

Hyperspectral Remote Sensing of Urban Areas: An Overview of Techniques and Applications

¹Helmi Z.M. Shafri, ²Ebrahim Taherzadeh, ²Shattri Mansor and ²Ravshan Ashurov

¹Geomatic Engineering Unit, Department of Civil Engineering, Faculty of Engineering,

²Spatial and Numerical Modeling Lab, Institute of Advanced Technology (ITMA),

Universiti Putra Malaysia (UPM), 43400 Serdang, Selangor, Malaysia

Abstract: Over the past two decades, hyperspectral remote sensing from airborne and satellite systems has been used as a data source for numerous applications. Hyperspectral imaging is quickly moving into the mainstream of remote sensing and is being applied to remote sensing research studies. Hyperspectral remote sensing has great potential for analysing complex urban scenes. However, operational applications within urban environments are still limited, despite several studies that have explored the capabilities of hyperspectral data to map urban areas. In this paper, we review the methods for urban classification using hyperspectral remote sensing data and their applications. The general trends indicate that combined spatial-spectral and sensor fusion approaches are the most optimal for hyperspectral urban analysis. It is also clear that urban hyperspectral mapping is currently limited to airborne data, despite the availability of spaceborne hyperspectral systems. Possible future research directions are also discussed.

Key words: Airborne, classification, hyperspectral, spatial, spectral, urban

INTRODUCTION

Population growth and urban expansion have advanced at an unprecedented pace over the past several decades. Although cities occupy only a small portion of the Earth's total land surface, almost half of the world's population lives in urban areas (United Nations, 2001). Urban growth has had increasingly significant socioeconomic and environmental impacts at local, regional and global scales (Berry, 1990). Cities are centres of human activity, and because of the boom of cities, urban mapping is becoming more significant. The purpose of urban mapping is to describe accurately the figure, structure, geography and relationships of the features in the city. Urban areas are characterised by a large variety of artificial and natural surface materials, influencing ecological (Arnold and Gibbons, 1996), climatic and energy (Oke, 1987) conditions. Changes in vegetation cover, air and surface temperature and air and water quality induced by urban expansion influence the microclimate of the human habitat, as well as climate dynamics and environmental changes at the local and regional scales.

Due to the rapid expansion and development of urban centres and cities, new methods are needed for the frequent updating of existing databases instead of standard methods, which are mostly based on field

investigations and the visual interpretation of aerial photographs. The traditional methods are time-consuming and expensive, and mapping activities often cannot keep up with the pace of urban development. Developments in remote sensing technology during the last several years provide an innovative set of airborne and spaceborne systems with improved spectral and spatial mapping capabilities. The types of remote sensing data required will depend on the thematic focus and the spatial scale of the analysis. For instance, regional scale analysis might require medium resolution multispectral data that can cover a vast area in one image. However, these datasets are insufficient to provide a detailed analysis of the scale of a single building or blocks of buildings, which pose a higher spectral heterogeneity and morphological complexity. To tackle this issue, the use of airborne hyperspectral remote sensing could serve as a source of high spectral and spatial resolution data.

A hyperspectral imaging sensor combines imaging and spectroscopy in a single system that often includes large datasets and requires new processing methods. Hyperspectral datasets are generally composed of approximately 100 to 200 or more spectral bands with relatively narrow bandwidths (5-10 nm), whereas multispectral datasets are usually composed of approximately 5 to 10, relatively wider bands (70-400 nm). Hyperspectral remote sensing has excellent potential

