Urban Growth Detection Using Texture Analysis on Merged Landsat TM and SPOT-P Data

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Abstract

This study illustrates an automated technique in which urban growth is effectively mapped and monitored. The methodology utilized digitally merged TM and SPOT-P data, resampled to 10 meters, for each of two years, 1990 and 1995. For each date, a two-step texturing analysis resulted in a binary "built/non-built" map defining urban versus non-urban super pixels. The results from the study clearly defined "growth" pixels for the five-year time interval. An accuracy of 92 percent was achieved. These "growth" pixels were then compared to a growth "potential" map produced by a GIS analysis based on environmental inducements and constraints to growth. Portions of the study area that were rated highest in growth potential in fact experienced the largest amount of urban expansion, both in total area and in percent of class.

Introduction

Urbanization is occurring on all five of the major continents. As of 1990, 77 percent of the North American population lived in cities greater than 50,000 (de Blij and Muller, 1994, p. 27). Like most cities in the United States, Salt Lake City is expanding rapidly into adjacent landscapes. This change in land use is of concern to planners and various government agencies, because this growth has profound impacts on the available water resources, agricultural land, and limited remaining space. A spatio-temporal analysis of growth patterns is essential in order to develop sufficient infrastructure to support the growth. Of particular interest to planners are the available tools and information that can be used to monitor such growth.

The characterization and classification of urban areas has received attention since the early Landsat years with MSS data (for examples, see Gordon (1980), Forster (1980) Jensen and Toll (1982), Forster (1983), and Ridd *et al.* (1983)). With the introduction of higher spatial resolution imagery, such as TM and SPOT data, and other technological advancements, came more detailed investigations of the urban area such as spatial/spectral data merging (Welch and Ehlers, 1987; Chavez *et al.*, 1991; Zhang, 2001). Urban growth analyses became more sophisticated with the use of a variety of image processing techniques (Martin, 1989; Fung and Zhang, 1989; Gong and Howarth, 1990; Gong *et al.*, 1992; Mouat *et al.*, 1993; Kwarteng and Chavez, 1998). Madhavan *et al.* (2001) examined urban growth mapping and modeling using the V-I-S analysis (Ridd, 1995). Still other techniques include post-classification feature extraction (Zhang, 2001) and post-classification comparison (Ji *et al.*, 2001), principal components analysis (Li and Yeh, 1998), and integration of remote sensing and GIS (Weng, 2001) for the purposes of monitoring urban expansion.

The purpose of this paper is to explore a simple and effective method to (1) distinguish "built" from "non-built" pixels at a meaningful scale of resolution to serve professional planning, and, (2) to apply the technique to imagery from two dates in order to monitor and measure urban growth patterns accurately enough to serve as a planning instrument. A texture analysis procedure is presented for this purpose. No attempt is made to identify the type of urban use, or any classification other than a binary decision: whether a pixel represents a built feature, or not. The implication is that the "built" pixel represents an urban feature and the "non-built" feature does not. For this study, the term "built" is operationally defined as features with a concentration of roads and structures sufficient to be considered urbanized. Pixels exhibiting a change from non-built to built between two dates may be said to represent urban growth for that time interval. It will be shown that the distinction between the terms *built* and *urban*, although a fine point, is quite significant with regard to texture. Toward the end of this paper, the growth pixels are compared to a map of growth "potential" that was previously created from a dataset of environmental inducements and constraints to growth, and also the accuracy assessment.

