ESTIMATION, MAPPING AND CHANGE ANALYIS OF IMPERVIOUS SURFACE AREA BY LANDSAT REMOTE SENSING

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ABSTRACT

Increasing population, new development in lake and river recreation areas, and growing towns all translate into increasing impervious surface areas across Minnesota. As urban stormwater runoff from impervious areas can have profound negative impacts to receiving waters, it is a critical new component of statewide stormwater education and management efforts. This paper describes the methods and results of Landsat classification and mapping of impervious surface area for the entire state of Minnesota, including approximately 500 cities and high priority sensitive lake watersheds for 1990 and 2000 census periods. From 1990 to 2000 the estimated amount of impervious area for the state increased 145,830 ha, from 1.2 to 1.9% of the total land area. The Landsat-based processing and classification provides critically important, consistent and multi-date, data for any area of Minnesota. It is envisioned that this data and updates, will be the foundation of Minnesota's stormwater management efforts.

INTRODUCTION

The amount of impervious surface in a landscape is an important indicator of environmental and habitat 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 increases water runoff, and hence, is a primary determinant of stormwater runoff volumes and quality in urbanized areas. Imperviousness is also the primary determinant of stream habitat quality. 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 impervious cover information is fundamental for watershed planning and management.

Minnesota, like many areas of the United States, has witnessed a prolonged period of rapid growth of permanent and seasonal populations, especially in high demand lake and stream recreation areas and manyt municipalities. Adding future growth projections of as much as 100+ percent in most of our prime lake district areas over the next 30 years, there is significant concern about the impacts to our recreational water resources as new developments of homes and associated commercial/industrial zones create new stormwater discharges to lakes and streams, and considerable new amounts of impervious surfaces.

Increases in impervious surfaces can have profound negative impacts to streams, lakes and habitat for fisheries and wildlife, as well as water quality (Figure 1). Over the past few years, the percent impervious cover has emerged as the key factor to explain and generally predict the degree of impact severity to streams and watersheds. For example, it has been generally found that most stream health indicators decline when watershed impervious cover exceeds 10 percent (Schueler and Holland, 2000). Lakes and streams of the Northern Lakes and Forests ecoregion (NLF) of northern Minnesota, and other areas with cold and cool water fisheries (e.g., trout), are extremely sensitive to new thermal, total phosphorus and sediment loads. For example, Minnesota urban stormwater runoff generally has total phosphorus concentrations (the key aquatic management nutrient) in the 150 to 650 ppb range while typical

NLF streams values are 30 to 50 ppb range (or an increase of 3X to 13X). It is no surprise that these lakes cannot be expected to assimilate these shock impervious area loadings. Hence, continued growth, expected to occur over the next three decades, should be accompanied by carefully designed, operated and maintained stormwater runoff controls as required by new federal and state stormwater permits and Total Maximum Daily Load (TMDL) allocations for municipal stormwater sources.

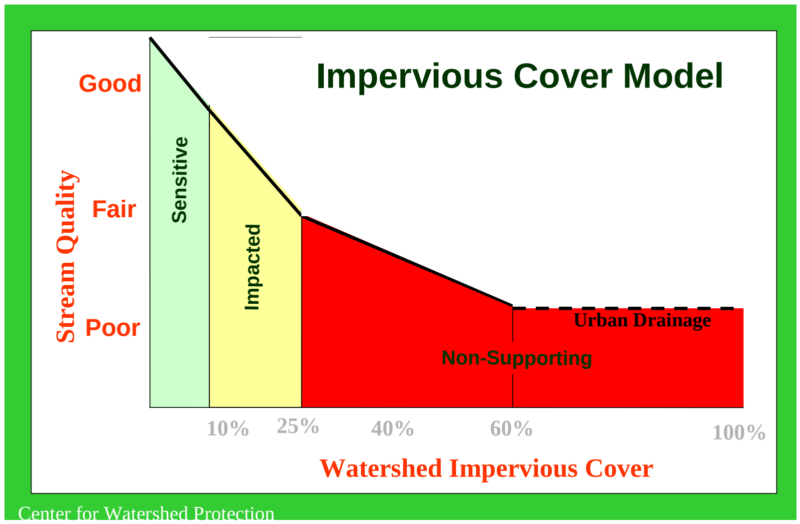


Figure 1. Model of impact of impervious surface on stream quality.