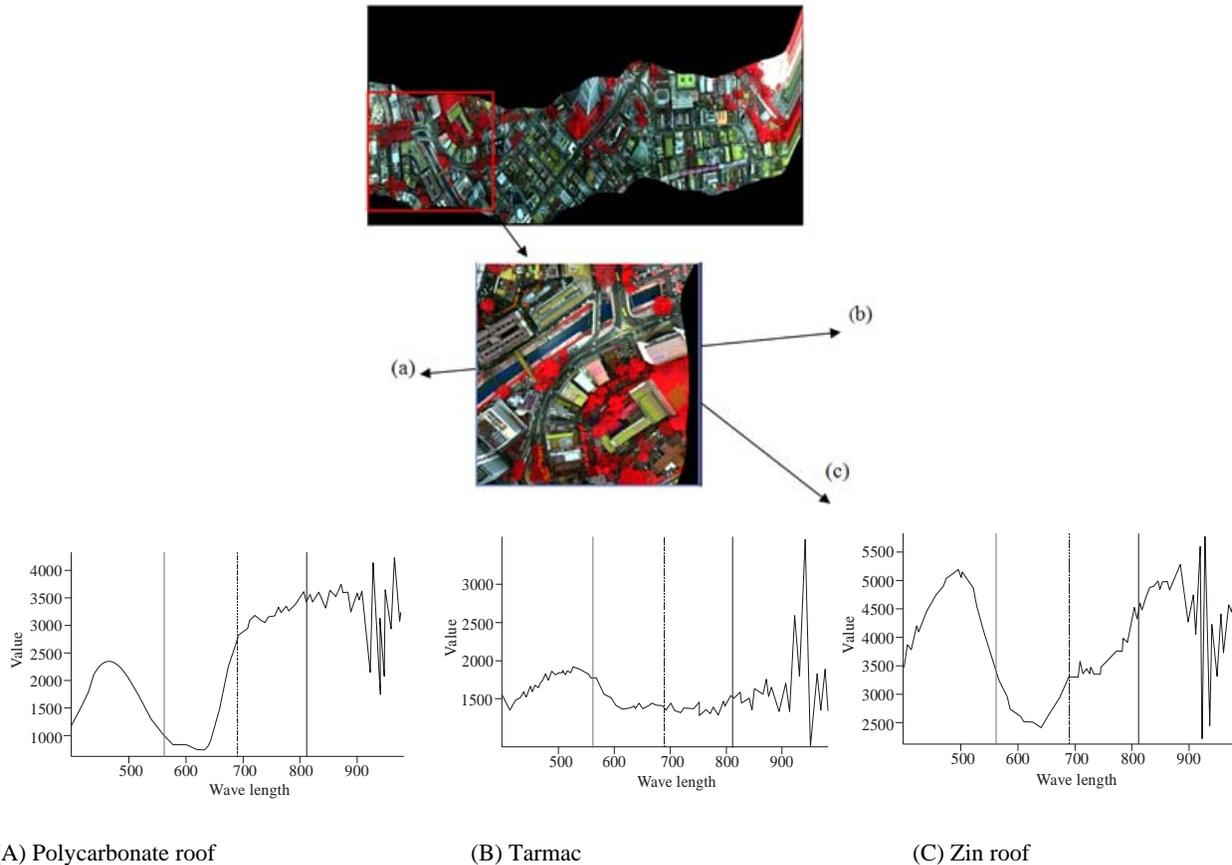


Fig. 1: Urban spectra from an AISA sensor for an urban scene in Kuala Lumpur, Malaysia

for analysing complex urban scenes. Applications within urban environments are still rare, with only a few studies having explored the capabilities of hyperspectral data to map urban land cover. Despite the advantages of hyperspectral data, knowledge concerning the spectral characteristics of man-made surface types is lacking, and little research has focused on the spectrometry of urban materials (Ben-Dor *et al.*, 2001b). Most of the traditional methods devoted to hyperspectral image processing conduct data analysis without taking into account spatial information. Pixels are processed individually, as an array of spectral data without any spatial structure. Standard classification approaches are widely used (e.g., k-means, fuzzy-c-means, hierarchical classification). Linear modelling methods, such as Partial Least Square (PLS) analysis, or nonlinear approaches, such as Support Vector Machine (SVM), are also used at different scales. However, with the development of high spatial resolution sensors, coupling spectral and spatial information when processing complex images appears to be a relevant approach.

In this study, studies and methods that are related to urban classification using hyperspectral remote sensing

data are reviewed. Several examples of urban applications of hyperspectral remote sensing are also discussed. Finally, through this review, gaps to be filled by further research are identified, and recommendations are given.

