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Integrating imaging spectroscopy (445–2543 nm) and geographic information systems for post-disaster management: a case of hailstorm damage in Sydney

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Abstract. This paper demonstrates a methodology for the analysis and integration of airborne hyperspectral sensor data (445–2543 nm) with GIS data in order to develop a vulnerability map which has the potential to assist in decision making during post-disaster emergency operations. Hailstorms pose a threat to people as well as property in Sydney, Australia. Emergency planning demands current, large-scale spatio-temporal information on urban areas that may be susceptible to hailstones. Several regions, dominated by less resistant roofing materials, have a higher vulnerability to hailstorm damage than others. Post-disaster operations must focus on allocating dynamic resources to these areas. Remote sensing data, particularly airborne hyperspectral sensor data, consist of spectral bands with narrow bandwidths, and have the potential to quantify and distinguish between urban features such as roofing materials and other man-made features. A spectral library of surface materials from urban areas was created by using a full range spectroradiometer. The image was atmospherically corrected using the empirical line method. A spectral angle mapper (SAM) method, which is an automated method for comparing image spectra to laboratory spectra, was used to develop a classification map that shows the distribution of roofing materials with different resistances to hailstones. Surface truthing yielded high percentage accuracy. Spatial overlay technique was performed in a GIS environment where several types of cartographic data such as special hazard locations, population density, data about less mobile people and the street network were overlaid on the classified geo-referenced hyperspectral image. The integrated database product, which merges high quality spectral information and cartographic GIS data, has vast potential to assist emergency organizations, city planners and decision makers in formulating plans and strategies for resource management.

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1. Introduction

Hailstorms can cause substantial damage to property anywhere in the world. For instance, on 14 April 1999, a thunderstorm was detected forming approximately 115 km south of Sydney, Australia, near Nowra. Within 25 minutes the storm unleashed a maelstrom of icy fury, as the largest hailstones ever recorded in Sydney crashed down from the skies at over $200\,\mathrm{km\,h^{-1}}$. The storm carved a path of destruction resulting in an estimated damage bill of 1.5 billion dollars (Fire News 1999). Table 1 shows the total estimated financial losses incurred by hailstorms and other catastrophes from 1967 to 1998.

While the prevention of hailstorms is a myth, the management of dynamic resources for rescue and post disaster operations is an important issue. From a disaster management perspective it is vital to develop a database that shows areas with different degrees of vulnerability from hailstorms. Hailstorm vulnerability can be assessed in different ways, one of which is by mapping the type of roofing material used for constructions, since different roofing materials have varying degrees of resistance to hailstones. There is a high correlation of damaged roofs to the material composition of the roofing material, which in turn determines their resistance to hailstones (Andrews and Blong 1997, Vorobieff *et al.* date unknown).

The roof is the first point of impact from the hailstorm and thereafter severe damage is caused to the houses and property. Various studies indicate that tiles, gutters, windows, brittle cladding materials and metal sheeting are all at risk during heavy hail. Thin metal sheeting is dented or even penetrated, while tiles develop hairline cracks and are often shattered under the impact of hailstones. Age and impact location are important factors for many roofing materials (Vorobief *et al.* date unknown). A study carried out by Andrews and Blong (1997) reported that tile roofs were the most commonly damaged roof type. The study ranked roof materials in decreasing order of vulnerability to damage: aluminium, fibro, slate, tiles and iron. Roofs contributed as one of the major cost items accounting for 22% of the total cost.

Research in the past has explored the use of remote sensing data to study urban surfaces mainly by means of classification of multi-spectral data materials (Lo 1997, Forster 1983, Heiden *et al.* 2001). All these studies confirmed the inadequacy of spectral resolution of broadband sensors to detect and map urban features. Bhaskaran *et al.* (2001a) demonstrated a methodology that used airborne remote sensor data to map vulnerability from hailstorms in Sydney. Furthermore, urban

Table 1. Largest Australian insured catastrophic losses 1967–1998 (Insurance Council of Australia).

Event	Location	Date	Insured loss (A$ million)
Earthquake	Newcastle	1989	1125
Cyclone Tracy	Darwin	1975	835
Hailstorm	Sydney	1990	385
Cyclone Wanda	Brisbane	1974	330
Bushfires	Victoria, South Australia	1983	325
Hailstorm	Brisbane	1985	300
Thunderstorm	Sydney	1991	225
Hailstorm	Sydney	1986	160
Hailstorm	NSW	1976	130
Cyclone Madge	Northern Australia	1973	150
Cyclone Althea	Townsville	1971	150

feature objects occur heterogeneously in space and do not follow any specific pattern, which compounds the problem of their systematic identification. Since details extracted from broadband sensors such as Landsat, SPOT and other optical remote sensor data have proven to be inadequate for sub-pixel analysis of urban regions, the superior resolution (spatial and spectral) of an airborne hyperspectral data (HyMap) was considered and used in the study.