In Minnesota, there are more than 200 Municipal Separate Storm Sewer System (MS4) communities that are required by the Stormwater Program to begin stormwater pollution prevention planning and implementing urban Best Management Practices (BMPs). Included in these efforts are: public education and outreach; public participation/involvement; illicit discharge, detection and elimination; construction site runoff control; post-construction site runoff control; and pollution prevention/good housekeeping. The MS4 cities must identify best management practices and measurable goals associated with each minimum control measure. Defining impervious cover should be one of the first steps for the MS4s.

Given the number and size of areas of interest, an economical and consistent method for mapping impervious surface area is needed. A number of studies, including Bauer et al. (2004), Civco and Hurd (1997), Jantz et al. (2005) and Ridd 1995), have shown that remote sensing has the potential for monitoring impervious surface area. Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) data have several advantages for this application: synoptic view of multi-county areas, digital, GIS compatible data, availability of data since 1984, and economical costs. This paper extends the methods and results of our previous classifications (Bauer et al., 2004) of the Twin Cities Metropolitan Area to the entire state of Minnesota for two time periods, 1990 and 2000.

METHODS

Multitemporal Landsat Thematic Mapper (TM) digital imagery were acquired and analyzed for two time periods, 1990 and 2000. The key steps in the procedures were image acquisition; rectification and land cover classification; development and application of a regression model relating percent impervious to Landsat TM tasseled cap greenness, and accuracy assessment (Figure 2).

Landsat Image Acquisition, Rectification and Land Cover Classification

The 19 Landsat satellite images required to cover the state of Minnesota were rectified to the UTM coordinate and projection system to an RMS error of 1/4 pixel (7.5-meters) using approximately 25 ground control points per image. Nearest neighbor resampling to a 30-meter pixel size and the coordinates of the final image were adjusted to values evenly divisible by 30. Following rectification the imagery was transformed to tasseled cap values.

For 1990, classifications from the Minnesota GAP analysis performed by the Minnesota Dept. of Natural Resources were used. The GAP processing and classification procedures are described by Lillesand et al. (1998). The mean overall accuracy for the level 1 GAP classes that we used was 91%. The 2000 classifications used a combination of spring, summer and fall Landsat TM images and the tasseled cap greenness, brightness, and wetness features, with a k-nearest classifier (Yuan et al., 2005). The average overall classification accuracy for the 2000 statewide cover type classification was 84.5% with a Kappa statistic of 0.81.