TECHNIQUES FOR THE HYPERSPECTRAL ANALYSIS OF URBAN AREAS

Analytical techniques for hyperspectral data analysis can be based on information extracted from the same dataset utilising the spectral information and/or combination of spectral-spatial techniques. However, datasets from different sources can be utilised simultaneously with techniques known as data fusion. For the spectral data utilisation, the reflectance profiles from every single pixel will be utilised. Figure 1 shows several typical reflectance profiles of urban features that can be extracted from an urban scene using an airborne hyperspectral sensor. In this example, urban spectra from the AISA sensor are shown.

However, the spatial components (spatial structures) are often associated with features related to texture, size, shape and the spatial continuity of neighbouring pixels

(association). Often, high spatial resolution will be needed for excellent extraction of this information. In image interpretation, a number of elements must be considered before arriving at conclusions about features; considering only one element may lead to erroneous object identification. Thus, spectral-spatial analyses of hyperspectral images are logical steps for the most accurate extraction of urban features from hyperspectral data.

Spectral-based approach: Spectral-based techniques make use of the spectral information (spectra) that can be extracted from pixels; therefore, they are also known as the pixel-based methods. Spectra can be extracted by using the standard approach, and they are processed using soft or hard classification strategies. Mixed pixels can be a common phenomenon, as urban areas are highly heterogeneous. Standard pixel-based classification, such as the Spectral Angle Mapper (SAM), Maximum Likelihood, Mixture Tuned Matched Filtering (MTMF) and SVM, can be utilised and have shown good results for urban hyperspectral classification. The pioneering effort to map urban environments using hyperspectral sensors by (Ben-Dor *et al.*, 2001a) has shown the enormous potential of hyperspectral data, despite the use of only the VIS-NIR region of the electromagnetic spectrum. The authors investigated the use of spectral information in mapping urban areas. Compact Airborne Spectral Imagers (CASI), which cover the visible (VIS) and near-infrared (NIR) spectral regions (0.4-1.1 μm), were used to identify the urban environment. The authors built the new Pure Urban Spectral Library (PUSL), which covers certain urban material. The results obtained by these researchers showed that the spectral region used in this study indicates that urban objects have significant spectral fingerprints in this spectral region that enable reasonable spectral recognition, and minor spectral variations among targets could be easily used to spatially distinguish similar objects. A spectrally based MTMF classifier was found to work satisfactorily with airborne data.

As the use of hyperspectral technology progresses, it is clear that a comprehensive spectral library will be needed as a reference and validation source. Toward this effort, Herold *et al.* (2004a) examined the spectral complexity and unique spectral characteristics of urban environments through the development of a comprehensive regional field spectral library of more than 4500 individual spectra. With the availability of space-borne hyperspectral sensors such as Hyperion, Cavalli *et al.* (2008) investigated its use for urban mapping. These researchers obtained consistent results with the use of SAM in classifying Hyperion satellite and MIVIS airborne hyperspectral data, indicating the potential use of such data.

The straightforward utilisation of classifier and data inputs can be the simplest approach, and its exhibits

acceptable accuracy that is comparable to, for example, SVM. Several researchers have tried slightly different approaches to spectral-based analysis, such as via information fusion or transformation methods. Demir and Erturk (2008) studied a technique to increase the classification accuracy of hyperspectral images by fusing spectral magnitude features and spectral derivative features. These researchers used Principle Component Analysis (PCA) as a feature extraction method to reduce the final number of features of the hyperspectral data before feature fusion. These authors also used spectral derivatives (first and second) to improve spectral discrimination and identification. The classification method used in this study was the SVM. Their result showed that if the first spectral derivative features are fused with the magnitude features, the classification accuracy is more significantly improved (94%) than by using magnitude features only, and further combination with the second spectral derivative features can further improve the classification accuracy. Based on published work, the SVM seem to be the most effective method in the classification of hyperspectral data (Melgani and Bruzzone, 2004; Camps-Valls and Bruzzone, 2005; van der Linden *et al.*, 2007; Fauvel *et al.*, 2007; Waske *et al.*, 2009; Misman *et al.*, 2010; Shafri and Zeen, 2011).

