ABSTRACT

Landsat TM data have been used to map the percentage of impervious surface area of the seven-county Twin Cities Metropolitan Area in 1986, 1991, 1998 and 2000. Following classification of land cover types, a regression model relating percent impervious surface area to “tasseled cap” greenness was used to estimate the percent impervious surface area for pixels classified as urban or developed. Eighty to 90% of the variation in imperviousness is accounted for by greenness. Over the entire seven-county area the amount of impervious area increased from 8.8 to 14.1% between 1986 and 2000. Classification of the Landsat TM data provides a means to map and quantify the degree of impervious surface area, an indicator of environmental quality, over large geographic areas and over time at modest cost.

INTRODUCTION

The amount of impervious surface in a landscape is an indicator of environmental quality (Arnold and Gibbons, 1996). Impervious surfaces are defined as any surface which water cannot infiltrate and are primarily associated with transportation (streets, highways, parking lots and sidewalks) and building rooftops. Imperviousness directly affects the amount of runoff to streams and lakes and is related to non-point source pollution and water quality of surrounding lakes and streams. Imperviousness is also related to energy balances and urban heat island effects, as well as to the aesthetics of landscapes and habitat degradation and fragmentation. Conversion of rural landscapes to urban and suburban land uses is directly related to increasing amounts of impervious surface area. Arnold and Gibbons (1996) suggest that impervious surface area provides a measure of land use that is closely correlated with these impacts. It therefore follows that maps of impervious surface area can be useful inputs to planning and management activities.

Stocker (1998) suggests four ways to generate percent impervious surface area maps: ground surveys, Global Positioning Systems, aerial photo interpretation and photogrammetry, and satellite remote sensing. Ground surveys are expensive and generally not practical for mapping impervious surfaces of large areas. While GPS is useful for assisting in collecting field data, it too is not easily implemented for mapping large areas. Remote sensing, in the form of aerial photography, has been an important source of land use-land cover information for many years and impervious surface area can be readily interpreted from aerial photo (Draper and Rao, 1986). However, the cost of aerial photography acquisition and interpretation of cover types is prohibitively expensive for large geographic areas. An alternative is to acquire the needed information from digital satellite imagery such as the Landsat Thematic Mapper (TM) or Enhanced Thematic Mapper Plus (ETM+). This approach has several advantages: (1) the synoptic view of the sensor provides coverage (albeit at 30-meter spatial resolution) of large, multi-county geographic areas, (2) the digital form of the data lends itself to efficient analysis, (3) the classified data are compatible with geographic information systems, eliminating the need to digitize interpreted information, and (4) land cover maps can be generated at considerable less cost than by other methods. A number of studies (Civco and Hurd, 1997; Ji and Jensen, 1999; Ridd, 1995) have demonstrated the feasibility of using multispectral satellite data to classify impervious surface area in urban environments.
This study evaluated whether Landsat imagery (Figure 1) can be used to estimate the percentage of impervious surface area across the Twin Cities Metropolitan Area (TCMA), Minnesota. The TCMA includes seven counties totaling 7,700 km$^2$ or about 3,000 square miles. The area includes a diversity of land cover classes. High and low density urban development characterizes the central portions of Minneapolis-St. Paul and their suburbs, while several rural land uses such as agricultural cropland, grassland, wetlands and forests, as well as small towns, are dispersed across the surrounding area. With a 15% increase in population from 2.29 million in 1990 to 3.53 million in 2000, the proportion of impervious area is undoubtedly increasing. While it’s generally agreed or assumed that the amount of impervious surface area is increasing with population growth and urbanization, very little work has been addressed at quantifying it in Minnesota. Our objective has been to develop methodology to use Landsat TM data to map impervious surface area and to quantify the changes over time. We have developed an approach to directly estimate the percent impervious surface at the pixel level rather than applying average impervious coefficients to land use classes derived from image classification.

Figure 1. Landsat TM image of TCMA with overlay of county boundaries.

**METHODS**

Multitemporal Landsat Thematic Mapper (TM) digital imagery were acquired and analyzed for four times during the past 15 years: 1986, 1991, 1998 and 2000. The key steps in the procedures were image acquisition, rectification and classification; development and application of a regression model relating percent impervious to Landsat TM tasseled cap greenness, and accuracy assessment.