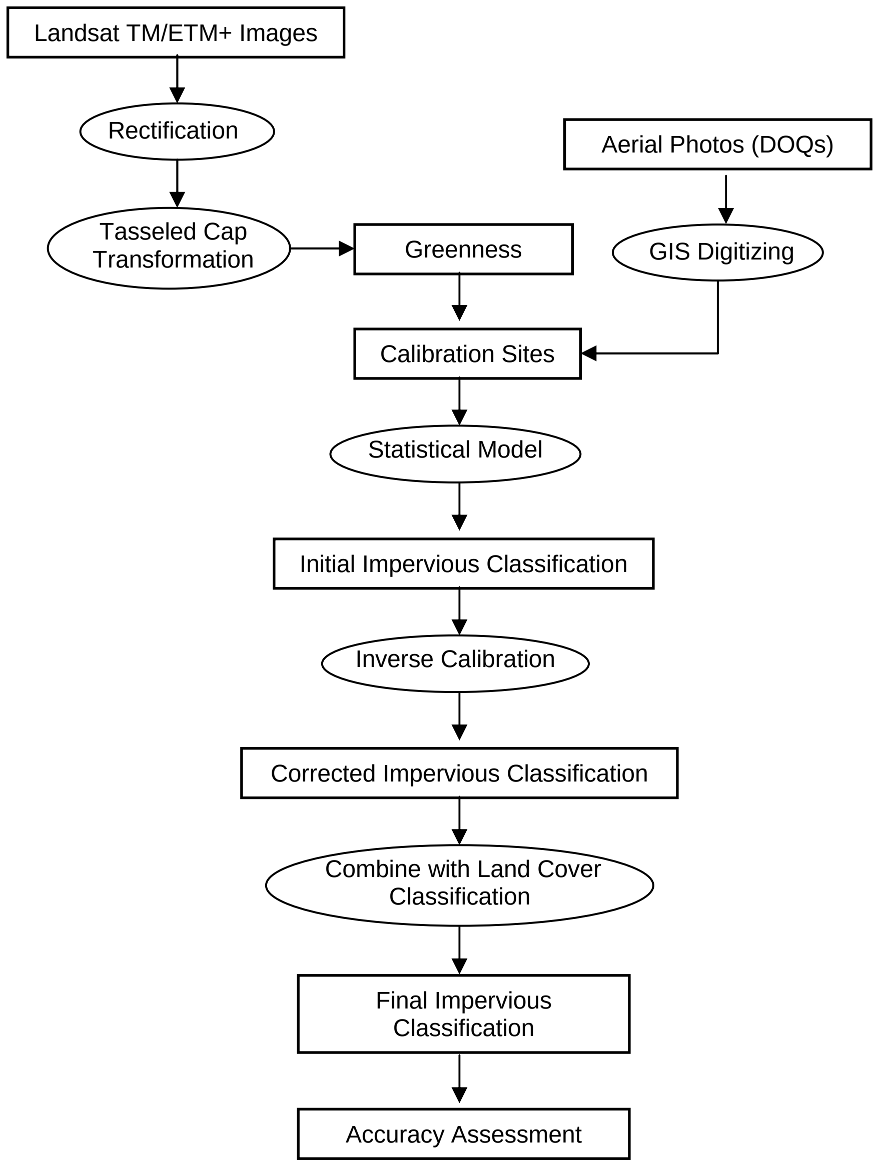


Figure 2. Flowchart of impervious estimation and classification procedures.

Impervious Surface Area Classification

Model calibration sites were randomly selected and high resolution aerial imagery was used to determine the amount of impervious surface within each calibration site. Approximately 50 sites, distributed across the image, were collected for each image. Impervious surface area was determined from the 1991 1-meter resolution DOQs for 1990 and from 2003 1-meter resolution color DOQs (FSA-NAIP imagery) for 2000. Percent impervious surface area was calculated for each site by hand digitizing impervious surface within the site.

The measurements of impervious surface area from the calibration sites were used to develop a least squares regression model relating percent impervious to the Landsat tasseled cap greenness (Crist and Cicone, 1984) responses for each of the summer Landsat images. Greenness is sensitive to the amount of green vegetation and therefore is inversely related to the amount of impervious surface area.

An independent sample of approximately 25 accuracy assessment sites were selected from each of the Landsat images to measure the accuracy of the Landsat-derived impervious surface estimates. The sites were randomly selected and compared with high resolution aerial photography. Accuracy was evaluated by regression analyses of measured vs. predicted amounts of impervious area.

To remove estimation bias an inverse calibration was computed from the linear fit of the actual vs. predicted plot and applied to the impervious surface classification (Walsh and Burk, 1993). Accuracy of Landsat derived impervious surface estimates was reassessed following the inverse calibration. Although in most cases the inverse calibration did not significantly affect the R^2 or standard error, the bias is removed. This is apparent from the reduction in the intercept and an increase in the slope.

Non-urban areas from the land cover classifications were masked and reclassified as zero percent impervious surface values. The 2000 land cover classification map was utilized as the primary identifier of urban in order to have consistent comparisons of the urban areas between the two years. Our methods, then assume that areas identified as urban in 2000, but not developed in 1990 will have a high greenness value (due to vegetative cover) in the 1990 imagery and thus will be modeled as having low to no impervious surface in the 1990 era. Areas of bare soil in agricultural fields in 1990 that are urban in 2000 will have low greenness values in each date causing errors in the modeling of impervious surface for 1990. Utilizing the 1990 GAP classification to remove the "cropland" and "grassland" areas from the areas considered as urban for 1990 minimized this error.

The majority of the Landsat imagery used was cloud and haze free, however, in the few areas with clouds, the cloud and cloud shadows were manually digitized to create a "cloud" mask that was overlaid on the impervious surface classification and all pixels within it were given a value of zero. It should be noted that there was very little area where both clouds and urban overlapped.

Mines, considered as urban in the 2000 land cover classifications, needed to be identified for further processing in the impervious surface classification. Bare soil is classified in the impervious models as having a high degree of impervious surface due to its low greenness value. Much of the area of mines is a mix of compacted soil and gravel roads surrounded by bare soil making separation of the impervious surface from bare soil difficult. At the time that this data set was produced data identifying the location and extent of all mines, small and large, in the state did not exist. However, there was data produced by the Minnesota DNR – Division of Lands and Minerals that identified the locations of active mining areas in the Mesabi Iron Range where the majority open pit mines are located. This data set was used to force the pixel values that fell within the iron mines data to an impervious value of zero.

