applied, and these would allow for seasonal variations in UEQ and people's perceptions of it.

The inclusion in this study of the parameter AOD, representing air quality, was due to its perceived overriding importance in the environmental quality of modern cities. It is thought that the apparently lower relevance of AOD compared with the other parameters mapped in this study is due to some inaccuracy in the mapping of AOD over the urban area. In this case, pending further development in the technology for air-quality mapping over urban areas, GIS overlay of the three parameters VD, BD and BH has been found to give a good representation of UEQ. This provides an easily computed, absolute index of UEQ from readily available data, and will enable planning and environmental authorities to compare objectively different city districts and to monitor changes over time, as well as to make absolute comparisons with other cities. In the case of GIS building data being unavailable, VD at high resolution derived from satellite images is the best single indicator of UEQ.

Acknowledgements. Grant no. G-U171 from the Hong Kong Polytechnic University supported this research.

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Appendix

Field questionnaire administered at 76 points (608 respondents), accompanied by field photos exemplifying high-quality and low-quality environments for each parameter.

Q1. Some places in Hong Kong suffer from very serious air-pollution problems but others do not. How polluted is this place (0 – 100)?
Q2. Some places in Hong Kong are very hot and uncomfortable but others are not. How hot and uncomfortable is this place (0 – 100)?
Q3. Some places in Hong Kong are very noisy and disturbing but others are not. How noisy is this place (0 – 100)?
Q4. Some places in Hong Kong are fresh and green with lots of vegetation but others are not. How would you rank this place (0 – 100)?
Q5. Some places in Hong Kong are full of high-rise buildings but others are not. How would you rank this place (0 – 100)?
Q6. Some places in Hong Kong are densely built-up and congested but others are not. How would you rank this place (0 – 100)?
Q7. How do you rank the overall environmental quality in this place (0 – 100)?