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Segmentation-based and rule-based spectral mixture analysis for estimating urban imperviousness

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Abstract

For detailed estimation of urban imperviousness, numerous image processing methods have been developed, and applied to different urban areas with some success. Most of these methods, however, are global techniques. That is, they have been applied to the entire study area without considering spatial and contextual variations. To address this problem, this paper explores whether two spatio-contextual analysis techniques, namely segmentation-based and rule-based analysis, can improve urban imperviousness estimation. These two spatio-contextual techniques were incorporated to a classic urban imperviousness estimation technique, fully-constrained linear spectral mixture analysis (FCLSMA) method. In particular, image segmentation was applied to divide the image to homogenous segments, and spatially varying endmembers were chosen for each segment. Then an FCLSMA was applied for each segment to estimate the pixel-wise fractional coverage of high-albedo material, low-albedo material, vegetation, and soil. Finally, a rule-based analysis was carried out to estimate the percent impervious surface area (%ISA). The developed technique was applied to a Landsat TM image acquired in Milwaukee River Watershed, an urbanized watershed in Wisconsin, United States. Results indicate that the performance of the developed segmentation-based and rule-based LSMA (S-R-LSMA) outperforms traditional SMA techniques, with a mean average error (MAE) of 5.44% and R^2 of 0.88. Further, a comparative analysis shows that, when compared to segmentation, rule-based analysis plays a more essential role in improving the estimation accuracy.

Keywords: Linear spectral mixture analysis; Segmentation-based analysis; Rule-based analysis; Urban imperviousness

1. Introduction

The increase of urban impervious surface coverage in a watershed has received significant attentions recently (Arnold and Gibbons, 1996). Generally, when the percent impervious surface area (%ISA) coverage reaches 10% or higher, water quality degradation can be detected, and apparent degradation has been found when the %ISA within a watershed approaches 30% (Arnold and Gibbons, 1996). The existence of a significant amount of urban impervious surfaces in a watershed can result in an "urban stream syndrome" with increased hydro-period variability and degradation of water quality (Meyer et al., 2005). Therefore, accurate estimation of urban imperviousness is essential for watershed management and planning.

Recently, %ISA information has been estimated using remote sensing techniques, including manual digitization or automatic image processing. With automatic image pro-

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cessing techniques, such as artificial neural network, regression tree, regression analysis, and linear spectral mixture analysis (LSMA), %ISA has been extracted from medium- and coarse-resolution remotely sensed data with some success (Weng, 2012). Within them, LSMA has proven successful in mapping urban imperviousness in urban areas (Wu and Murray, 2003; Weng, 2012). LSMA assumes that the spectra of a mixed pixel is a linear summation of the spectra of each pure land cover (e.g. endmember) within that pixel, weighted by percent areal cover (Roberts et al., 1998). For urban environments, Ridd (1995) developed a vegetation–impervious surface–soil (V–I–S) model, which assumes that each pixel in an urban/suburban area is composed of three basic land cover types, namely vegetation, impervious surfaces, and bare soil. When applied to satellite remote sensing imagery, however, impervious surfaces have rarely been considered as an individual endmember as they include a large number of materials with significantly different spectra. To address this problem, Wu and Murray (2003) developed a vegetation-high albedo- low albedo-soil (V-H-L-S) model to characterize urban environments of Columbus, OH, United States, and found that urban impervious surfaces can be estimated through summing the fractional covers of high albedo and low albedo materials. Recently, Zhang et al. (2014) applied a high albedo-low albedo-vegetation (H-L-V) model to estimate %ISA in high-density urban areas, and a high albedo-low albedo–vegetation-soil (H-L-V-S) model to quantify %ISA in low-density urban areas.

Although a variety of LSMA models have been developed for accurate estimation of %ISA. Several problems still exist. One major problem is the selection of endmember classes and their corresponding spectra. In urban areas, for example, major endmember classes include high-albedo materials, low-albedo materials, vegetation, and soil. High-albedo materials, however, may include clouds, metals, concrete, glass, dry soil, and/or sand, etc., and low-albedo materials may include asphalt, shade, moist soil, water, etc. To address this problem, a number of techniques, including normalized spectral mixture analysis (NSMA), derivative spectral unmixing (DSU), and weighted spectral mixture analysis (WSMA), multiple endmember spectral mixture analysis (MESMA), have been developed (Somers et al., 2011; Feizizadeh and Blaschke, 2013). All of these techniques, however, can be categorized as global techniques, without considering spatio-contextual variations. Spatio-contextual information, however, has proven essential in remote sensing image classification, information extraction, and change detection applications (Atkinson and Naser, 2010; Moser et al., 2013). Although important, spatio-contextual techniques have been rarely incorporated into LSMA for estimating %ISA (Shi and Wang, 2014). Several exceptions include the spatially adaptive spectral mixture analysis (SASMA) and prior-knowledge-based spectral mixture analysis (PKSMA) (Deng and Wu, 2013; Zhang et al., 2014), and spatial spectra mixture analysis (Shi and Wang, 2014). This research explores whether two spatio-contextual analysis techniques, (1) segmentation-based analysis and (2) rule-based analysis, can provide a better selection of endmember classes and their spectra, and further improve the accuracy of %ISA estimates. Specifically, image segmentation was initially applied to divide a remote sensing image into a number of homogeneous segments, and within each segment, the types and spectra of each endmember classes were selected. With the segment-based endmembers, an LSMA was then applied for each individual segment. With the resultant fractional values of each endmember, a rule-based analysis was applied to derive the %ISA. The advantages of the proposed segmentation-based and rule-based LSMA (S-R-LSMA) method lie in its ability in better incorporating spatio-contextual information in addressing spectral and spatial variability issues associated with LSMA.

2. Study areas and data

Milwaukee River Basin, Wisconsin, United States has been selected as the study area for this research (see Fig. 1). Milwaukee River Basin is located in Southeastern Wisconsin along Lake Michigan, and covers a geographical area of 2280 km^2. Within the basin, urban land covers (Milwaukee City) can been found in the southern portion, and rural land covers, including forest lands, planted/cultivated lands, open water, and wetlands, dominate the northern part.

A Landsat Thematic Mapper (TM) image acquired on November 6, 2001 was employed in this study. This image has a spatial resolution of 30 m and 7 multispectral bands. In addition to the Landsat image, aerial photographs acquired in 2001 were obtained for assessing the model performances. These two datasets were obtained from the American Geographical Society Library (AGSL) at University of Wisconsin-Milwaukee. All of these datasets were re-projected to the Universal Transverse Mercator (UTM) projection with a datum of World Geodetic System 84 (WGS84).

3. Methods

To incorporate spatio-contextual information into LSMA, we implement the S-R-LSMA method, which consists four steps, including (1) Image pre-processing, (2) image segmentation and segment-based endmember extraction, (3) fully-constrained LSMA, and (4) rule-based analysis. The diagram of these steps is illustrated in Fig. 2.

3.1. Image preprocessing

In order to carry out the S-R-LSMA model, a prerequisite step is to pre-process the acquired images. First, we performed an atmospheric correction using the ATCOR module provided by ERDAS Imagine, a commercial remote sensing image processing program. Results indicated that no atmospheric correction was necessary due