Study Area

The Wasatch Front in Utah is one of the areas of rapid urban growth in North America. This study focuses on Metropolitan Salt Lake City, specifically Salt Lake County and southern Davis County. The study area has a diverse topography. The Wasatch Mountains bound the area on the east, while the Oquirrh Mountains border the west side. The Great Salt Lake and surrounding wetlands create a natural intrusion into the northwest corner of an otherwise long, narrow buildable urban area. What results for this study area is a corridor approximately 50 kilometers north-south and 25 kilometers east-west (southern section), and about 10 kilometers (northern section adjacent to Great Salt Lake). A substantial variety of landscapes exist in this mid-latitude city, including foothills, rangelands, dry farms, irrigated farmlands, wetlands, and shoreline features. The most complex landscape, however, is that of the pattern of urbanization, with a highly fragmented rural-urban fringe. Urban growth along the Wasatch Front has increased steadily over the past several years. From 1990 to 1996, Salt

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Photogrammetric Engineering & Remote Sensing
Vol. 68, No. 12, December 2002, pp. 1283–1288.

0099-1112/02/6812–1283$3.00/0

Lake City experienced a population increase of 7.9 percent (U.S. Bureau of Census, 1997). More remarkable, however, is the increase in the cities of West Jordan and South Jordan at 34.2 percent and 92.5 percent, respectively, during the same period. This study is aimed at monitoring urban growth from 1990 to 1995 across a very diverse study area.

Data Description

For each of the two dates, 1990 and 1995, both SPOT-P and Landsat TM data were selected. The SPOT-P data are used for their 10-meter spatial resolution in order to enhance cartographic detail. The TM 30-meter data are used for their multi-spectral, environmental value, because one of the intended uses was to observe land-cover character as an environmental backdrop to the urban growth pattern. The TM and the SPOT-P data were digitally merged for each of the two dates. It should be noted that, for the central purpose of this study, to distinguish built from non-built features through texture analysis, the panchromatic SPOT data alone would be sufficient and the 10-meter spatial resolution would be effective. However, because the project was funded by planning agencies (note acknowledgment at the end), with a desire to show environmental conditions giving way to urban expansion, it was determined to merge the TM data with the SPOT-P data at the outset. The fused image aided in the interpretation phase as well as for the display of results for the planners. Clearly, it is the SPOT-P data that drive the texture analysis.

In 1990, TM data were collected in mid-summer, 20 June, to capture full vegetation canopy. In contrast, the SPOT-P data were collected on 03 April, early spring, in order to avoid interference from vegetation in distinguishing urban structures. For 1995, the TM data were collected in June, coincident with the June 1990 data. Unfortunately, cloud-free SPOT-P data were not available for early spring. Consequently, autumn data from November were used to capture vegetation in a leaf-off condition. The six-month difference in the collection period of SPOT-P data caused potential for shadowing differences due to differences in the sun angle, which probably played into classification errors to be noted later. This circumstance was unavoidable. Contemporary black-and-white aerial photography was available for the entire study area for both dates. The photography served for general orientation as well as the basis for accuracy assessment.

Methodology

The first task was to co-register all data sets to a common geodetic base from the variety of county and city base maps. The base map sources included NAD (North American Datum) 27 and NAD 83, some in State Plane coordinates, others in the UTM (Universal Transverse Mercator) projection. The transformation of all data sets was to the WGS (World Geodetic System) 84 datum and UTM projection. SPOT-P data were rectified to ground control points (GCPs) for each date, and TM data were co-registered to the SPOT-P data and then resampled to 10 meters. Co-registering the 1995 data to 1990 data was achieved to a root-mean-square error (RMSE) of 0.269 pixels. A high-pass filter was performed on both of the SPOT-P data sets, for the purpose of accentuating cartographic detail. A low-pass filtering procedure was performed on the TM data in order to smooth blockiness after resampling from 30-meter pixels to 10-meter pixels, prior to merging the TM and SPOT data sets (after Chavez *et al.*, 1991). Six TM bands were merged with the panchromatic band of SPOT for each of the two years. Figure 1 displays the 1990 merged data for a portion of the study area and can be compared with Figure 2 of the same area for 1995. Band 5 was removed from the 1990 merged data set (and also the 1995 merged data set) for the purpose of performing a texture analysis. Band 5 was selected due to its utility in identifying urban features, such as roads (Moller-Jensen, 1990).