**Landsat Image Acquisition, Rectification and Land Cover Classification**

Multitemporal Landsat 5 TM or Landsat 7 ETM+ imagery (path 27, rows 28-29) covering the TCMA were acquired for classification of land cover as follows: June 2 and August 23, 1986; June 19 and September 4, 1991; May 18 and September 7, 1998; April 29 (ETM+), June 8, and 12 September 2000. Following the land cover classifications the August and September images were used for impervious classification.

The Landsat imagery was rectified to the UTM projection system (ellipsoid GRS80, datum NAD83, zone 15) using ERDAS Imagine 8.5 software. The images were georeferenced to a Minnesota Department of Transportation base map using approximately 60 ground control points, primarily road intersections, evenly distributed across the entire image. A first order polynomial model was used for the rectification with nearest neighbor resampling. The overall root mean square (RMS) errors were less than 7.5 meters (1/4-pixel).

The emphasis and objective of this paper is on classification of impervious surfaces, but we rely on the land cover classification for separation of urban and rural landscapes as described by Sawaya et al. (2001). The classifications, using a combination of supervised and unsupervised training and maximum likelihood classifier, included a late May or early June image together with a late August or early September image. For 2000, a third early spring image was included. The combination of early and late summer dates has yielded the most accurate...
classifications and is particularly useful for separating forests and wetlands from annual crops, such as corn and soybean, for which the predominant response in the first image is the soil background. The overall classification accuracies for level 1 classes of agriculture, forest, wetland, urban and water were 95.9, 95.2, 95.2 and 94.9% for 1986, 1991, 1998 and 2000, respectively, with Kappa statistics ranging from 0.93 to 0.95.

Development and Application of Impervious – Greenness Model

In a preliminary analysis of 10 locations in the metro area we varied the proportion of impervious surface area (as measured on digital orthophoto quads) within polygons of Landsat imagery and found a strong relationship ($r^2 = 0.92$) to “tasseled cap” greenness. The tasseled cap transformation is an orthogonal transformation of the reflective bands of the TM data (Crist and Cicone, 1984) in which the first component, brightness, is related to the amplitude of reflectances associated with soils and impervious surfaces such as concrete and asphalt. The second component, greenness, is orthogonal to brightness and is strongly related to the amount of green vegetation and therefore inversely related to the amount of impervious area. Greenness is independent of brightness and increases with increasing proportions of green vegetation, regardless of whether the background or surrounding surface is soil, concrete or asphalt. For a given percentage of impervious surface area, the greenness value will be the same regardless of the background material (e.g., asphalt or concrete).

Area of Interest (AOI) samples representing varying percentages and kinds of impervious surfaces were selected for sites distributed across the TCMA. Impervious surface percentages were determined from NHAP aerial photography (1986) or digital orthophoto quarter quads (DOQQ) (1991, 1998, and 2000). Color infrared aerial photography (NHAP, NAPP and Minnesota DNR) was also used to assist in the identification of impervious vs. pervious surfaces. AOI’s varied in size from 20 to 100 pixels and were drawn using ESRI ArcView 3.2.

In ArcView, separate shapefiles were created for each of the four images to match the registration of each and maintain precision in digitizing. Polygons were digitized based on pixel boundaries and added to an “AOI” shapefile. Polygons were drawn so that each AOI would contain only whole pixels, not partial pixels. This was done because ERDAS Imagine software includes the value of an adjacent pixel for calculations if the AOI boundary includes the center point or the boundary midpoint of the adjacent pixel. All impervious areas within the AOI were then identified by visual inspection of the DOQ and carefully digitized as polygons and added to a separate shapefile. The percent impervious surface for each AOI was calculated by dividing the area of the impervious surface polygons by the total area of the AOI polygon. Examples of typical AOI’s are shown in Figure 2. Digitizing impervious areas for each AOI over the DOQ provided a very accurate determination of percent impervious area. AOI’s were selected to represent percent impervious values (0 – 100), along with different types of impervious surfaces and vegetation.

![Figure 2. Example areas of interest with varying degrees of impervious surface area overlaid on DOQQ.](image-url)
To calculate the mean ‘greenness’ value for each AOI, the ArcView shapefile (pixel-based AOI) was loaded into ERDAS Imagine and converted to an AOI file, which was then overlaid on the tasseled cap greenness imagery. Each individual AOI was selected and added to the signature editor to determine the mean ‘greenness’ value. The values for percent impervious and mean ‘greenness’ for each AOI were entered into a statistical software package where the regression equation (2nd order polynomial) was computed with greenness as the independent variable (X) and percent imperviousness as the dependent variable (Y). Coefficient of determination ($R^2$) and standard error were used to evaluate the strength of the greenness-impervious relationship. The strongest relationship was with second order polynomial equations.