The spectral transformation of hyperspectral data into different domains, such as wavelet coefficients, might be a useful strategy to improve the classification accuracy of urban features, as shown by Misman *et al.* (2010). Overall, spectral-based technique provides a simple and straightforward approach to extracting information-rich spectral component of hyperspectral pixels for urban applications.

Spectral and spatial combination approach: Despite the simplicity of using spectral or spatial-based only processing methods, utilising only one component of the data limits the exploitation of the full potential of hyperspectral data. An important research area for the remote sensing of urban landscapes would be to incorporate both the spectral and spatial dimensions in data analysis (Herold *et al.*, 2004a). A significant number of works involving hyperspectral data processing focus on exploiting the spectral component without incorporating the spatial information (Plaza *et al.*, 2009). For urban area mapping, due to the high level of heterogeneity and man-made infrastructure, the integration of high spectral and spatial information is necessary to achieve accurate mapping output. For instance, spectral information is needed for materials classification, and spatial information is needed for the accurate delineation of building edges and road networks. This approach is an area of intensive research at present for which several algorithms have been developed. This method is also known as object-oriented classification (Fauvel *et al.*, 2007; Dell'Acqua *et al.*, 2004; Benediktsson *et al.*, 2005).

Among the earliest research published on the spectral-spatial approach for hyperspectral analysis is that by Dell'Acqua *et al.* (2004). These researchers examined new methods for the classification of hyperspectral remote sensing data with the primary focus on multiple classifications and spatial analysis to improve mapping accuracy in urban areas. These researchers compared spatial reclassification and mathematical morphology approaches and combined spectral and spatial classifiers in a multi-classification framework, and their results show that their proposed approach leads not only to higher overall accuracies but also equal or higher accuracies for all the individual classes. Since that finding, the combined spectral-spatial approach has been adopted more widely.

Furthermore, Palmason *et al.* (2003) considered the classification of remote sensing data from an urban area with both high spectral and spatial resolution. The considered morphological approach only uses one data channel for processing. The morphological approach was applied in experiments on high-resolution DAIS remote sensing data from an urban area. These researchers computed the first principal component of the data and used it as the basis for the construction of morphological profiles to use the spectral information. A neural network classifier with one hidden layer was used to classify the data. Their results indicated the importance of using good feature extraction mechanisms with the morphological approach. The use of the morphological profile gave much higher overall accuracies compared with the case in which a single-band principal component was used (a greater than 24.5% increase), especially when the decision boundary feature extraction for neural networks was applied to the morphological profile.

The method was further advanced by Palmason *et al.* (2005), as morphological profiles were constructed with a repeated use of morphological opening and closing operators with a structuring element of increasing size, starting with the original panchromatic image. These researchers' approach used independent component analysis instead of principle component analysis to produce an extended morphological profile. Maximum likelihood classification was applied, and classification was performed for the data in the full feature space (102 data channels), the Decision Boundary Feature Extraction (DBFE) data and Nonparametric Weighted Feature Extraction (NWFEE). The results obtained by these authors indicate the performance of the statistical maximum likelihood classifier is more than 4% in terms of overall test accuracies. The overall accuracy (OA) using the DBFE technique is the highest.

A more advanced method based on mathematical morphology for hyperspectral data that makes use of both spectral and spatial information for classification was proposed by Benediktsson *et al.* (2005). The proposed method is used as a preprocessing method for neural network classifiers and is compared with more conventional classification methods with different types of

statistical computations and feature extraction. In fact, Fauvel *et al.* (2007) extended the approaches by Benediktsson *et al.* (2005) and used both spatial and spectral information for classification. These authors' approach is based on the fusion of the morphological information and the original hyperspectral data, i.e., the two vectors of attributes are concatenated into one feature vector. The proposed approach also shows excellent results with a limited training set using SVM. As SVM was found to be more accurate and robust for hyperspectral data analysis, many researchers have adopted the classifier in the spatial-spectral classification approach.