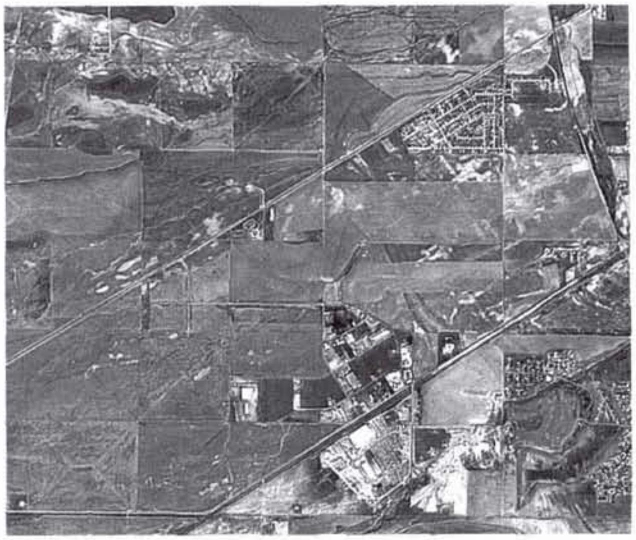

Figure 1. Merged TM and SPOT-P data for 1990 showing evidence of suburbanization.

Figure 2. Merged TM and SPOT-P data for 1995 showing evidence of continued urban growth.

Texture Analysis

The differentiation between built and non-built areas is detected through a texturing procedure. Two types of texture analysis were used. The first procedure was performed on band 5 of the merged data sets for each of the two years. This process entails a systematic assessment of brightness values in a moving 3 by 3 window, with the variance of the nine pixels being assigned to the central pixel. Each pixel is assigned a new brightness value, constituting a "gray map" on a 0 to 255 scale. This first texturing procedure is part of the ERDAS IMAGINE® image processing software.

The second texture process, performed on the product of the first texture procedure for each date, consists of an algorithm defined in Ridd *et al.* (1993) called TEXT. The algorithm allows the user to select a super pixel size (e.g., 2 by 2, 3 by 3, ..., N by N) that moves systematically throughout the image, assigning the variance of pixels within each super pixel to the super pixel. The first texturing procedure performed in ERDAS measures continuous variation, while this second texturing procedure measures variation in discrete "blocks" or super pixels. Super pixels with high variance indicate high spatial frequency, typical of urbanized features. Low variance suggests non-urbanized places.

The next task is to determine a threshold for distinguishing between built and non-built super pixels with a user-defined threshold (e.g., 60 percent, 70 percent, ...). If the super pixel value is greater than the user-defined threshold value, the super pixel window is classified as "built." If the value is less than the threshold value, then the super pixel is classified as "non-built." Each super pixel is evaluated only once in the built/non-built classification. The resulting product is a digital, binary (built/non-built) map. The optimal combination of super pixel size and percentage threshold is determined by trial and error through overlaying the individual products on the image in various places and checking against aerial photography.

Growth Detection and Analysis

The year 1990 serves as the baseline date for this study (Figure 1). The pixels designated as built for 1990 were removed from the 1995 merged data set through a masking procedure in ERDAS IMAGINE®. The texture analysis was performed on the remainder of the 1995 image using the same procedure, producing a similar binary map. The super pixels defined as built in the 1995 masked image represent urban growth during the five-year interval.

Figure 3. Merged TM and SPOT-P data for 1995 with the growth up to 1990 masked out (white pixels) and the growth from 1990 to 1995 identified by the TEXT algorithm (black pixels).

Results

1990 Data Texture Analysis

Upon completion of the first texture analysis measuring continuous variance, the TEXT algorithm was invoked. Several iterations of the texturing algorithm, TEXT, were performed and checked against various portions of the study area. The combination of pixel size and threshold that best accomplished the separation of built and nonbuilt areas was a 3 by 3 superpixel with a 60 percent threshold. Based upon a random sample of 100 points across the study area, an overall accuracy of 94 percent was achieved, as assessed against a 1990 valley-wide aerial photo mosaic as ground truth.