Hyperspectral data, due to their narrow bandwidth and fine spectral resolution, have the potential to distinguish between various surface materials (Goetz 1992, Roessner *et al.* 1998, Bhaskaran *et al.* 2001b). The overall shape of a spectral curve and the position and strength of absorption bands of hyperspectral data can be used to identify and discriminate materials in an urban area (Bhaskaran and Datt 2000). The potential of hyperspectral data has been demonstrated by other studies such as Ridd *et al.* (1997), Hepner *et al.* 1998, Crowley and Zimbelman (1996), Fuimie and Marino (1997) and Roessner *et al.* (1998). Identification and quantification of urban feature objects by using the albedo and chemical composition of materials were also demonstrated by Bianchi *et al.* (1996), Fuimie and Marino (1997) and Roessner *et al.* (1998). Crowley and Zimbelman (1996) used AVIRIS data to map alteration minerals on the slopes of Mt. Rainier to delineate hazardous sectors, to develop a model that has the potential to be applied to other areas. A supervised classification of surface materials in an urban environment was created by analysing the airborne HyMap data (Bhaskaran and Datt 2000) in the urban areas of Perth, Western Australia and later in Sydney, Australia. Ben-Dor *et al.* (2001b) demonstrated that in the terrestrial urban environment two major aspects can be remotely sensed: natural targets (e.g. soil, water and vegetation) and man-made targets (e.g. buildings, pools, roads and vehicles).

However, we believe that there have been few studies that explore the potential of analysing and integrating high-resolution airborne hyperspectral data with GIS data for mapping vulnerability in urban areas. Furthermore the HyMap remote sensing data have not been used for mapping vulnerability in urban areas.

2. Objectives

The broad objectives of this paper were to explore the potential of HyMap data and to map vulnerable areas that may be affected by future hailstorms. Specific objectives were:

(a) to create a spectral library of urban surface materials, especially roofing materials by using a field spectrometer under artificial illumination and sunlight;
(b) to map the vulnerability of urban areas to hailstorm hazard by analysing the hyperspectral sensor data; and
(c) to integrate classified hyperspectral data with GIS data for demonstrating the potential of providing intelligent information and decision support systems to emergency organizations.

3. Study area and airborne HyMap data

A narrow transect (3 km × 19 km) covering the region from Concord, located to the south of the Parramatta River, to the Forestville region located to the north of the Parramatta River, was mapped using the airborne HyMap sensor in early September 1999, by HyVista Corporation, Sydney, Australia. For the purpose of exploring the full potential and capability of hyperspectral data, it was necessary to select a study area which had various types of roofing materials representing different land use and functions such as residential, commercial, educational, industrial. These areas had a mixed type of land use and the occurrence of a wide variety of roofing materials in close proximity. From the objective of the study and potential of future hailstorm damage this was considered to be an ideal study area and a potentially vulnerable region.

The HyMap sensor provides 126 bands across the reflective solar wavelength region of 0.45–2.5 μm with contiguous spectral coverage (except in the atmospheric water vapour bands) and bandwidths between 15–20 nm. HyMap provides a high signal to noise ratio ($>500:1$) and therefore renders high image quality. Figure 1 shows the study area south of the Parramatta River imaged by the HyMap sensor as well as by aerial photo images.

4. Preliminary field check

A good understanding of the surface features is essential for accurate analysis of the Hymap image. A database was created for different land uses, showing the material composition of the surface features, which ranged from roof types (terracotta tiles, concrete tiles, slate tiles, corrugated fibro and metal) to concrete pavers and bitumen. The database was created by surveying the study area with the aid of a laptop and high-resolution aerial photo image as well as other GIS layers such as street network and census layers. Most of the materials fell into the category of terracotta tiles, concrete tiles, slate tiles, corrugated fibro and metal roofs, pavers and bitumen which were found almost exclusively in some places and in a mixed form in others. Since the spatial resolution of the HyMap image was $5\,\text{m} \times 5\,\text{m}$, care was taken to examine those areas that could also be spatially resolved on the Hymap image. Apart from the material composition, the age, location, use and function of the sampled rooftops were also recorded. In some instances where the roofs could not be seen directly, local but reliable knowledge was obtained from staff working at these places.

5. Methodology

Various samples of urban surface materials, mainly consisting of roofing materials, were collected from different sources. Some of the surface materials used in the analysis are as follows:

- Terracotta tile
- Concrete paver
- Brick
- Bitumen
- Sandstone
- Vegetation
- Wood
- Metal
- Slate
- Corrugated fibro
- Clay brick (red)
- Birch
- Concrete brick
- Basalt
- Marble