Importantly, Fauvel *et al.* (2006) investigated the classification of hyperspectral data with high spatial resolution from urban areas. These researchers' study area was in Italy, and their approach was based on using several principal components from hyperspectral data and morphological profiles. The deficiency of the approach is that it is primarily designed for the classification of urban structures and does not fully utilise the spectral information in the data. Similarly, a pixel-wise classification solely based on the spectral content can be performed. The proposed approach is tested in experiments on ROSIS data from urban areas. Significant improvements are achieved in terms of accuracies compared with results obtained for approaches based on the use of Morphological Profiles (MPs) based on PCs only and conventional spectral classification. This proposed method is based on the fusion of the morphological information and the original hyperspectral data. These researchers used SVM as final classification method, their results were classified into 3 levels (spatial information only, spectral and fusion of spectral and spatial), and they showed that the fusion of spectral and spatial information led to improved classification accuracy. For instance, with one dataset, the overall accuracy is increased from 79 to 83% without any feature reduction and to 87% with feature reduction. The proposed approach also shows excellent results with a limited training set.

Furthermore, Bruzzone *et al.* (2007) proposed the new context-sensitive semi-supervised classification technique based on SVM. This technique aims to exploit the SVM method for image classification by properly fusing spectral information with spatial context information. The main property of the proposed context-sensitive semi-supervised SVM (CS4VM) adaptively exploits the contextual information in the training phase of the classifier without any critical assumption on the expected labels of the pixels included in the same neighbourhood system. Their results showed that the CS4VM technique allows the proper fusing of spectral and spatial-context information, thereby improving the performance in terms of classification accuracy and robustness to small-sized and/or noisy training sets, and the overall accuracy that they were able to achieve in this study was 93.71%.

In their study, Plaza *et al.* (2009) discussed, among others, the importance of SVM, morphological profiles, Markov Random Field (MRV) and hierarchical segmentation methods for urban mapping. The morphological profile, Markov Random Field (MRV) and hierarchical segmentation methods are based on spatial and spectral integration and were found to be significant in improving urban classification.

Interestingly, Velasco-Forero and Manian (2009) examined the spatial smoothing over the original hyperspectral data based on wavelet and anisotropic partial differential equations using composite kernels in graph-based classifiers. These kernels combine spectral-spatial relationships using smoothed and original hyperspectral images. These researchers used the semi-supervised SVM and graph-based methods as classification methods. In their approach, spatial information is extracted by first preprocessing the hyperspectral image using efficient image enhancement algorithms. This enhanced spatial information is then combined with spectral information via kernels in a semi-supervised graph-based framework for classification. These authors' results show that this method improves the classification accuracy by approximately 1% using wavelet smoothing compared with graph-based methods. Good classification accuracies were obtained by applying this method for classifying other hyperspectral datasets with more classes and a minimum of labelled samples. The proposed scheme has lower computational cost and can work with a small number of labelled samples. These researchers also showed that the proposed methodology gives good performance (88.2%) with this image.

Importantly, Tarabalka *et al.* (2009) modified the method and proposed a new classification method for hyperspectral images that uses both spectral and spatial information. These researchers' method combines the results of a pixel-based classification that came out the SVM method and the segmentation map obtained by partitional clustering using majority voting. The results of their study show that the new classification scheme improves the classification accuracies and provides classification maps with more homogeneous regions compared with pixel-wise classification. The proposed method performs particularly well for the classification of images with large spatial structures and when different classes have dissimilar spectral responses and a comparable number of pixels.