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 is shown in Figure 3. The second order regression model has an R^2 of 0.91 and standard error of 10.7. Similar relationships were found for the other 1990 and 2000 images. 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 only applied to the areas classified as urban.

Figure 4 shows an example of the agreement between measured and Landsat estimates of percent impervious areas for the same area as Figure 3 following the inverse calibration. The statistics for all of the images for both the 1990 and 2000 classifications were consistent with R^2 values ranging from 0.80 – 0.94 with standard errors (RMSE) of 7.7 to 15.9 (Figure 5). Figure 6 combines the data from all classifications for 1990 and 2000 to assess the overall accuracy. Agreement between measured and Landsat estimates of percent impervious was very high for both time periods with R^2 values of 0.86 and standard errors of 11.8 and 11.7.

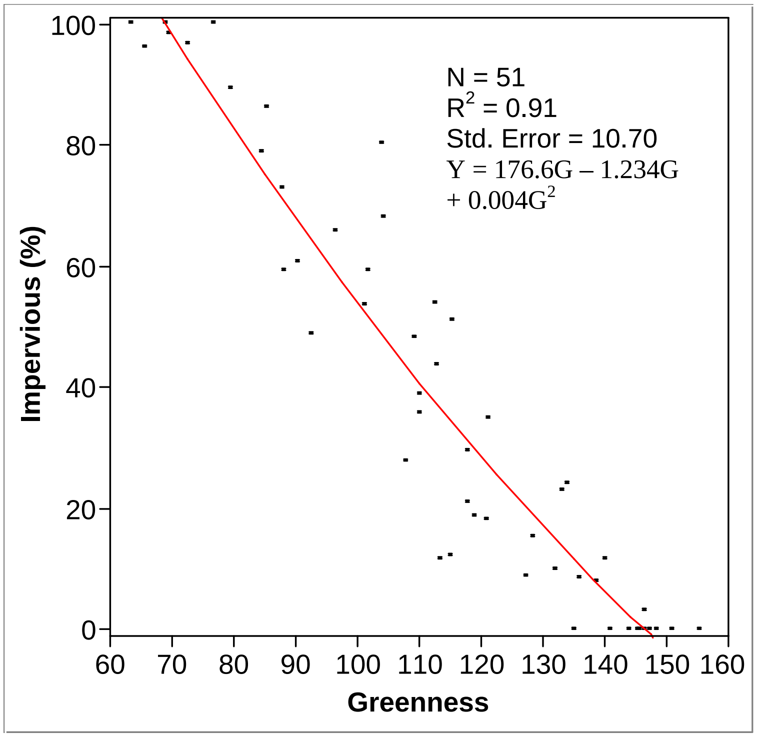


Figure 3. Relationship of Landsat TM tasseled cap greenness to percent impervious surface area for path 28/row 28, August 2000, that includes St. Cloud (Figure 6).

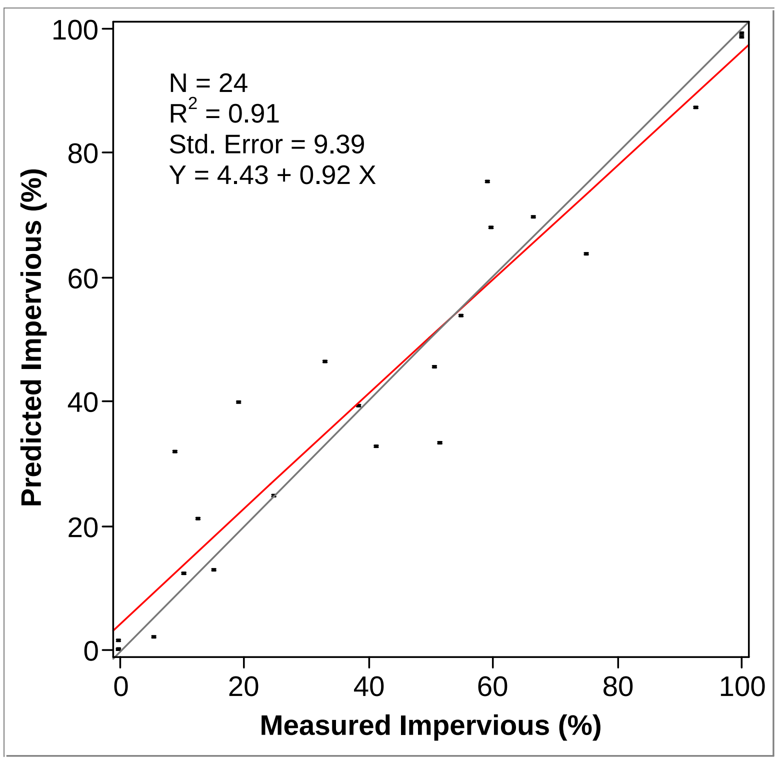


Figure 4. Comparison of measured (from DOQQ) and Landsat estimates of percent impervious surface area following inverse calibration for the same image as in Figure 3.