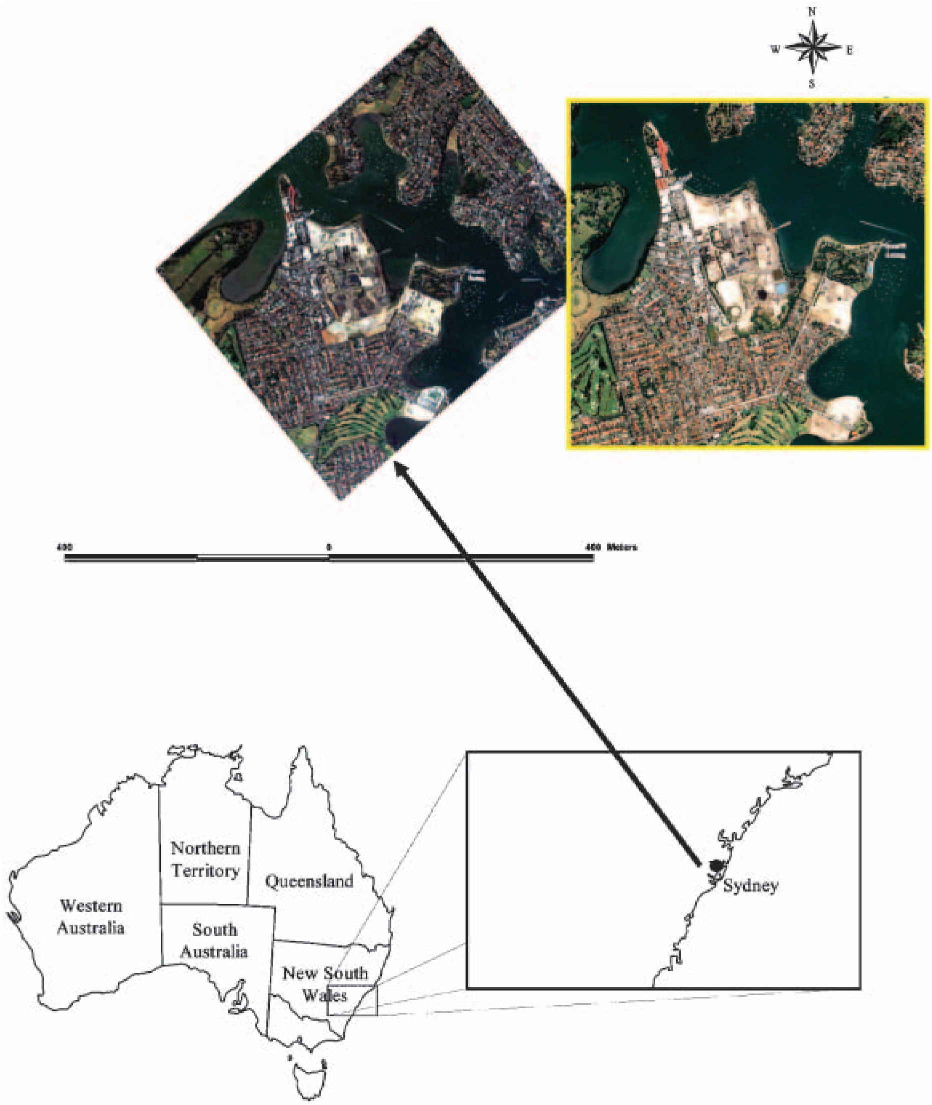

Figure 1. Study area (Concord Bay, Sydney) exposed by HyMap sensor (left) and aerial photo (right).

Apart from the types of roofing materials collected, particular care was also taken to collect weathered and non-weathered materials. One of the aims was to generate a reference spectral library consisting of different types of spectra from roofing materials. The HyMap sensor covers the reflective VIS (0.4–0.7 μm), NIR (0.7–1.1 μm) and SWIR (1.1–2.5 μm) wavelengths. A FieldSpec® Pro Full Range (FR) spectroradiometer from Analytical Spectral Devices (ASD, Boulder, CO, USA) that measures reflectance in the VIS, SWIR I and II was used to collect reflectance using a Spectralon white reference panel. The spectrometer unit incorporates three spectrometers to cover the 0.350–2.500 μm wavelength. The

HyMap image has 126 bands, which were reduced to 115 bands due to poor data quality in bands 63–67, 94–97, 125 and 126. This was done for two reasons: firstly to avoid data from pronounced absorption features operating outside the atmospheric window such as water near 1.4 μm and carbon dioxide at 1.9 μm and secondly to avoid some noisy bands in the sensor. Channels of HyMap and spectrometer wavelengths were configured and the empirical line correction method was employed to convert the radiance to apparent reflectance values. The image was classified by the Spectral Angle Mapper (SAM) method, a supervised classification provided with the ENVI/IDL software. Accuracy of the classified image was estimated by visiting selected sites on the field. Various GIS layers were spatially overlain onto the classified image to assess the most vulnerable regions. The entire methodology is summarized in figure 2.

5.1. *Spectral library of urban surface materials*

The spectra of urban materials were measured under artificial illumination in the laboratory. A spectral library of pure urban materials was created and resampled to match the 126 channels of HyMap. A second batch of spectra was generated under natural light. A clear and sunny day was chosen for collecting spectra from surface materials. This exercise was carried out between 12 p.m. and 1 p.m. in order to reduce the effect of the sun angle. The two urban spectral libraries were named urban spectra artificial light (USAL) and urban spectra natural light (USNL). Figures 3(*a*, *b*) (radiance data) show some laboratory and HyMap image spectra respectively.

5.2. *Image calibration*

In order to compare hyperspectral image radiance spectra directly with field reflectance spectra, the encoded radiance values in the image must be converted to reflectance. The empirical line method was used to convert the image radiance data to reflectance. The empirical line calibration technique is used to force image data to match selected field reflectance spectra (Roberts *et al.* 1985, Conel *et al.* 1987, Kruse *et al.* 1990). Field reflectance spectra were acquired for two ground targets that had a wide albedo range and were large enough to recognize in the image. Known dark (concrete) and bright targets (sandstone) from the Hymap image were selected and paired with the reference spectra of the same objects for the empirical line calibration. A linear regression was calculated between the reference spectra and the image spectra for each of the 126 Hymap bands. The regression lines were used to predict the surface reflectance spectrum for each pixel from its original image spectrum (ENVI Tutorials 1999).