Using high-resolution remote sensing data, Fauvel *et al.* (2005) considered the classification of urban areas. Two datasets, one panchromatic and one hyperspectral, were used to classify an urban area. These researchers' method was based on mathematical morphology to utilise the spatial information, and the Neural Network (NN) method was used as the classification method. The approach of this study was based on building a morphological profile by a composition of geodesic opening and closing operations of different sizes. Principle component and independent component analysis

were applied to reduce the dimensionality of the hyperspectral data. The authors applied feature extraction methods, such as Discriminant Analysis Feature Extraction (DAFE) and Decision Boundary Feature Extraction (DBFE) before applying their method to hyperspectral data. The results show that the best overall accuracy related to hyperspectral data was obtained by using extended morphological profiles based on the principle component. The morphological profile also shows good potential for extracting buildings and their shadows and the shapes of building, which is useful for visual interpretation.

Interestingly, Camps-Valls *et al.* (2010) investigated a graph kernel for spatial-spectral remote sensing image classification with SVM. These researchers discovered the limitations of the Previous Spatial-Spectral Kernels. Thus, the authors introduced a novel graph-kernel model that can overcome the limitations of the previous kernel; their results show that the graph kernel is a powerful alternative to existing approaches, and they generalise previous approaches to kernel-based spatial-spectral classification. Furthermore, the approach has the advantage of getting rid of a spatial preprocessing step and computing the similarity among both the labelled samples and those in their neighbourhood at different scales. The capabilities of the method are illustrated in several multi- and hyperspectral remote sensing images acquired over both urban and agricultural areas.

Based on the several recent studies reviewed, research that focuses on the use of hyperspectral data for urban areas is now moving mainly toward the integration of spectral and spatial components of hyperspectral data, with SVM being the most optimal classification scheme. However, despite the power of the techniques demonstrated, layman users of hyperspectral data might find it difficult to apply these methods, as they are yet to be readily available in many commercial remote sensing software.

SENSOR FUSION FOR URBAN MAPPING

Currently, almost all hyperspectral data acquired over urban areas are taken exclusively from airborne platforms because the current space-based hyperspectral data are only provided by Hyperion with a 30 m spatial resolution. Furthermore, it is often difficult to obtain cloud-free data, especially for tropical regions. As hyperspectral data are lacking in terms of stereo imaging, cloud penetration, weather limitation or heights determination, it is often necessary to use data acquired from different sensors. Light Detection and Ranging (LiDAR) and Interferometric Synthetic Aperture Radar (IFSAR) data are popular because they provide accurate height information for data calibration and information extraction. SAR is useful when information cannot be obtained under cloud cover or due to weather restrictions (ref). Thermal data can also be used for analysing the urban heat island. As future sensors are to be launched,

on-board satellite platforms, such as the planned ENMAP mission, Marino *et al.* (2000) utilised the combination of LiDAR and hyperspectral data in urban tree species detection and obtained improved accuracy in the use of fused datasets. The creation of a 3D urban GIS database for more efficient urban planning will obviously benefit from the combinations of hyperspectral data with LiDAR or IFSAR data (Wicks and Campos-Marquetti, 2010). Overall, data fusion of urban areas can consist of multi-sensor combination, 2D/3D data fusion, multi-resolution data fusion and multi-temporal combination (Gamba *et al.*, 2005). Data fusion at different levels for the characterisation of urban areas is a key topic in this domain.

The significant advantage of sensor fusion approaches (such as hyperspectral and LiDAR) is that they provide a holistic approach to urban mapping. For instance, hyperspectral data provide details on surface material types and conditions, while LiDAR provides geometrical and structural information. When these approaches are combined, an overall analysis can be conducted for an urban area for various applications.

Applications: In general, urban land use and land cover mapping can directly benefit from the high level of detail provided by hyperspectral data. Applications of hyperspectral data in urban mapping are mostly in the realm of detecting and impervious surfaces (e.g., roads, rooftops, buildings), as these features are the most common in an urban scene. However, it is also interesting to note that urban green features such as urban forests can also benefit from the technology, despite their relatively smaller extent in an urban environment. In fact, (Roessner *et al.*, 2001) stated that effective methods for mapping urban surface cover types can be used for evaluating ecological conditions in urban structures and supporting updates of biotope mapping.