While the 94 percent accuracy is notable for an automated procedure, a certain amount of "hand-editing" was done in order to correct the 6 percent margin of error, because this data set would be used as a baseline by which to measure the growth from 1990 to 1995. There were errors of omission and commission. The omission errors were surfaces such as golf courses with their uniform cover of grass. From a built/non-built standpoint, these may not be considered errors, given the operational definition of "built" in the study. However, the planners on the project, unable to think of such sites as non-urban, suggested these sites be filled in. In the edited version, these were filled in as built. Commission errors were features such as wetland margins and some stream courses. The entire valley was evaluated and assessed in terms of accuracy, and errors were corrected.

1995 Data Texture and Growth Analysis

Figure 3 shows the same portion of the study area as Figures 1 and 2, using the 1995 merged dataset with the 1990 urbanized area masked out (white pixels), with the growth pixels (black pixels) identified by the TEXT algorithm.

The same accuracy assessment procedure using 100 random points that was used for the 1990 binary image was used for the 1995 built/non-built image, using 1995 aerial photos for ground truth. Table 1 shows the results of the accuracy assessment. The classified data results are shown as rows in the matrix and the reference data (ground truth) are shown in the columns. In the classified map, nine random points fell within the built area, while 91 points fell in the non-built area. The disproportionate share of the randomly selected points is due to the fact that the proportion of growth in relation to the remaining non-built area is small. Of the non-built land in 1990, 8.3 percent became built by 1995.

Of the nine points classified as built, seven points were actually built. These seven "built" points fell in areas of new construction in the study area, including subdivision extensions at the urban fringe (as clearly seen by comparing Figures 1, 2, and 3), new shopping facilities, ground disturbed for airport expansion including a new runway, and infilling of older residential neighborhoods with new housing. Of the 91 points classified as non-built, 85 actually remained non-built. These points fell in areas such as agricultural fields, mountain foothills, untouched and naturally vegetated lands, and large portions of undisturbed private property.

Also indicated in Table 1 are the errors of omission and commission. Two of the nine pixels classified as built were actually not built, resulting in a 22 percent error of commission. Six of the 91 pixels classified as non-built were actually built, resulting in a 7 percent error of commission.

TABLE 1. 1990–1995 GROWTH ACCURACY ASSESSMENT

	B	N	Σ	Commission Errors	User's Accuracy
B	7	2	9	22%	78%
N	6	85	91	7%	93%
Σ	13	87	100		
Omission Errors	46%	2%			
Producer's Accuracy	54%	98%			