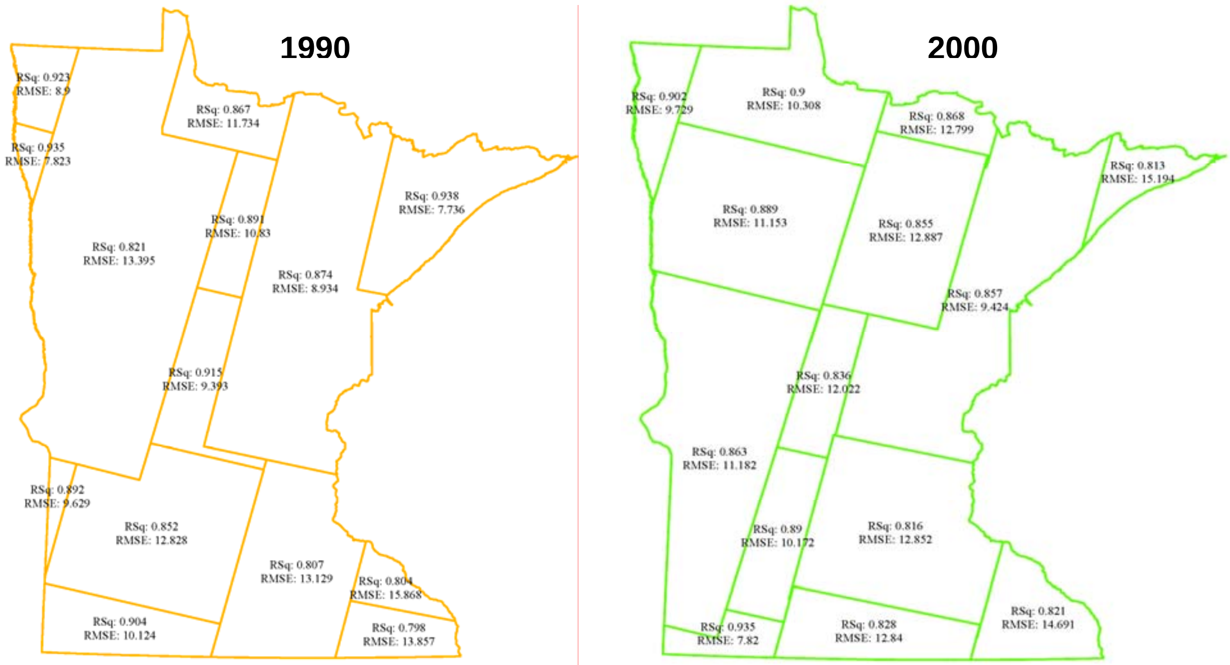


Figure 5. Statistics summarizing classification accuracies for 1990 and 2000 classifications.