Roof type mapping: Roof types and conditions are important information that can be extracted from hyperspectral data (Marino *et al.*, 2000). Knowledge roof material types can assist applications such as disaster preparedness (Bhaskaran *et al.*, 2001), and solar photovoltaic energy modelling can be conducted by combining hyperspectral and LiDAR data (Szykier, 2008) as well as for urban heat island assessment (Ben-Dor *et al.*, 2001b).

Road type and conditions mapping: The management of urban areas is closely linked with the quality of the transportation network. It has been shown that poor road conditions, such as presence of cracks and potholes, can be detected from very high spatial resolution imagery. The availability of high spectral and spatial resolution hyperspectral imagery could provide additional information for detecting road materials and conditions simultaneously, thereby facilitating a more efficient management approach (Herold *et al.*, 2004b).

Urban tree monitoring: Urban forests are typically defined as woody vegetation in an urban area and are usually limited to the trees in the city in contrast to grass and shrubs. The effect of urban forests on urban heating, cooling, carbon sequestration, air and water pollution remediation, flood abatement, noise reduction, human mental health, wildlife habitat and pollution reduction have all been documented for many years (Jensena *et al.*, 2009). Importantly, Artigas and Yang (2004) evaluated the use of hyperspectral data for urban wetland mapping in the New Jersey Meadowlands from hyperspectral images captured by an airborne imaging spectroradiometer (AISA). This study indicated that hyperspectral images might be used on their own to detect urban marsh features that are ecologically significant. Furthermore, Lulla (2009) discussed the potential of hyperspectral data for urban forest application as one of the most important components of urban geography. Interestingly, Jensena *et al.* (2009) concluded that urban LAI can be accurately estimated using AISA+ hyperspectral data and that it would benefit cities' green initiatives.

Urban heat island: The Urban Heat Island (UHI) effect is one of the most typical phenomena of the urban climate. In a UHI, the temperature of the central urban locations are several degrees higher than those of nearby rural areas of similar elevation (Chou, 1985). UHIs have been indirectly related to climate change, due to their contribution to the greenhouse effect and therefore to global warming. It is obvious that air temperatures in urban areas are higher than those of the surrounding countryside. Several studies have contributed to the use of remote sensing imagery to understand UHI effects. In fact, Jung *et al.* (2004) attempted to model the effect of vegetation on UHI using hyperspectral remote sensing images.

Urban flash flood: Most of the land surface of an urban area is covered by impervious materials. These materials cause reduced infiltration and accelerated runoff that result in flooding (Brun and Band, 2000). Floods and flash floods, as well as disasters of hydrographic origin triggered by floods, are among the most destructive disasters in terms of loss of life and property. Remote sensing and GIS have great potential to assess numeric, accurate and valuable information of disasters of hydrographic origin. Advances in satellite technologies in particular enable researchers to study the progress of natural disasters immediately prior to, during and after their occurrence. In recent years, there has been growing public and scientific interest in the phenomenon of flash flooding in urban areas. The increase of impervious areas as a consequence of urbanisation has a great effect on flash flooding. Thus, to accurately map impervious surfaces in urban areas and detect the different materials, high spatial and spectral resolution is necessary (Weng, 2011). Traditional multispectral images are unsuitable for

researches in complex landscapes. With the advent of new hyperspectral remote sensors that are able to capture image in both high spatial and spectral resolution, it should be possible to detect and identify minerals, ground vegetation and man-made materials, which cannot be distinguished with broadband sensors.

However, one caveat of airborne hyperspectral data is the cost involved and the practical limitations of operation. Space-based hyperspectral remote sensing could provide cheaper data with wider coverage, but even the coming ENMAP hyperspectral system is limited to a resolution of 30 m. This level of spatial resolution will not be suitable for combined spectral-spatial approaches, and new methods will therefore need to be developed to facilitate efficient approaches for hyperspectral data with coarse resolution.