92% Overall Accuracy

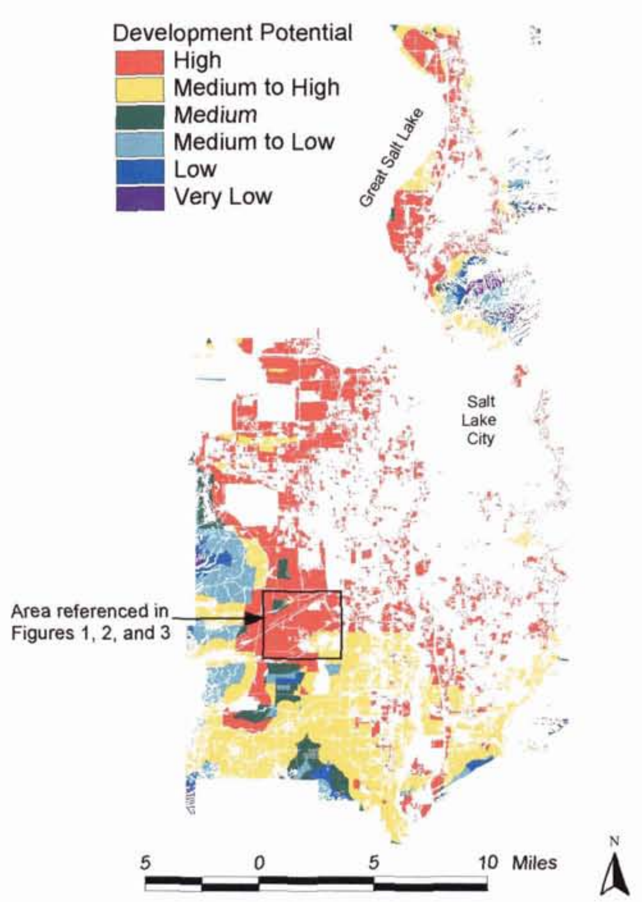

Plate 1. Development potential map for the Salt Lake Valley created from GIS layers of environmental inducements and constraints (Farmer *et al.*, 1997). Red indicates high potential for urban development and purple indicates very low potential.

Concerning the two errors of commission for the "built" pixels, these errors relate to a change in patterns of moisture content in wetland areas. That is, the texturing process and consequent function of the algorithm that separates built pixels from non-built pixels is sensitive to changes in surface moisture, such as around the margins of playas in the northwest portion of the study area around Great Salt Lake. Thus, the boundary, and only the boundary, not the entire playa, was classified as built, when it is not built.

Regarding the six built pixels mis-classified as non-built (an omission error of 46 percent), three occurred in well-established neighborhoods or commercial areas, while the remaining three errors occurred in areas of new growth. In reference to the three errors that occurred in well-established residential and/or commercial areas, two of the three fell on vegetated areas such as parks, or mature trees, which have quite uniform texture. The remaining error occurred on the border of a mature subdivision.

The remaining three errors occurred in new subdivisions next to established subdivisions, where the land is cleared but so little construction of roads and buildings has begun as to present a rather uniform texture. Examples can be seen in Figure 3 as compared to Figures 1 and 2. This point demands some explanation as relating to the terms *built* and *urban*. From the planners' point of view, the land is committed to urban use, and therefore should be so considered. From the viewpoint of the definition of *built*, the site is not yet built, and should be designated as non-built. Thus, three of the six pixels "mis-classified" as non-built are in fact non-built, based on the texture analysis. The algorithm is doing its job. This can be seen in Figure 3 where several patches of cleared land on the edge of subdivisions have spots of (black) pixels where homes are begun. Looking back to Figure 2 demonstrates the accuracy with which the algorithm has actually detected the actual homes under construction vs. the cleared land not yet built upon, therefore non-built. From the planners' view these may be errors of omission. From the definition set forth at the outset of the paper, they are correctly classified.

Growth Potential Analysis

This part of the paper extends beyond the central purpose of the study, but provides a useful application. A GIS analysis of development potential produced by Farmer *et al.* (1997) is seen in Plate 1. The purpose of the analysis was to develop a digital database of environmental factors that either induce or constrain urban growth. The inducements to growth were existing roads and a land-use master plan. The environmental constraints used in the analysis were factors such as susceptibility to faulting, flood-prone zones, slopes greater than 30 percent, wetlands, and the Wasatch National Forest. Each of these factors was given a weighted value in accordance with a simple linear model. The weighted value of each of the development factors was determined by consultation with a local transportation planning agency. Existing roads and land-use layers were given higher weights, while other geophysical factors were assigned lower weighted values. Development potential was ranked, based on the model, with six categories ranging from low to high as seen in the development potential map in Plate 1. The purpose here is not to explain or evaluate the simple growth model, but to take it as given, and determine whether the growth patterns as determined from the present study fell into growth categories as predicted (Farmer *et al.*, 1997).

