

Land Use Dynamics of Chester County, Pennsylvania, from a Satellite Remote Sensing Perspective

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Abstract

The potential for using satellite data in regional planning is suggested by analyses of land cover change for a rapidly urbanizing county in Pennsylvania. Land classification maps can be generated from satellite imagery with relative ease on an annual basis, enabling communities to track the loss of their forested and agricultural lands, and the growth of residential areas and urban centers in a timely manner. Additionally, the satellite enables planners to compare spatially and temporally such environmental indicators of urbanization as surface temperature, vegetation fraction and impervious coverage. Estimates of changes in a region's evaporative energy losses, which can be related to stormwater runoff, are also possible if the satellite data is combined with a surface climate model. Urban planners and environmental agencies can use the demonstrated techniques to monitor their region's microclimate - bearing in mind its implications for human comfort and the creation of sustainable living conditions.

Introduction

In the early 1900s, H. G. Wells envisioned that our cities' physical forms would evolve through a process of diffusion, such that they would eventually take on many of the characteristics of what he termed "country" (Levy, 1994). Today, the diffusion of urban centers has advanced so far that the boundaries of older cities have begun to overlap, and the modern metropolis is really a vast urban field with multiple centers (Spire, 1984). The traditional model of a downtown core surrounded by concentric rings of growth - as reflected in the meteorological adage, the urban heat island - is no longer applicable. Instead, sprawling urban areas have become interconnected features of today's world. This interconnection is more than just visual, as displayed by maps of urban extent like Figure 1; it is also environmental. For example, a key element in the current debate over uncontrolled growth is the impact of urbanization on regional land cover. Land cover, i.e. grass, concrete, soil, etc., largely dictates the energy exchanges that occur between the earth and atmosphere and thus, is one of the primary determinants of a region's microclimate. Individual land use decisions and their microclimatic effects then become integrated into "mesoclimatic zones" that "mirror" the form of urban development (Chandler, 1976). Through satellite remote sensing, this additional component of urban interconnectedness can be monitored.

In regional planning, multi-spectral satellite imagery is

generally regarded, if it is at all, as a potential source of data for generating land cover maps. These maps show the distribution and amount of such basic land cover types as urban development, forest, low vegetation, bare soil and water. The thermal and near infrared bands, however, contain additional quantitative information on the surface microclimate. This data extends the utility of the image beyond that of a qualitative aerial photograph and allows a region's mesoclimatic zones to be visualized. The ability to derive useful environmental indicators of urbanization from multi-spectral satellite data has been well established (Carlson and Arthur, 2000; Owen *et al.*, 1998; Carlson *et al.*, 1997). Some of the more traditional parameters include fractional vegetation cover, radiant surface temperature and evapotranspiration fraction. An analysis of these parameters over time for pixels that represent developing regions can be used to assess the trend in the environmental impact of urbanization.

Since regional land cover changes brought about by human activity tend to occur incrementally, it can be difficult for communities to realize the extent of their development and therefore the changes in their environment. Information derived from the satellite can thus potentially provide a frequent assessment of urban development from a conventional land use perspective, as well as from a more comprehensive environmental viewpoint. Such up-to-date information can then enable regional planners, and other interest groups, to make informed decisions from an extensive

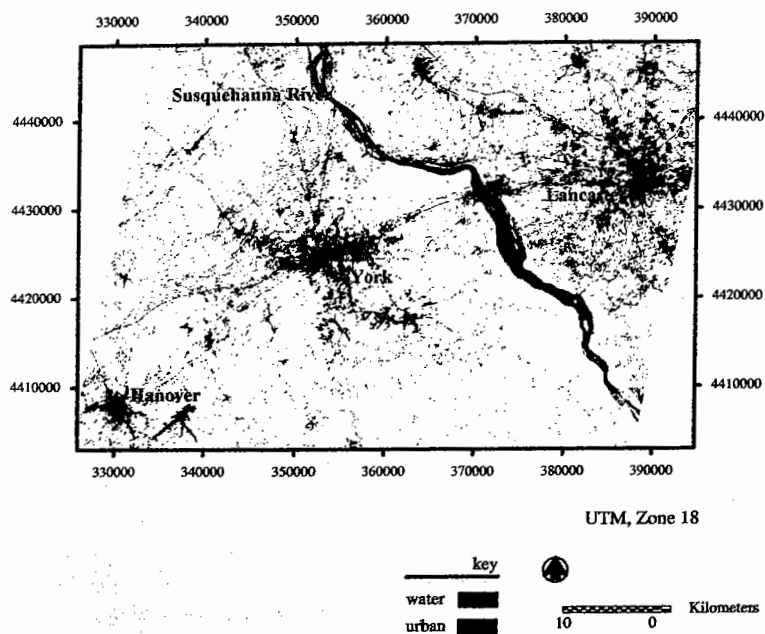


Figure 1 Urban extent for parts of Lancaster, York and Adams counties in southeastern Pennsylvania. Urban coverage is based on a 1987 Landsat TM derived land cover map. The Susquehanna River is also shown as a natural barrier to urbanization.

foundation. The purpose of this paper, which constitutes part of a larger study on the microclimatic effects of urbanization (Carlson and Arthur, 2000), is to present an analysis of the land cover changes for a rapidly urbanizing county in Pennsylvania. The analyses involve land cover classifications derived from Landsat TM imagery, as well as additional physical parameters obtained from collateral measurements by the NOAA-9 and NOAA-14 satellites' Advanced Very High Resolution Radiometer (AVHRR). The intent of relating such information is to foster an appreciation for the capabilities of satellite remote sensing in the realm of urban geography.