The ERDAS Imagine 8.5 spatial modeler was used to develop models to convert the greenness images to impervious surface images based on the regression. For each pixel, the greenness value was entered as the X value of the polynomial equation. The output (Y) was rescaled from 1 to 100, corresponding to percent impervious area surface. The final impervious surface classifications were then combined with a non-urban mask developed from the land cover classifications. Applying a non-urban mask was necessary to filter out bare fields, extraction, and water bodies.

An inverse calibration procedure (Walsh and Burk, 1993), based on the errors of the classification determined from an independent set of AOIs was applied to the initial impervious classification. With the inverse method the satellite estimate of the proportion of impervious area was the independent variable and the ground measurements from the DOQQ’s were the dependent variables. Use of the post-classification calibration method increased $R^2$ values 1 – 2% and decreased the standard errors of the estimates of impervious area from 7.8 to 6.4%.

To measure accuracy, the estimated percent impervious surface area from the Landsat classifications was compared to the measured percent impervious surface area with independent samples of AOIs that had not been used to develop the regression models. Both variables were calculated in the same way as for the training samples.

RESULTS AND DISCUSSION

We have found a strong relationship between Landsat tasseled cap greenness and percent impervious surface area. An example of the relationship of greenness to percent impervious surface area and the regression model for the 2000 TM data is shown in Figure 3. The second order regression model has an $R^2$ of 0.91 and a standard error of 11.7. Similar relationships were found for the other three years (Table 1). By considering greenness and percent impervious area as continuous variables we can use a regression model to estimate the percent impervious area of each Landsat pixel. The resulting classification provides a continuous range of impervious area from 0 – 100%. Because of possible similarity and confusion between bare soil and impervious areas, the impervious classification is used only for the areas already classified as urban or developed.

![Figure 3](image-url)
Table 1. Statistics describing (a) relationship between Landsat TM greenness and percent impervious surface area and (b) evaluation of Landsat estimates of percent impervious surface area.

<table>
<thead>
<tr>
<th>Year</th>
<th>Greenness vs. % Impervious Area</th>
<th>DOQ Measurements vs. Landsat Estimates of % Impervious Area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>R²</td>
</tr>
<tr>
<td>1986</td>
<td>55</td>
<td>0.93</td>
</tr>
<tr>
<td>1991</td>
<td>84</td>
<td>0.93</td>
</tr>
<tr>
<td>1998</td>
<td>81</td>
<td>0.92</td>
</tr>
<tr>
<td>2000</td>
<td>59</td>
<td>0.91</td>
</tr>
</tbody>
</table>

Figure 4 compares measurements from DOQs to Landsat estimates of impervious surface area for an independent set of test areas for the 2000 data. The two are highly correlated \( (r = 0.95) \) with a mean difference between the two estimates of less than 0.5%. The standard error for the Landsat estimates is 8.1%. Similar results were found for the other three years (Table 1). These accuracies compare very favorably to the 71 to 94% accuracies reported by Flanagan and Civco (2001) for a study in which they compared artificial neural network and subpixel classification approaches for mapping impervious surface area of four municipalities in Connecticut.

Figure 4. Comparison of measured (from DOQQ) and Landsat estimates of percent impervious surface area following inverse calibration.

Land cover and impervious surface classification maps for 2000 for the seven-county area and at a larger scale for a smaller area east of St. Paul are shown in Figures 5 and 6. A difference between these classifications and most others is that they are percent impervious on a scale of 0 to 100, providing the means for displaying the results in any combination of classes (e.g., the ranges suggested by Arnold and Gibbons (1996) for protected (0-10%), impacted (10-25%) and degraded (25-50%) to describe the relationship between amount of impervious area and environmental quality of watersheds. A further advantage of the method is that although a majority of pixels in urban areas are mixtures of two or more classes, it is not subject to problems and errors of assigning a mixed pixel to one class in a set of discreet classes as in maximum likelihood classification such as in the study by Plunk et al. (1990). It also is not affected by the variation in percent impervious area in a given class (e.g., medium density residential) when average impervious coefficients are assigned to each land covers class as in the procedures used by Dguchi and Sugio (1994) and Giannotti and Prisloe (1999).
Given the success of mapping impervious surface for the individual years, the next step in our investigation was to compare the maps and area statistics, examining changes in the amount of impervious surface over the 15-year period. Figures 7 and 8 show maps of the increasing amount of impervious area from 1986 to 2000. Most of the increases are at the periphery of already developed areas. The areas showing decreases in degree of impervious are most likely classification errors caused by errors in registration, especially along roads, and fields of bare soil.