The growth pixels resulting from this phase of the project were then divided according to growth potential class based on a development potential map. Results from this analysis are seen in Table 2. Growth per class was assessed based on number of hectares. Column two shows the total area in each class, in hectares. The "Percent of Total Area Urbanized" column is a statement of the percentage of land area within each growth

TABLE 2. 1990–1995 GROWTH PER GROWTH POTENTIAL CLASS—AREA IN HECTARES

Growth Potential Class		1990 Area In Hectares	Growth 1990–1995 In Hectares	% Total Area Urbanized 1990–1995
1	Low	156	8.3	5.3
2		417	23.6	5.7
3		804	27.6	3.4
4		1,164	22.8	2.0
5		8,798	773.6	8.8
6	High	10,980	1,000.4	9.1
All Classes		22,319	1,856.3	8.3

potential class that became "built" during the five-year period. A moderate amount of growth occurred in areas least likely to experience growth, namely, classes 1 and 2 with 5.3 percent and 5.7 percent of their total respective areas becoming built. Low growth occurred in areas identified as a moderate likelihood of growth. By far, however, the largest amount of growth took place in classes 5 and 6, which, according to the growth potential model, were most likely to experience urban growth, with 8.8 percent and 9.1 percent, respectively, becoming urbanized during the period. Nearly 1800 hectares (4500 acres) became urbanized in classes 5 and 6 over the five-year span.

Discussion

It is acknowledged that fusing the TM data with the SPOT-P data was unnecessary for the texture analysis and determination of built/non-built mapping. However, adding the TM multiband data to support the planning interests in the study provided a useful backdrop for super pixel and threshold determination, as well as for interpreting and understanding the results.

Several conclusions may be drawn from the study. First, the texture procedure employed with 10-meter satellite data is quite effective in differentiating built from non-built pixels in the metropolitan complex of the Wasatch Front, with accuracies in excess of 90 percent. At this level of spatial resolution, urban and regional planning purposes are well served in determining the extent of the built environment. Application of the technique over time provides an effective tool to identify, map, monitor, and quantify patterns of growth and change. The procedure and products have been sufficiently useful to the participating planning agencies to fund the project into four phases thus far.

Second, the distinction between *built* and *urban* definitions becomes central to the question of accuracy. For the planners' purposes the term "urban" is more meaningful in the context of land use. Lands committed to golf courses, large school grounds, and open parks are certainly urban in terms of land use. However, in the context of concentrations of streets and structures, they are not built upon. Accuracies displayed in Table 1 are conservatively stated, in favor of the planners' preference. Actually, in the context of the built versus non-built distinction, the texturing algorithms have done better than the table indicates. One lesson from this task is to stay with the science and technology for the interpretation and accuracy of the stated objective, and let a GIS overlay alter the remote sensing product for the planners' purposes. Explanation of errors could then focus on technical matters such as rectification and co-registration, seasonal affects of shadow angle and moisture change, and key issues of super-pixel selection and threshold.

Regarding the latter, it is clear that the selection of super pixels is tied to the question of spatial detail desired. Threshold determination, on the other hand, is more of an experimental, subjective judgment. When in doubt, in applying samples of different thresholds to various portions of the image, the investigator may lean toward the conservative, less built, or the liberal, more built choice. In the processing of the 1990 data, the 3 by 3 super pixel and 60 percent threshold worked very well across the variety of environmental mixes in the study area.

A final note about spatial resolution and super-pixel selection is in order. While remote sensing investigators in urban areas from early on eagerly awaited higher spatial resolution, for purposes of texture analysis, resolutions better than 10 meters may well be counter productive. At one meter, a tractor in a farm field may appear as "built." And at some regional level of analysis, a 30-meter or greater IFOV may be optimal. From the present study, it appears from Figures 1, 2, and 3 and the accuracies achieved, that 10 meters is quite suitable for general planning and growth analysis.

Acknowledgment

This project was funded by The Wasatch Front Regional Council (a multi-county transportation planning agency) and the planning division of the Utah Department of Transportation.

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(Received 26 September 2001; revised and accepted 23 March 2002)