Land cover mapping

A source of image data for mapping and analysis of land cover changes has been available ever since the launching of the first earth observation Landsat satellite in 1972 (Fox, 1991). The addition of the Landsat Thematic Mapper (TM) sensor ten years later improved the ability to discriminate between land surface types due to its greater spectral and spatial resolution. The TM can sense seven separate bands in the electromagnetic spectrum ranging from visible to thermal infrared and at nadir, or zero scan angle, has a surface resolution of approximately 30 meters for all bands except the thermal, which is at 120 meters. Local satellite overpass is every 16 days at approximately 10 a.m. with a swath width of 185 kilometers. With these features, the TM is capable of providing geographical data to a potentially wide range of users, many of whom may unfortunately be limited in their ability to access, process and interpret the imagery. Since many mapping and analysis tools involving remote sensing from space are not yet widely in use, it remains for specialists in satellite image processing and interpretation to increase awareness of and provide instruction in the applications of

space methods (Denegre, 1994).

As an example here, the evolution of land cover for Chester County, Pennsylvania, is presented based on maps derived from Landsat TM imagery for the years 1987, 1988, 1991, 1993 and 1996. Each image was registered to a zone 18 UTM map base using USGS 1:100,000 maps for reference. At least 20 ground control points clearly identifiable on both the image and the corresponding map were chosen for each year, and the coefficients of second order polynomials relating map and pixel coordinates were determined using least squares estimation. The same transformation was applied to all bands, and images were resampled to a 25-meter grid using the nearest neighbor criteria. These georeferenced TM images were then used to generate the land cover maps.

Such satellite-derived maps are based on the belief that different surfaces have distinguishable and separable spectral characteristics. Using the ERDASTM Imagine image processing program, a supervised classification was performed by demarcating selected areas of known land cover using manually drawn polygons; in order to ensure representativeness, several areas were chosen throughout the image for each land cover type. Collectively, the pixels within each of these polygons were assumed to represent the spectral characteristics of the given land type. Normal probability distributions describing the chance of finding a pixel from a particular land class at a certain position in multi-spectral space were then estimated from the polygon "training sets." The remainder of the image pixels were placed in the land cover category that their spectral characteristics resembled most closely, based on the statistical criteria of the maximum likelihood decision rule (Richards, 1993). *A priori* knowledge was not assumed, so weighting factors for all classes were left at one, and since thresholding techniques were not applied, all pixels were classified irrespective of how small the actual probability of class membership was.

The result was a thematic rendition of the satellite image with each pixel having a single value associating it with a particular surface type. The map for the base year of 1987 is shown in Figure 2. It possible to achieve more land class separation using this technique than is displayed in the figure. However, most of the work presented here combines several classes into four Anderson Level I land cover categories: urban or built-up land, agricultural land, forest land and water (Anderson *et al.*, 1976). The agricultural category is a composite of the bare soil and vegetated classes that are shown in Figure 2, while the urban or built-up category is actually made up of

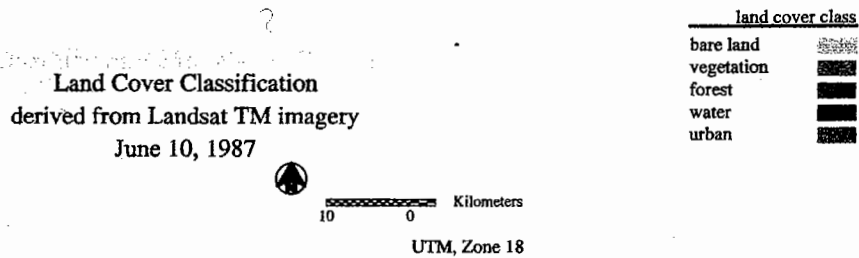
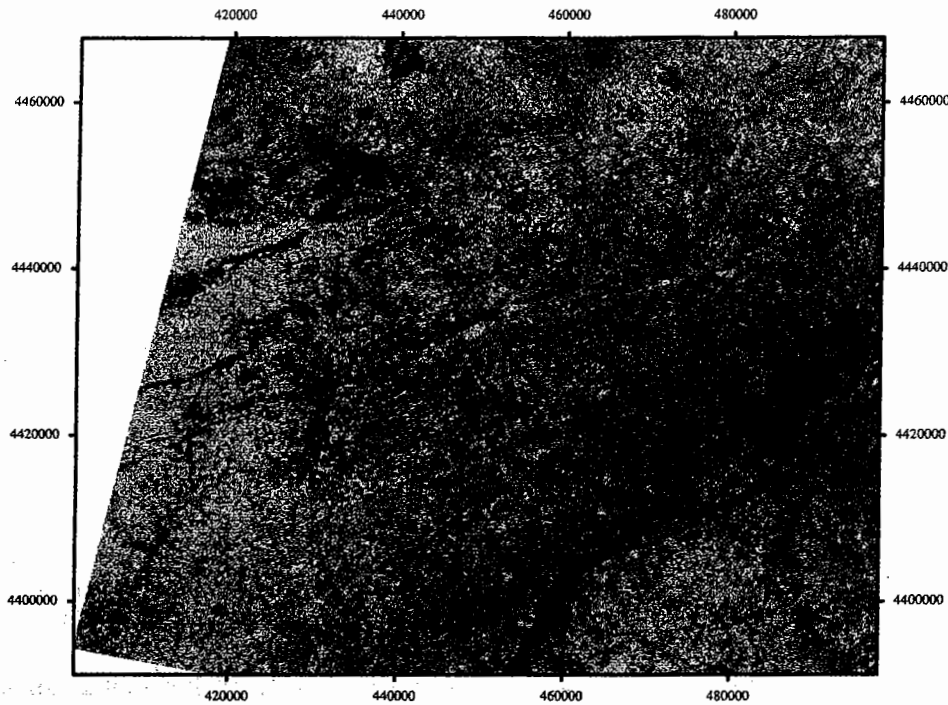


Figure 2 Land cover map of Chester County in southeastern Pennsylvania. Chester County is outlined in black, and the surrounding areas, which exert influence on the county's land use patterns, are also shown. The Delaware River is in the east, with the urban centers of Philadelphia, Pennsylvania, (NE) and Wilmington, Delaware, (SE) stretched along it.

more descriptive subsets that are not displayed here (dense commercial development, major roads and residential development).