CONCLUSION

Hyperspectral images with high spatial and spectral resolution, which can provide a large amount of detailed information, have been used in the mapping of urban areas. The high spectral and spatial resolution of these images enable critical data to be extracted using a plethora of analytical techniques. Conventional methods use only spectral information to classify such imagery, with spatial information being ignored. The methods used to map urban areas from hyperspectral imagery can generally be classified into spectral only and spectral-spatial fusion to improve the classification accuracy. Spectral-only methods provide results that are not sufficiently accurate to describe urban areas. To improve these methods, spatial information will need to be used together with spectral information, as urban areas have a complex mix of manmade and natural features.

Further research could test the use of image processing techniques for different study sites using different sensors or by developing novel techniques that might perform better. Techniques utilising both spectral and spatial components of hyperspectral data should be adopted if the full potential of hyperspectral data is to be exploited. However, this is not an easy task, as the methodology is challenging, and there is a lack of specially designed urban-oriented algorithms available in commercial remote sensing software. Such algorithms do exist, and more are being developed, but their use is limited to a small community of specialised researchers. However, it is always debatable whether it is necessary to combine spectral and spatial information, as this will demand intensive computing and complex processes. Most of the techniques presented in the literature are not available to the public and are restricted to within only a few groups of researchers. Furthermore, in many cases, spectral information is only sufficient to provide a high-accuracy outcome of hyperspectral image processing for urban areas. Nevertheless, once combined, spatial and spectral methods are more accessible to the wider

community, and the methods would be adopted more routinely to take advantage of the complementarities that both sources of information can provide. Such methods as MPs will always favour high spatial resolution data, such as airborne hyperspectral remote sensing, but it can be seen that it is useful for extracting the segments in an image, and with spectral information provided by classifiers such as SVM, a more optimal and complete mapping of urban infrastructure is now possible.

Despite all of these welcome developments, it remains uncommon for urban planners, social scientists or public health practitioners to make use of satellite imagery (Rashed, 2008). One of the reasons for this hesitance is the significant technical complexity by which many remote sensing scientists have isolated themselves. Despite the advantages offered by the spectral-spatial combination approach, there are still challenges in defining the rule-set parameters for the detection of different urban features. Furthermore, a more generic model would be needed to standardise object-based mapping throughout different urban environments acquired by different sensors and resolutions.

Challenges also lie in exploring new frontiers of hyperspectral applications for urban areas and making it more economical and practical for local municipalities and governments to use hyperspectral-based methods. It is recognised that cities and municipalities have limited budgets that must balance many different requirements and services. Thus, there are still setbacks for hyperspectral applications, as data acquisition is normally expensive, and the analysis can be too complex. Perhaps with the emergence of more cost-effective UAV and satellite-based hyperspectral sensors with high spatial and spectral resolutions in the near future, a more widespread use of hyperspectral technology for urban mapping will be seen. There is no doubt that the immense spectral resolution of hyperspectral sensor systems enables thematically comprehensive and spatially detailed characterisations of the urban environment. However, current hyperspectral sensor systems that show a spatial resolution that is useful for urban applications are limited to airborne platforms. The next high-resolution hyperspectral satellite sensor, EnMAP, is supposed to be launched by 2013. This system will feature a spatial resolution of 30 m and will cover the spectral range of 420-2450 nm with approximately 200 bands.

One possible direction of future research is to use wavelet coefficients as surrogates for spectral information, as this approach could improve accuracy. Wavelets could also be used to extract edges and morphological changes of features. Thus, a wavelet-combined spatial-spectral process might provide the foundation for further advancement. To date, no studies have investigated the effects of data on wavelet spectra in the classification of urban data. Much effort is still needed to operationalise the use of hyperspectral remote sensing

for continuous urban monitoring in terms of systems and algorithm development. If this step is achieved, the goal of green and sustainable city development will move closer toward realisation. Despite issues related to practicality and cost-effectiveness, airborne hyperspectral remote sensing can still be used as a baseline to develop new approaches for the utilisation of cheaper multispectral satellite systems for urban mapping, such as WorldView 2. In addition, a comparison of MP and wavelet methods with and without hyperspectral information could also be performed to examine an interesting topic of future research.

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