In this study several known targets such as sandstone, terracotta and vegetation were used during the SAM technique. All these images came up with different percentages of roofing materials. For instance, when terracotta tile was used as the known target during calibration the SAM, a high percentage of terracotta tiles were yielded in the output classification. This percentage reduced when other known targets such as sandstone and vegetation were used. This clearly indicates that to classify particular roofing materials the best option would be to use the same feature as the known target for calibration. Present spatial resolution of airborne hyperspectral sensor data does not enable spectral unmixing especially in this study where the roofing materials occur spatially in a juxtaposed manner. As a result, a single pixel at a 5 m × 5 m spatial resolution results in spectral confusion

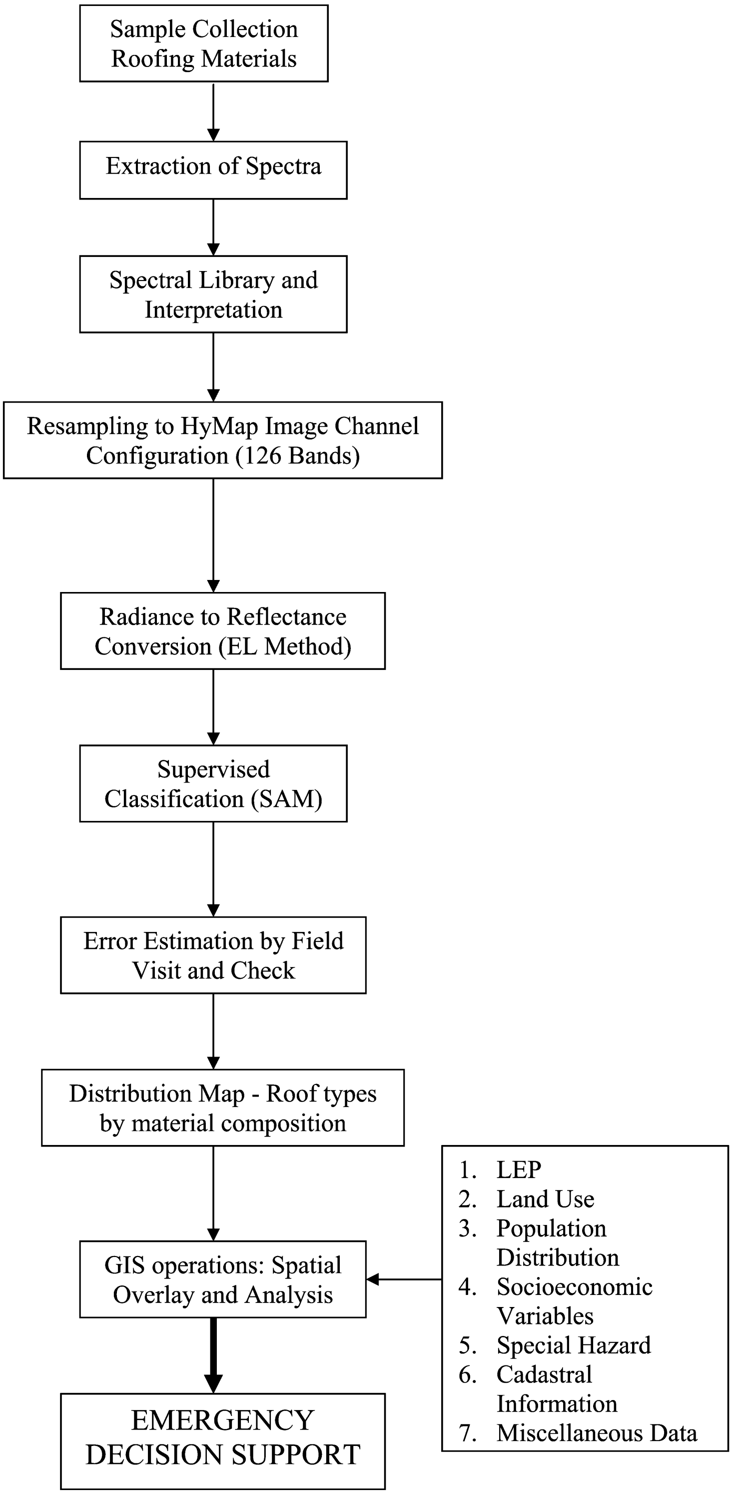

Figure 2. Methodology.