The county, outlined in black, is located in southeastern Pennsylvania with the state of Maryland bordering to the south and Delaware to the southeast. The western half of the county is largely agricultural and forested, while most development is located in the eastern region and along the Chester Valley, which runs west-east through the middle of the county. The Schuylkill River borders the county along the northeast where high levels of development are also noted. The region's land use patterns reflect external influences with continued suburban expansion outward from Philadelphia in the east, as well as the development of Delaware's bedroom communities in the southeast.

Urban Growth

Table 1, based on the TM derived maps, displays the

Table 1 Chester County, Pennsylvania, from 1987 to 1996. The percentage of land in each class is given based on the TM derived land cover maps that were generated using a supervised maximum likelihood classification scheme.

	Urban or built-up	agricultural (bare/vegetated)	forest	water	cloud
1987	10.9	71.8	16.8	0.5	0.0
1988	11.6	70.8	16.9	0.6	0.1
1991	15.1	69.3	15.1	0.5	0.0
1993	16.3	67.5	14.7	0.4	1.1
1996	19.0	65.9	14.7	0.3	0.1

incremental changes in the four main land cover classes that occurred in Chester County between 1987 and 1996. During this nine year period, urban or built-up land increased from approximately 11% of the county's pixel-based land parcels to 19%, while agricultural (bare/vegetated) land decreased from approximately 72 to 66%, and forest decreased from

approximately 17 to 15%. This loss of predominantly agricultural land to urban or built-up land agrees with the assessment of the Chester County Planning Commission that the region's growth patterns reflect a spread of development into rural areas, many of which are becoming more suburban in character (Chester County Planning Commission, 1988).

In order to determine specifically where the urban growth was occurring, a more in-depth change analysis was applied to the TM derived land cover maps. First, the classified pixels were aggregated to 1-km² blocks by calculating the percentage of each class within the given area. The change in urbanization for a specific site was determined by subtracting the initial year's 1-km² percent urban or built-up land value from the final year's. McNemar's test (Agresti, 1990) was used in order to be certain that the changes were a result of expansion from a pre-existing urban base, rather than just due to fluctuations from year to year because of classification errors. The test is one of marginal symmetry for a 2 x 2 table based on repeated observations, i.e. dependent samples. The matrix shown in Table 2 was generated for each 1-km² area using the 1600 classified TM pixels within the 1-km² block for the two years in question. The main diagonal elements (shaded) represent pixels that did *not* experience a change in class between the two years; the unshaded elements are those pixels that changed from not developed to developed or vice versa.

In McNemar's test, a null hypothesis of no change over time is equivalent to a hypothesis of symmetry. In other words, if there has been no change in percentage developed land over the two years in question, then the off-diagonals must be either zero or equal - as many pixels went from undeveloped to developed as went from developed to undeveloped. A z² value can be calculated where

$$z^2 = \frac{(x_{12} - x_{21})^2}{x_{12} + x_{21}}$$

Comparing the result to a chi-square distribution density function with one degree of freedom determines the p-value, $p(\chi^2 \geq z^2)$, the probability of obtaining a χ^2 greater than or equal to the calculated z² value. If this probability is less than 0.001, then there is strong evidence that there has been a significant and *systematic* change in land use over time. In general, this study focused on the effects of substantial urban growth so that the result of the McNemar test was always significant and not necessarily required to validate the basic change in urbanization calculation.

For example, these techniques were applied to Chester County's 1987 and 1996 TM derived land cover maps in order to locate municipalities with 1-km² regions that had a 1996 percent urban or built-up land value greater than that in 1987 by at least 20. Figure 3 displays a particular 1-km² region where a housing development was built between 1987 and 1996. The top square for each year is the Landsat TM satellite image of the area, while the bottom square is the land cover map derived from the satellite image. The urban or built-up land in this 1-km² region went from 1.5% of the

area in 1987 to 40.8% in 1996. This absolute change in percent urban or built-up land of 39.3 was significant at the 0.001 level based on the McNemar test, confirming that the difference in urban coverage was systematic rather than random — a fact readily apparent to the eye.

All the municipalities that exhibited similar urban expansion between 1987 and 1996 are shaded in Figure 4, which uses a Delaware Valley Regional Planning Commission (DVRPC) map of the county's municipalities as a base (DVRPC, 1994). As the DVRPC noted, the county's development patterns generally follow the main transportation corridors US 30, US 202 and PA 3, which are sketched on the figure. The TM derived land cover maps obviously capture the same growth patterns that are projected for the year 2000 by the Chester County Planning Commission (CCPC). In these projections, the mid-eastern section of the county becomes densely developed along the road systems, and the distinct centers of development of earlier years become more of a continuous urban mass stretching through Chester's eastern half (CCPC, 1988).