For the 7-county TCMA the percent impervious area increased from 8.8% in 1986 to 14.1% in 2000 (Figure 9). The greatest changes occurred in Anoka and Carver Counties where the impervious area more than doubled. In Ramsey County, the most densely populated county in the state, impervious area increased only slightly after 1991. An additional advantage of the digital, GIS compatible maps available from the Landsat classifications is the capability to easily generate maps and area statistics for any smaller area, for example, cities. Figure 8 includes the City of Woodbury, one of the most rapidly growing areas, in the state during the 1990’s. The change statistics for Woodbury and two other suburban cities, Eagan and Plymouth, are shown in Figure 10.

While we believe the results are highly accurate, we also know there are several sources and kinds of errors in the impervious surface area maps. One is that are some areas in Figures 7 and 8 that show decreases in the percent impervious from 1986 to 2000. While not impossible, in most cases it appears to be areas of bare soil in the August/September classifications. There are also registration errors which can show up as decreases in impervious area; this is noticeable along roads. There is also some evidence that more rural roads were classified as urban/developed in the 2000 classification. There could also be errors introduced by tree cover obscuring streets, sidewalks and rooftops and increasing the level of greenness in those pixels. However, the selection of training sites includes such areas and the regression model was based on actual imperviousness, not what was visible from above. We have made evaluations in six residential areas with large trees along the streets with measured impervious values from 37 to 58% and found that the average difference between the Landsat-estimated percent impervious and the actual amount is 3.5% for the 2000 data.

CONCLUSIONS

A strong relationship between impervious surface area and greenness enables percent impervious area on a pixel basis to be mapped with Landsat TM data. We believe the Landsat-derived estimates and maps of impervious surface area are superior to those that might be obtained by the assigning standard percentages of impervious area to the various land use classes from either interpretation of aerial photography or classification of digital satellite data. Traditionally, land cover mapping has involved aerial photography interpretation and, more recently, manually digitizing the polygons for input to a GIS and generation of maps. While these methods produce maps with high resolution, they are expensive and time consuming. The Landsat classification method provides uniform results over a large area at a resolution of 30 meters. These results can be readily incorporated into a GIS for further analysis with other data on land and water resources, as well as socioeconomic data. The increasing availability of satellite imagery makes this kind of approach a feasible way of obtaining impervious surface area information over large geographic areas. We have been working with the Metropolitan Council, the regional planning and policy agency for the seven-county Twin Cities metropolitan area. The Council and several local cities are finding the maps to be useful inputs to hydrology and runoff models and planning future development.

Possible improvements in the approach which we are considering include the use of a sub-pixel classification approach (Flanagan and Civco, 2001; Ji and Jensen, 1999). Although our present approach has provided satisfactory results, the use of different spectral end members for grass, trees, and impervious surfaces may lead to improvements. And, because some users are interested in having maps with higher spatial resolution than 30 meters we are examining the use of the 15-meter panchromatic band available with Landsat-7 ETM+ data, as well as data from the commercial high-resolution satellites, IKONOS and QuickBird satellites. Initial results for IKONOS and QuickBird indicate that impervious areas can be accurately mapped with this new source of data. This may be especially useful for city scale mapping, although likely not for an area as large as the TCMA because of the number of images involved and the cost of image acquisition.
Figure 5. Level 1 land cover classification with impervious surface area mapped as a continuous variable from 0 to 100 percent for the urban-developed class. A higher resolution map of the eastern TCMA is shown in Figure 6.
Figure 6. Land cover and impervious surface classification map for the eastern TCMA. The legend is the same as for Figure 5.

Figure 7. Changes in amount of impervious surface area from 1986 to 2000 for the TCMA.
Figure 8. A larger scale map of changes in amount of impervious surface for the eastern TCMA. The legend is the same as for Figure 7.

Figure 9. Changes, by county, in the percent of impervious surface area from 1986 to 2000.
Figure 10. Changes in the percent of impervious surface area from 1986 to 2000 for three suburbs of Minneapolis-St. Paul.

REFERENCES


ASPRS Annual Conference Proceedings
May 2004 * Denver, Colorado

ASPRS – 70 years of service to the profession