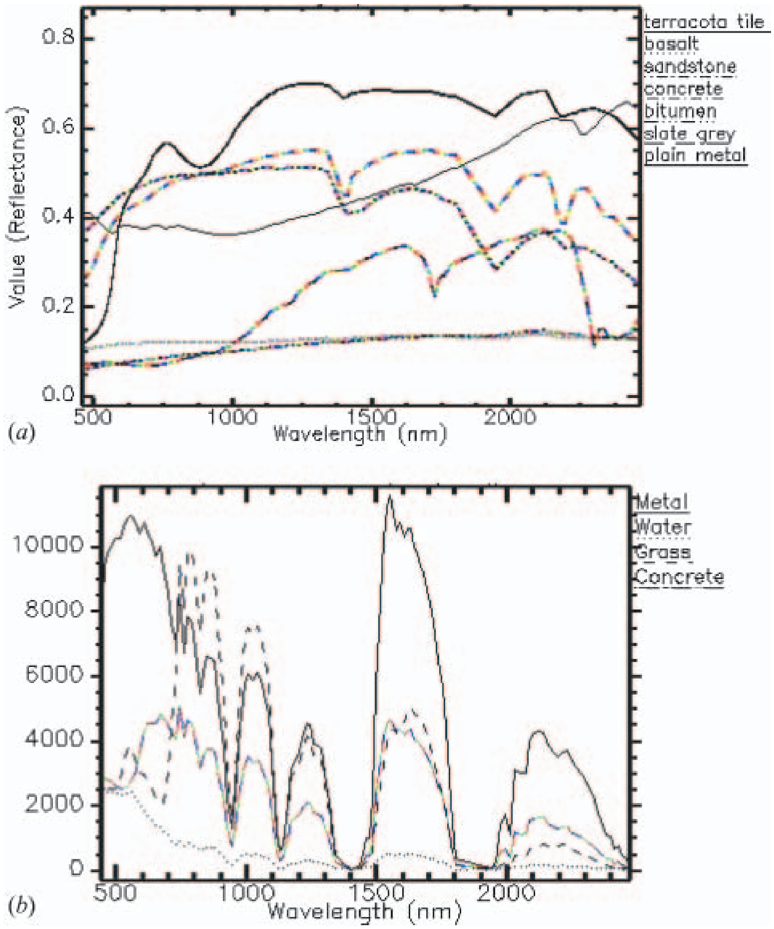

Figure 3. Spectra from (*a*) laboratory (reflectance) and (*b*) image (in radiance).

in heterogenous urban areas. An improved spatial resolution will result in identification of pure end-members and a more accurate surface abundance map. At the moment hyperspectral sensors are carried on aircraft. The future will see Earth observations by these sensors from space-borne platforms. The proposed spatial resolution is rather broad to be useful for much urban analysis, but it is expected that the resolution will improve in time. Until then airborne hyperspectral data will be the most effective scale independent source of studying urban surfaces. The high cost of acquiring airborne hyperspectral data is an impediment to its widespread use.

6. Results

Results included a calibration of spectra (reference and image), a spectral library of surface materials and interpretation, classification map of roof types, and finally integration of image analysis results with other surface data.

6.1. *Interpretation of urban roof spectra*

Generally, the total reflectance of a given object across the entire visible region (also termed albedo) is strongly related to the physical condition of the relevant targets (shadowing effects, particle size distribution, refraction index, etc.), whereas the spectral peaks are more related to the chemical condition of the sensed target (specific absorption). Several urban related chromophores do provide significant absorption features in the VIS-NIR, such as chlorophyll (at 0.68 μm) and iron oxides (at 0.50, 0.56 and 0.88 μm; Hunt *et al.* 1971). In addition to these specific absorption features the shape of the spectral curve also is important in distinguishing urban surface materials (Bhaskaran and Datt 2000).

Unlike concrete and terracotta, metal roofs show a high reflectance in the visible range due to the presence of steel and aluminium. Terracotta is mainly composed of clay, which shows strong absorption peaks in the VIS range and in the far infrared region at around 2160 nm, due to the presence of hydroxide ions in kaolinite, a naturally occurring mineral found in clay-based materials. This absorption feature at 2160 nm is notably absent from other roof types such as metal, slate, and concrete. However, older terracotta shows higher absorption when compared to newer terracotta due to weathering and fading of the original colour. Concrete tile roofs show high reflectance in the VIS but generally are featureless throughout the spectrum. Roofing slate is a dense natural material that is practically non-absorbent. The colour of slate is determined by its chemical composition. Because these factors vary from region to region, slate is available in a variety of colours. These same factors also influence how vulnerable slate is to changing colour upon exposure to the weather. In the study this character of slate made it difficult to detect slate roofs accurately. The presence of dark objects such as bitumen and basalt (figure 3(*a*)) created some difficulty in identification which was due to their low albedo values across the entire spectrum, with no absorption signals. The reflectance of urban materials is a mixture of both chemical (specific absorption behaviour) and physical (specific albedo behaviour) chromophores. In the field, both mechanisms are active, whereas in the laboratory the chemical effects are more pronounced, assuming that the physical effects, such as illumination, particle size and sample geometry, are constant (Ben-Dor *et al.* 2001).

6.2. *Mapping vulnerable regions by supervised classification: Spectral Angle Mapper (SAM)*

SAM is an automated method for comparing image spectra to individual spectra or a spectral library (Boardman, Huntington 1996, Boardman, unpublished data, 1992, CSES 1992, Kruse *et al.* 1993). The SAM classification was used for comparing image spectra to the reference spectra. The SAM algorithm determines the similarity between two spectra by calculating the spectral angle between them as unit vectors in spectral space with dimensionality equal to the number of bands (ENVI Tutorials 1999). A classified image was produced by supervised classification in which each pixel was assigned to a class roofing material (figure 4(*a*, *b*)).

The study area is dominated by old and new terracotta tile roofs. The predominant land use is residential, interspersed with some commercial establishments along the major highways and some industrial facilities, which had metal roofing. Some of the residential dwellings were made of concrete structures, which appear in a random manner in the classified image. Some educational institutions in the study area had roofing materials consisting of concrete and metal while their surrounds were made up of concrete pavers. From the pattern of the land use and distribution of surface materials one can assume that the main threat from

(*a*) (*b*)

Figure 4. (*a*) HyMap image (RGB 2,17,47) over study area of Concord Bay, Sydney. (*b*) Classified (SAM) HyMap image. Colours indicate roof types as follows: blue = terracotta; red = concrete; white and yellow = metal; green = slate.

hailstorms would be to residential areas since terracotta roofs are more susceptible to hailstones.