Urban or built-up land as a function of parcel size

Chester County's urban growth patterns can be further examined if the urban or built-up land parcels are stratified by size. ERDASTM Imagine's clumping procedure was used with each TM derived land cover map. All contiguous pixels classified as urban or built-up land were incorporated into one larger parcel based on a new thematic code that was

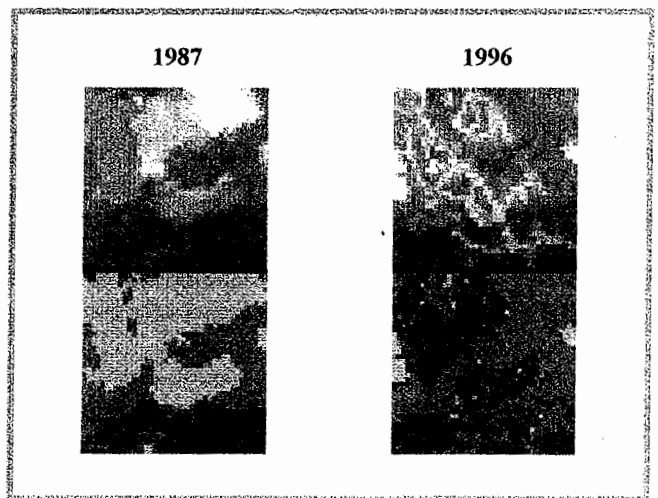


Figure 3 An example of a 1-km² region in Chester County exhibiting a 1996 percent urban or built-up land value greater than that in 1987 by at least 20. The subset is centered near 442509 easting and 4433074 northing (UTM coordinates) in Uwchlan township. The top square is the Landsat TM satellite image of the region using the 3,2,1 band combination. The bottom square is the land cover map for the same area as derived from the satellite image. The color scheme for the land cover map is the same as that in Figure 2.

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Figure 4 Chester County municipalities. Those municipalities with 1-km² areas experiencing an absolute increase in percent urban or built-up land greater than or equal to 20 between 1987 and 1996 are shaded in gray. The major transportation corridors are sketched on top, and arrows represent the external influences on growth. The base map is from the Delaware Valley Regional Planning Commission.

assigned to all the pixels in the clump. The resulting parcels that were less than 0.01 square kilometers (one hectare) in area were removed, and then the remaining parcels were partitioned into four categories of increasing size. Figure 5 shows the results of this analysis for Chester County based on the 1987, 1988, 1991, 1993 and 1996 TM derived land cover maps. In the figure, the total number of urban or built-up land parcels from the clumping procedure was calculated for each year and the percentage of parcels within each size category plotted.

It is apparent that the biggest parcels (those greater than 10 km²) are generally becoming more numerous as time progresses. Correspondingly, the medium- and big-sized parcels (0.1 to 10 km²) are decreasing in relative number. The greater percentage of larger parcels could be a result of the movement of individual medium and big parcels into the largest size category due to their continual growth, or the pattern could signify that the medium- and big-sized parcels expanded and merged. An apparent subtle growth in the smallest size group is also occurring — probably the result of an increase in separate suburban housing developments. However, individual expansion or agglomeration is not sufficient to replace the declining numbers of medium- and big-sized parcels.

Accuracy Assessment

These land cover analyses are, of course, questionable unless a case is made for the validity of the maps that have been used. Thus, the accuracy of the 1987 Chester County land cover map (Figure 2) was assessed by using a corresponding Planning Commission map as "truth." Depicting land use as of January 1987, the commission's

map was primarily based on aerial photography from 1985 and tax assessment data for 1987. The minimum tract size for a parcel to be included on the map was five acres, and woodlands were defined as tree masses in excess of ten acres (CCPC, 1988). Features selected for comparison in the two maps needed to be at the same resolution; thus, sample points for the accuracy assessment were chosen by randomly passing a 9 x 9 filter over the TM derived land cover map. Regions having at least 65 pixels (10 acres) of the same class within the 81-pixel sample were then selected. 150 UTM coordinate points representing the center of each filter kernel with an 80% majority class were extracted in this manner. The majority class was taken as the TM derived land cover map value, and a UTM grid overlaid on the Planning Commission's map was used to determine the corresponding reference or "truth" value. An error matrix, the standard reporting format for accuracy assessments (Congalton, 1991), was then completed. The sample size of 150 was chosen based on Congalton's (1991) rule of thumb that each class in an accuracy assessment should add a minimum of 50 samples to the total count in order to fill the error matrix adequately enough to discern confusion between classes. Since water was not considered a major component in Chester County's land cover change analysis, only the urban or built-up land, agricultural land and forest land were included in the sampling procedure.

The resulting error matrix is given in Table 3. Columns represent the land cover class designated by the reference data, while rows indicate the class determined for the same sample area by the supervised classification process used with the TM satellite images. The sum of the diagonal elements (shaded) represents the total number of correctly classified pixels; when divided by the total sample size, the

overall accuracy of the map is determined. The user's accuracy is calculated by dividing the number of correctly classified pixels in a land cover category by that class's *row* total. The result represents the probability that a user of the map will find the land cover to be as stated in the classification map if the location of the pixel is

actually visited. On the other hand, the producer's accuracy reflects how well the classification technique succeeded in defining all the pixels that actually represent a given class. It is calculated by dividing the number of correctly classified pixels in a land cover category by that class's *column* total. The KHAT statistic incorporates information from all three accuracy values into one measure (Congalton, 1991).

For the 1987 Chester County TM derived land cover map, the

Changes in Urban or Built-up Land by Parcel Size

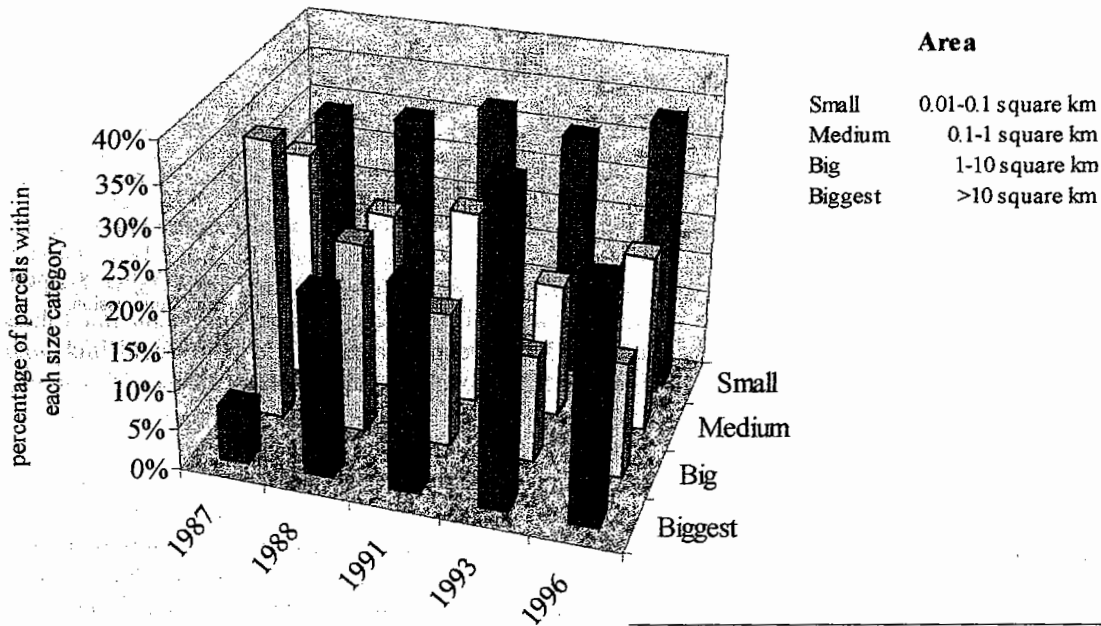


Figure 5 Parcel size frequency for urban or built-up land in Chester County. For each year, the total number of urban or built-up land parcels from the clumping procedure were summed and the percentage of parcels within each size category plotted. The graphic is shown for visual interpretation, while a table is included with the actual values. Areas smaller than 0.01 km² are not represented.

Year	Small	Medium	Big	Biggest	Total
1987	29.5%	28.7%	35.0%	6.8%	100%
1988	30.0%	22.8%	24.1%	23.1%	100%
1991	32.6%	24.5%	17.0%	25.9%	100%
1993	30.6%	16.9%	13.5%	39.0%	100%
1996	33.9%	22.1%	14.4%	29.6%	100%

Table 2 Matrix used in McNemar's test. This 2 x 2 table was generated for each 1-km² area in Chester County using the 1600 classified TM pixels within the 1-km² block. Developed indicates that the pixel was classified as urban or built-up land, while not developed indicates that its class was either agricultural land, forest land or water.

		second year	
		developed	not developed
first year	developed	X ₁₁	X ₁₂
	not developed	X ₂₁	X ₂₂

Table 3 Error matrix used in the accuracy assessment for the 1987 TM derived land cover map of Chester County. Rows (classification map) represent the class given by the land cover map that was derived from the June 10, 1987 Landsat TM satellite image. Columns (reference data) represent the class given by the January 1987 Chester County Planning Commission's land use map assumed to serve as "truth." 150 points were sampled using the techniques described in the text.

		reference data			
		agriculture	forest	urban/built-up	row total
classification map	agriculture	68	10	9	87
	forest	3	42	1	46
	urban/built up	0	0	17	17
	column total	71	52	27	150

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overall accuracy was 85%, and the KHAT statistic showed that the maximum likelihood method avoided approximately 74% of the errors that a completely random classification would have generated. User's accuracies were 78% for agriculture, 91% for forest and 100% for urban, while producer's accuracies were 96% for agriculture, 81% for forest and 63% for urban. Since the land cover maps for 1988, 1991, 1993 and 1996 were generated by the same image interpreter, using the same technique and the same data source, it is assumed that these accuracy results are relatively transferable. The individual class accuracy values reflect the land cover map's tendency towards an over-classification as agriculture at the expense of forest and urban. The relatively low producer's accuracy for the urban or built-up land class demonstrates the supposedly poor ability of the classification process to discern all the developed sites within the region. Part of the problem was due to interclass confusion between densely developed areas and bare soil regions, which were included in the agricultural class. This is a common, and difficult to correct, error in satellite-based land cover maps. Using similar mapping techniques for Malaysia, Tin-Seong (1995) found that misclassifications between the medium density building and bare soil classes accounted for almost one-third of the total error; despite an overall accuracy of 79%. For the Chester County accuracy assessment, however, the disparity between societal and spectral land cover classifications was also an issue. The Chester County Planning Commission's 1987 land use map served as the reference source for this accuracy assessment, and maps based on spectral classes are not likely to replicate precisely those based on societal categories.

For example, in the Planning Commission's map, many of the parcels designated as urban or built-up land consisted of residential areas made up of single family homes on lots both greater and less than one acre, as well as townhouses, mobile home parks, apartment buildings, etc. Through ground observations, it has been noted that these developed, particularly suburban, areas display considerable variability in land cover, both between and within pixels. This is a trait that is not apparent in larger, more homogeneous parcels of forest or bodies of water. In residential areas, lawns and wooded lots can lead to a correct spectral classification as vegetated land or forest, although this will be inconsistent with the societal classification as urban or built-up based on the parcel's use. This difference in definition can make the assessment of accuracy difficult where communities are less densely developed; for instance, in the TM derived maps, these areas may have been included in the vegetation class, which was represented by agricultural land.