In many instances by a combination of hyperspectral analysis and scientific visualization (photo-interpretation using elements such as shape, colour, pattern and association) the land use may be determined, which in turn assists the spectral analysis of urban materials. Two twin structures belonging to the Department of Housing were initially recorded as concrete roofs, but the spectral analysis showed that they were indeed some type of metal roof. This was confirmed later to be corrugated iron during the field verification process. Reliable local knowledge was used wherever access to the roofs was impossible.

6.3. *GIS analyses*

The analysis of the hyperspectral data provided a major input in the form of distribution of roof types in the study area. Vulnerability from hailstorms or any other hazard can be assessed by a combination of factors such as roofing materials, land use, population density and demographic characteristics. Risk may be explained with the help of these variables if they can be analysed in combination and not separately from each other. Different layers of roof materials were generated from the classification and exported as a vector to a GIS. Integration of hyperspectral and GIS data revealed spatial patterns indicating vulnerability that was otherwise difficult to detect. For instance, if a certain area contained mainly a less resistant roof material such as terracotta tile, and a high population density with a majority of ethnic background, then the overall vulnerability of the area may be significantly higher as compared to an area occupied by more resistant roofs only. Spatial variations in vulnerability were mapped by spatial overlay technique. The classified image was geo-referenced to the Universal Transverse Mercator (UTM) projection system, zone 56. The census data provided by the Australian Bureau of Statistics (ABS) was used for creating new derived layers such as population density, percentage of less mobile people and socio-economic characteristics which were spatially overlaid (see figure 5(*a*, *b*)). When a seamless and accurate database can be created at a regional level, additional analyses such as shortest path and proximity analysis can be performed. An internet-based model can be used for sending and receiving processed and analysed spatial data rapidly across a wide area. This type of informed decision-making system is being developed at the New South Wales Fire Brigades.

7. Accuracy estimation

Surface truthing by random field check and current aerial photo images exposed over the study area revealed a high accuracy percentage (90%). Selected locations were visited on the field and cross-checked with the image classification. To verify the results of the spectral analysis and classification results, 40 randomly selected points were visited on the ground. The area around the golf courses to the south of the study area comprised terracotta type roofs, which were accurately detected by the SAM classification. The individual structures along Hilly Street were accurately identified by the classification. In some instances where the structures were found to have concrete and metal roofing materials together the classification matched the features accurately. The metal roofs along the highway were identified successfully. There were some areas with slate roofs in combination with concrete and terracotta, which were not clearly identified; this may be attributed to the inadequate spatial resolution of the HyMap image. Slate roofs were also identified accurately but there were many instances where other materials having similar spectral characteristics to slate such as bitumen and asphalt were wrongly classified as slate. It is our belief that a detailed analysis particularly of the spectral shape and curve of such practically non-absorbent materials may yield better results. The field verification confirmed the immense potential in integration of imaging spectroscopy for any urban region and its integration with GIS for informed decision making.

8. Scope and discussion

Emergency services have to make decisions at short notice, and these are influenced by numerous factors, most of which have a spatial and temporal dimension.