Unfortunately, there is no definitively correct answer to the debate over societal versus spectral definitions of urban land; each carries its own important information depending on the purpose of the classification. For example, in determining the environmental effects of urbanization, a spectral classification is possibly more instructive than one based strictly on land use. Distinct land use categories may present similar land covers. It is this latter feature that is

sensed remotely and that determines the environmental character of an area as perceived by its inhabitants (Ridd, 1995). With this in mind, a spectral classification can more clearly reflect the character of urban development and its possible deleterious impacts.

Environmental indicators of urbanization

Along the same lines, the satellite image, which drives the spectral classification, is much more than a picture; it contains quantitative data that is not retrievable from aerial photography — the mapping source used more frequently in regional planning. For example, Carlson and Arthur (2000) use the TM derived land cover maps discussed here, coupled with NOAA Advanced Very High Resolution Radiometer (AVHRR) data and a soil-vegetation-atmosphere-transfer (SVAT) surface climate model, in order to resolve changes in physical microclimate parameters down to a resolution of 1-km². The AVHRR sensor is different from the TM in that it has five spectral bands ranging from visible to thermal infrared wavelengths and a nadir surface resolution of 1.1 kilometer. Daily mid-afternoon coverage is provided with a swath width of 2700 kilometers. The images used in Carlson and Arthur (2000) were acquired in the summertime during clear skies. They were georeferenced to the same UTM map base as the Landsat TM imagery and resampled to a 1-kilometer grid using the nearest neighbor criteria. As discussed under *Urban Growth*, 1600 of the 25-meter classified TM pixels could then be aggregated to represent the land cover within each of the 1-kilometer AVHRR pixels. Since the AVHRR data was to be used for deriving physical surface parameters, the digital numbers were converted to at-sensor radiances through a radiometric calibration, and an atmospheric correction scheme based on the radiative transfer model MODTRAN (Kneizys *et al.*, 1996) was applied in order to estimate surface radiances.

From these surface values, a normalized difference vegetation index (NDVI) and radiant surface temperature were calculated for each pixel. Both of these parameters have been well established in the remote sensing literature (Knipling, 1970; Leprieur *et al.*, 1994; Prata *et al.*, 1995), so the discussion here will be limited. In short, the NDVI exploits the difference in the visible red and near infrared reflectance of healthy green vegetation in order to generate a quantitative indicator of the amount of vegetation per pixel. The NDVI values can be converted to a more physical measurement — fractional vegetation cover (Fr), defined as the proportion of a pixel covered by vegetation (Carlson and Gillies, 1995). The radiant surface temperature is calculated using Planck's law and a sensor's thermal band, which detects emitted radiation in a far infrared wavelength interval. The SVAT surface climate model, based on a surface energy balance, can be used to estimate soil moisture conditions for each pixel depending on its radiant surface temperature and fractional vegetation cover values. The parameter used here to define soil moisture is the evapotranspiration fraction (ET/Rn) - the fraction of net radiation (Rn) that is used in

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either the evaporation of moisture from the surface or in transpiration from plants. Theoretically, ET/Rn ranges from 0 to 1, with lower fractions representing drier surfaces and higher fractions representing more moist surfaces. This technique for estimating surface moisture remotely is known as the "triangle method"; Gillies and Carlson (1995) explain this method, along with the SVAT model, in more detail.

A variant of the fractional vegetation cover parameter (Fr) for urban or built-up areas is used here to examine Chester County's land cover patterns. If it is assumed that in the urban or built-up regions, surfaces not covered by vegetation consist primarily of buildings, parking lots and roads, the quantity 1-Fr can be considered as an estimate of the proportion of a pixel's surface that is essentially impervious to rainwater. Figure 6 shows an analysis of this impervious surface area parameter (ISA) for Chester County based on the Fr values for the AVHRR 1-kilometer pixels. Only those pixels that were identified by the TM derived land cover maps as having at least 25% urban or built-up land were included in the analysis. It is apparent that during this time period urban regions increased dramatically and with them, the spread of impervious surfaces. The same analysis is possible at a much higher resolution if the calculation of NDVI, Fr and ISA is based on the 25-meter Landsat TM pixel and its surface radiance values. Figure 7 uses this method to zoom in on the headwater region of the

Chester Creek watershed, which is near the city of West Chester in the eastern part of the county. Note that the percentage of a pixel covered by impervious surfaces generally decreases as the land cover class changes from commercial to residential development, reflecting the possibility of using ISA as a quantitative index that is capable of separating various urban classes.

Environmentally, these impervious surfaces prevent the infiltration of rainfall and lead to an increase in stormwater runoff, which induces localized drying and a decrease in evapotranspiration. Thus, the impact of increases in ISA should be detectable in the derived ET/Rn field, as estimated per pixel from the satellite data and the SVAT surface climate model. It is reasonable to assume that the only substantial, non-reversible surface moisture change in the study region is due to urbanization. Typically, if local changes are observed in the satellite derived surface moisture field in the absence of urban expansion, they are due to differences in farming practices from year to year or differences in the growing season at the time of image acquisition. Overall regional changes are generally due to short-term weather variations such as drought or heavy rainfall and render the image unusable for these purposes. Table 4 — based on two Landsat TM images for the entire Chester Creek watershed — provides evidence for these statements. It demonstrates that the average ET/Rn value for each of the three main

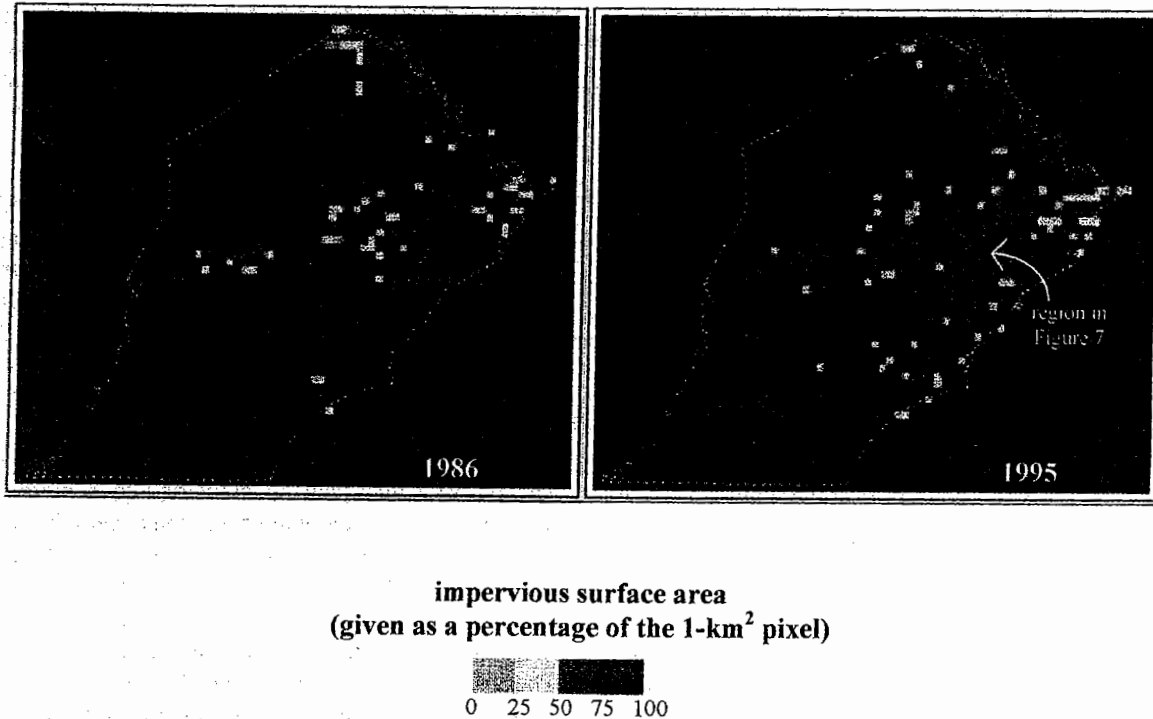


Figure 6 Impervious surface area (ISA) given as a percentage based on AVHRR data for 1-km² areas with at least 25% urban or built-up land. The percentage of urban or built-up land in each 1-km² area was determined using aggregates of the 25-meter TM derived land cover maps. The 1987 map was used with the 1986 AVHRR image, and the 1996 map was used with the 1995 AVHRR image. Black areas represent those AVHRR pixels that contained less than 25% urban or built-up land or that were outside Chester County, which is outlined by the dashed white line.

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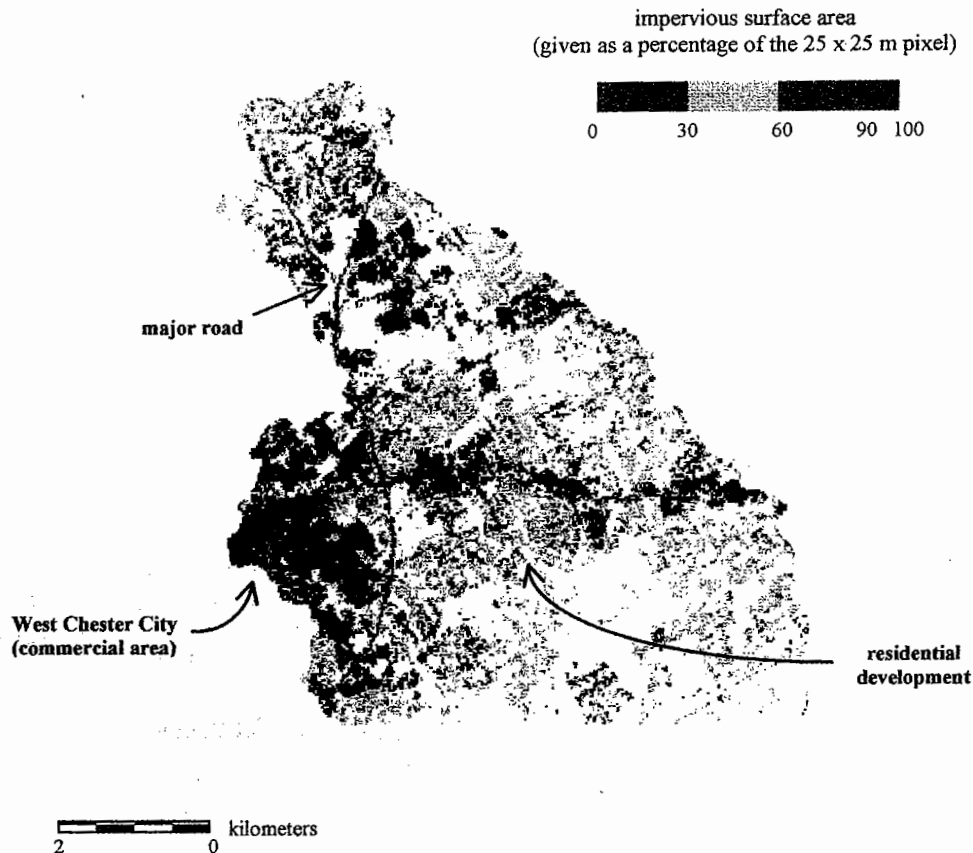


Figure 7 Impervious surface area (ISA) given as a percentage based on Landsat TM data for 25 x 25 m areas that were classified as urban or built-up land. The land cover class for the pixel was based on the TM derived land cover maps. White areas represent pixels that were not classified as urban or built-up. The sampling area is that of the headwater region for Chester Creek watershed; parts of East and West Goshen, Westtown and West Whiteland are shown.