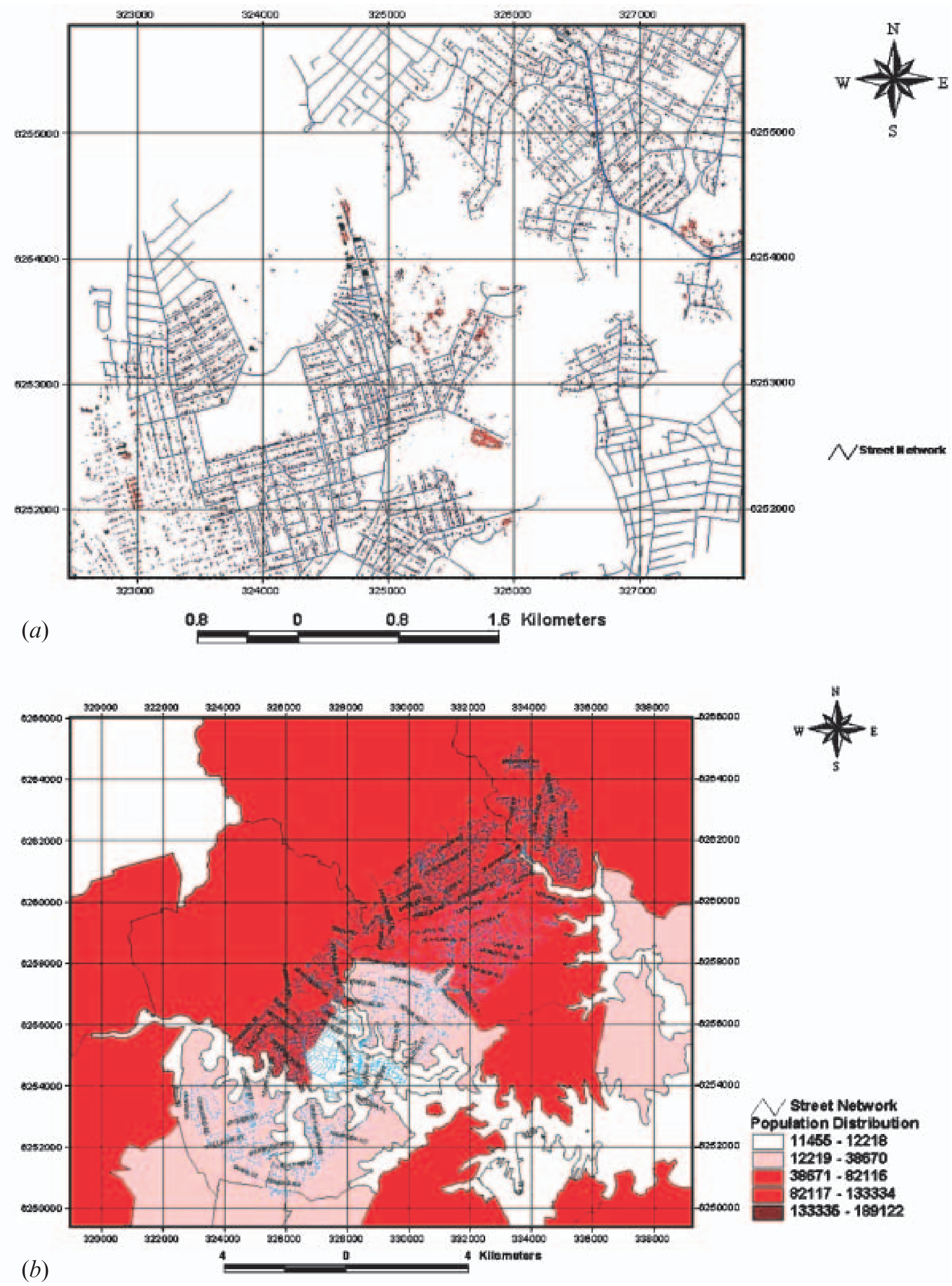

Figure 5. (*a*) Vector map of classified image; (*b*) GIS operations: spatial overlay.

For instance, the issue of resource allocation is influenced by spatio-temporal factors such as location of potential hazard prone regions, existing predominant land use, population density, socio-economic characteristics and so on. Since dynamic resources have to be managed in an efficient way the combined analyses of remote sensing data and GIS data are inevitable. There are many important aspects of such information, such as currency, accuracy and reliability. Integrated spectral analysis of hyperspectral and GIS data enables us to study complex urban areas and plan more effectively for emergencies.

The spatial resolution of hyperspectral data has to be sufficiently high particularly in urban areas due to the variations in the shape and size, heterogeneity and dense pattern of urban features. Systematic appraisal of what features need to be detected and analysed will lead to the selection of an appropriate spatial resolution, which will in turn increase the accuracy of spatial unmixing and will improve the sub-pixel analysis of urban areas. In the present study there were some instances where the spatial resolution was not good enough to determine the spectra of some features. Airborne hyperspectral sensor data have a definite advantage over proposed space-borne hyperspectral sensors in that they are scale-independent and may be flown over any region to the required resolution. This aspect is important for the study of urban areas given the irregularity and dynamism of urban features.

The variations within a surface material such as terracotta due to weathering, colour change, irregularity in the chemical composition and material composition may create problems in accurate analysis and mapping, but with a careful approach they may be addressed to some extent. For instance, tiles belonging to certain categories related to the age, colour or chemical composition may be classified and spectrally analysed separately. This may address the reasons for the differences in urban spectral characteristics of the same material over a period of time. It may be argued that the variables selected in the study may not show comprehensive overall vulnerability, but the objective was to demonstrate the utility and scope of integrating HyMap and GIS data for mapping vulnerability particularly in urban areas.

This indicates that there is tremendous scope for the application of imaging spectroscopy to problem solving but there is a need to approach this technology prudently. On the other hand it is quite clear that imaging spectroscopy and integration with GIS is arguably the best option for the study of urban areas.

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References

ANDREWS, K., and BLONG, R., 1997, March 1990—Hailstorm Damage in Sydney, Australia. *Natural Hazards*, **16**, 113–125.

BEN-DOR, E., LEVIN, N., and SARONI, H., 2001, A spectral based recognition of the urban environment using the visible and near-infrared spectral region (0.4–1.1 μm). A case study over Tel-Aviv, Israel. *International Journal of Remote Sensing*, **22**, 2193–2218.

BHASKARAN, S., and DATT, B., 2000, Sub-pixel analysis of urban surface materials: A case study of Perth, Western Australia. *Proceedings of the IEEE/International Geosciences and Remote Sensing Symposium, Honolulu, USA, 24–29 July 2000* (Piscataway, NJ: IEEE).

BHASKARAN, S., FORSTER, B., KUSUKAWA, M., and NEAL, T., 2001a, Applications of high spatial broad band sensors for vulnerability mapping—a case of hail storm disaster in Sydney, Australia. *Asian Journal of Geo-Informatics*, **1**, 53–61.

BHASKARAN, S., DATT, B., NEAL, T., and FORSTER, B., 2001b, Hail storm vulnerability assessment by using hyperspectral remote sensing and GIS techniques. *Proceedings of the International Geosciences and Remote Sensing Symposium, Sydney, Australia, 9–13 July 2001* (Piscataway, NJ: IEEE).