Anderson Level 1 land cover classes varies little from image to image. Note, however, that for a given year, ET/Rn decreases as the land type changes from forest to agricultural to urban or built-up. A lower ET/Rn value reflects a drier surface — indicative of an environment that is possibly dominated by runoff. For example, consider a basin's annual water budget, where precipitation minus evapotranspiration equals runoff, assuming no change in storage (Bedient and Huber, 1992). In this case, if annual precipitation stays relatively constant over time, reductions in evapotranspiration can be viewed as directly proportional to increases in runoff.

In an attempt to validate some of these potential relationships between urban growth, impervious surfaces and surface moisture, the AVHRR and TM data were combined in order to examine the same regions using independent data sources. Based on the TM derived land cover maps, 72 of the 1-kilometer AVHRR pixels in Chester County consisted of at least 25% urban or built-up land in 1987 and then continued to exhibit urban growth throughout the study period ending in 1996. Average ISA and ET/Rn values for these areas were determined for each year using

the surface radiances from the AVHRR pixels. The TM derived land cover maps were then used to calculate the corresponding average percentage of urban or built-up land. The results, given in Table 5, show that urban growth — detected independently using the Landsat TM satellite — leads to changes in environmental parameters, as measured by the AVHRR sensor. With continued expansion of urban or built-up land, the study sites, on average, gained impervious surfaces while they also became drier. This drying trend is seen by the decrease in the amount of available radiant energy used in evaporative processes; instead, more energy is used in a direct sensible heating of the atmosphere. Assuming the same amount of precipitation, the data given in Table 5 could signify an increase in surface stormwater runoff with continued development of Chester County.

Note that Table 5's ET/Rn values are higher than those given for the urban or built-up land in Table 4. This difference is most likely one of scale; Table 4 was based on the 25-meter Landsat TM pixel while Table 5 is a result of the 1-kilometer AVHRR pixel. At 25 meters, each pixel is generally composed of one land class, while the AVHRR pixels that

Table 4 Average ET/Rn values for all the Landsat TM pixels in the Chester Creek watershed that were classified as the particular land cover class for the year of image acquisition. The land cover class for each 25-meter Landsat TM pixel was based on the TM derived land cover maps. The fractional vegetation cover and radiant surface temperature values necessary to obtain ET/Rn were derived from the surface radiances of each Landsat TM pixel. The 1997 image was from a different study and was not one of the main images used in the land cover analyses that have been presented in this paper. The Chester Creek watershed covers a 61 square mile drainage area.

ET/Rn	1987 mean	standard deviation	1997 mean	standard deviation
forest	0.613	0.023	0.619	0.019
agricultural	0.576	0.046	0.565	0.054
urban/built up	0.516	0.082	0.516	0.084

Table 5 Statistics related to changes in percent urban or built-up land, impervious surface coverage and surface moisture for a continually growing pre-developed subset in Chester County. Values given are averages for the 72 1-km² regions that met the growth criteria. The physical parameters (ISA and ET/Rn) were derived from the 1-kilometer AVHRR pixels in 1986 and 1995, while the percentage of urban or built-up land was determined using aggregates of the 25-meter TM derived land cover maps for 1987 and 1996. All paired values for the two years are significantly different according to a two-sample t-test at the 0.0001 level.

	sample size	urban or built-up land	impervious surface	ET/Rn
1986(7)	72	34.8%	55.9%	0.62
1995(6)	72	50.3%	69.8%	0.59

were used only had to be composed of at least 25% urban or built-up land, leading to some dilution of the ET/Rn value by surrounding countryside or trees. It is also possible that the different overpass time for the two satellites plays a role. The effects of scale and time of day on these derived parameters are currently being addressed by the authors, and a transition to using the 25-meter Landsat TM pixel for both land cover mapping and surface climate work is being made.

Conclusions

If the full potential of the satellite is exploited in regional planning, the impacts of urbanization can be expressed not only in terms of temporal changes in conventional land cover classes but also of changes in physical land surface quantities. An illustration was given for Chester County, Pennsylvania. Basic land cover categories, such as urban or built-up land, vegetation, bare soil and forest, can be resolved down to approximately 25 meters using Landsat TM imagery. Individual land cover types can be clumped into contiguous parcels and then distributed based on size. With a series of maps, change analyses can demonstrate the overall evolution of land distributions, as well as locate specific sites of systematic growth.

Additionally, multi-spectral satellite imagery such as that from the Landsat TM or the NOAA AVHRR, offers regional planners access to such physical parameters as fractional vegetation cover, radiant surface temperature, impervious surface coverage and surface moisture on a per-pixel basis. Although more extensive work on the impacts of urbanization on the microclimate has been completed, the focus of this paper was the link between urban growth, impervious surface coverage and evapotranspiration — with urbanization shown to induce localized drying and potential increases in stormwater runoff.

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