Bianchi, R., Cavalli, R. M., Fiumi, L., Marino, C. M., Panuzi, S., and Pignatti, S., 1996, Airborne remote sensing in urban areas: examples and considerations on the applicability of hyperspectral surveys over industrial, residential, and historical environments. *The 2nd International Airborne Remote Sensing Conference and Exhibition, San Francisco, 24–27 June 1996* (Ann Arbor, MI: ERIM), Volume I, pp. 439–444.

Boardman, J. W., 1992, Sedimentary facies analysis using imaging spectrometry: a geophysical inverse problem. PhD thesis, University of Colorado, Boulder, CO, USA.

Boardman, J. W., and Huntington, J. F., 1996, Mineral mapping with 1995 AVIRIS data. *Summaries of the 6th Annual JPL Airborne Research Science Workshop, JPL Publication 96-4, Vol 1* (Pasadena, CA: Jet Propulsion Laboratory), pp. 9–11.

Centre for the Study of the Earth from Space (CSES), 1992, SIPS User's Guide, The Spectral Image Processing System, v.1.1, University of Colorado, Boulder.

Conel, J. E., Green, R. O., Vane, G., Bruegge, C. J., Alley, R. E., and Curtiss, B., 1987, Airborne imaging spectrometer-2: radiometric spectral characteristics and comparisons of ways to compensate for the atmosphere. *Proceedings of SPIE*, **834**, 140–157.

Crowley, J. K., and Zimbelman, D. R., 1996, Mapping hydrothermally altered rocks on Mount Rainier, Washington: application of airborne imaging spectrometry to volcanic hazards assessment. *Proceedings of the 11th Thematic Conference and Workshop on Applied Geologic Remote Sensing, Las Vegas, Nevada, 27–29 February 1996*, Vol, II, pp. 460–461.

ENVI Tutorials, 1999, ENVI version 3.2 July, 1999 Edition, pp. 191–302.

Fire News, 1999, New South Wales Fire Brigades. *Sydney Hail Storm Special*, **21**, NO. 12L.

Forster, B., 1983, Some urban measurements from Landsat data. *Photogrammetric Engineering and Remote Sensing*, **49**, 1693–1707.

Fuimie, L., and Marino, C. M., 1997, Airborne hyperspectral MIVIS data for the characterization of urban historical environments. *3rd International Airborne Remote Sensing Conference and Exhibition, Copenhagen, Denmark, 7–10 July 1997* (Ann Arbor, MI: ERIM), Volume II, pp. 770–771.

Goetz, A. F. H., 1992, Imaging spectrometry for Earth observations. *Episodes*, **15**, 1–14.

Heiden, U., Roessner, S., and Segl, K., 2001, Potential of hyperspectral HyMap data for material oriented identification of urban surfaces. *Proceedings of the IInd International Symposium on Urban Remote Sensing, Regensburg, Germany, 22–23 June 2001*, pp. 69–76.

Hepner, G. F., Houshmand, B., Kulikov, I., and Brayant, N., 1998, Investigation of the integration of AVRIS and IFSAR for urban analysis. *Photogrammetric Engineering and Remote Sensing*, **64**, 813–820.

Hunt, G. R., Salisbury, J. W., and Lehnoff, C. J., 1971, Visible and near infrared spectra of minerals and rocks: III. Oxides and Ox hydroxides. *Modern Geology*, **2**, 195–205.

Kruse, F. A., Kieren-Young, K. S., and Boardman, J. W., 1990, Mineral mapping at cuprite, Nevada with a 63-channel imaging spectrometer. *Photogrammetric Engineering and Remote Sensing*, **56**, 83–92.

Kruse, F. A., Lefkoff, A. B., Boardman, J. W., Heidebrecht, K. B., Shapiro, A. T., Barloon, J. P., and Goetz, A. F. H., 1993, The spectral image processing system (SIPS)—Interactive visualization and analysis of imaging spectrometer data. *Remote Sensing of Environment*, **44**, 145–163.

Lo, C., 1997, Application of Landsat TM data for quality of live assessment in urban environment. *Computers, Environment and Urban Systems*, **21**, 259–276.

Ridd, M. K., Ritter, N. D., and Green, R. O., 1997, Neural network analysis of urban environments with airborne AVRIS data. *Third International Airborne Remote Sensing Conference and Exhibition, Copenhagen, Denmark, 7–10 July 1997* (Ann Arbor, MI: ERIM), Volume I, pp. 197–203.

Roberts, D. A., Yamaguchi, Y., and Lyon, R. J. P., 1985, Calibration of airborne imaging spectrometer data to percent reflectance using field measurements. *Proceedings of the 19th International Symposium on Remote Sensing of Environment, Ann Arbor, MI, 21–25 October 1985* (Ann Arbor, MI: ERIM).

Roessner, S., Segl, K., Heiden, U., Munier, K., and Kaufmann, H., 1998, Application of hyperspectral DAIS data for differentiation of urban surface in the city of

Dresden, Germany. *1st EARSel Workshop on Imaging Spectroscopy, Zurich, 6–8 October 1998* (Zurich Remote Sensing Laboratories), pp. 463–472.

VOROBIEFF, G., PATERSON, D., and KNIGHTLEY, R., date unknown, Hailstone evaluation of cladding materials. CSIRO division of Building Construction and Engineering (internal report).