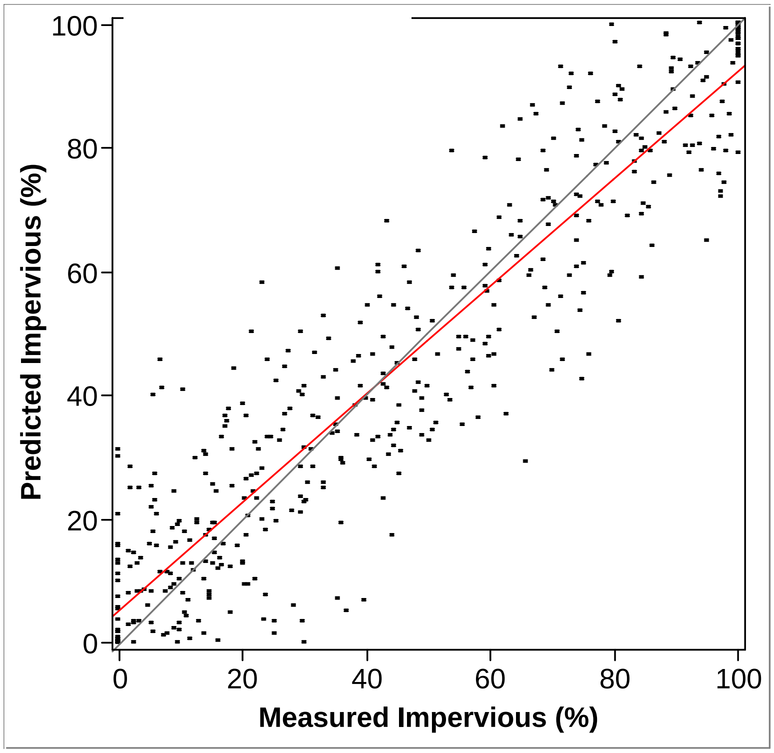
Examples of the impervious classifications and change maps for two areas, St. Cloud and Rochester, in east central and southeast Minnesota that are experiencing significant growth, are shown in Figure 7. The growth of urban area and accompanying increases in amount of impervious surface area are readily apparent. The large area covered by the classifications makes it impossible to show the entire state and see the relevant spatial detail. However, maps of the entire state with capability to roam and zoom are at: http://land.umn.edu/, along with statistics on amounts and changes in impervious area.

Table 1 lists the amount of impervious surface area for several selected cities and the entire state. Between 1990 and 2000 the amount of impervious area for the entire state increased 145,830 hectares, from 1.2 to 1.9% of the total land area, an increase of 53%.

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. 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.

In Minnesota, the Minnesota Pollution Control Agency is incorporating the impervious cover data, obtained from Landsat satellite remote sensing, into (1) fundamental watershed management efforts, (2) stormwater permit related planning by MS4 communities and (3) stormwater Best Management Practice monitoring efforts. It is likely that an increasing number of future MS4 community stormwater management efforts will have allotted phosphorus and sediment loading rates determined by formal TMDL allocation processes in order to restore and/or protect receiving water quality and habitat -- based on impervious cover and associated stormwater management practices. The consistent and quality assured impervious surface data provided the Landsat classifications for over 200 MS4 communities, covered by the phase II stormwater regulations, is critical to developing new watershed management strategies for protection as well as for rehabilitation.



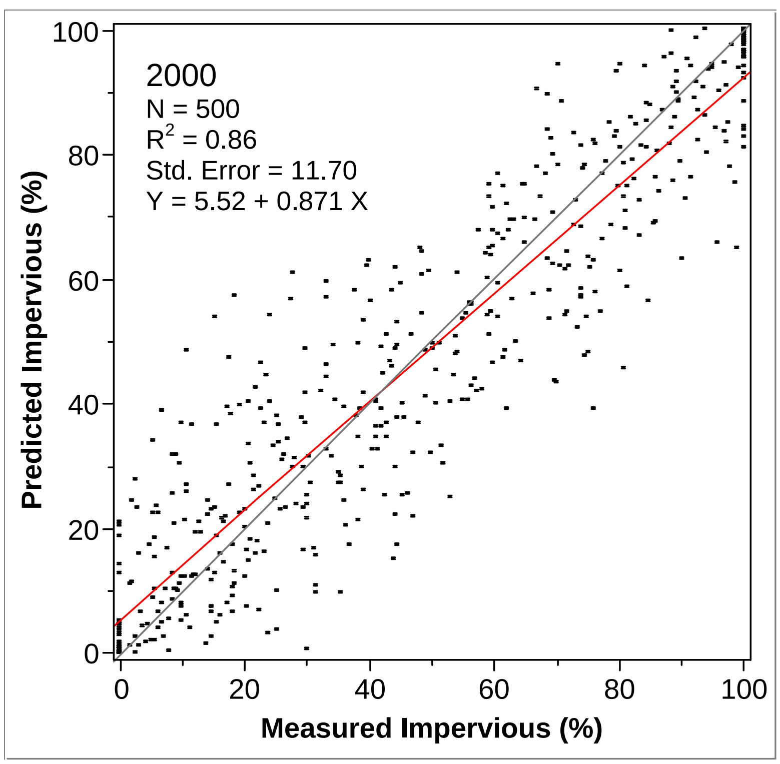


Figure 6. Evaluation of accuracy assessment statistics for 1990 and 2000 for entire state.

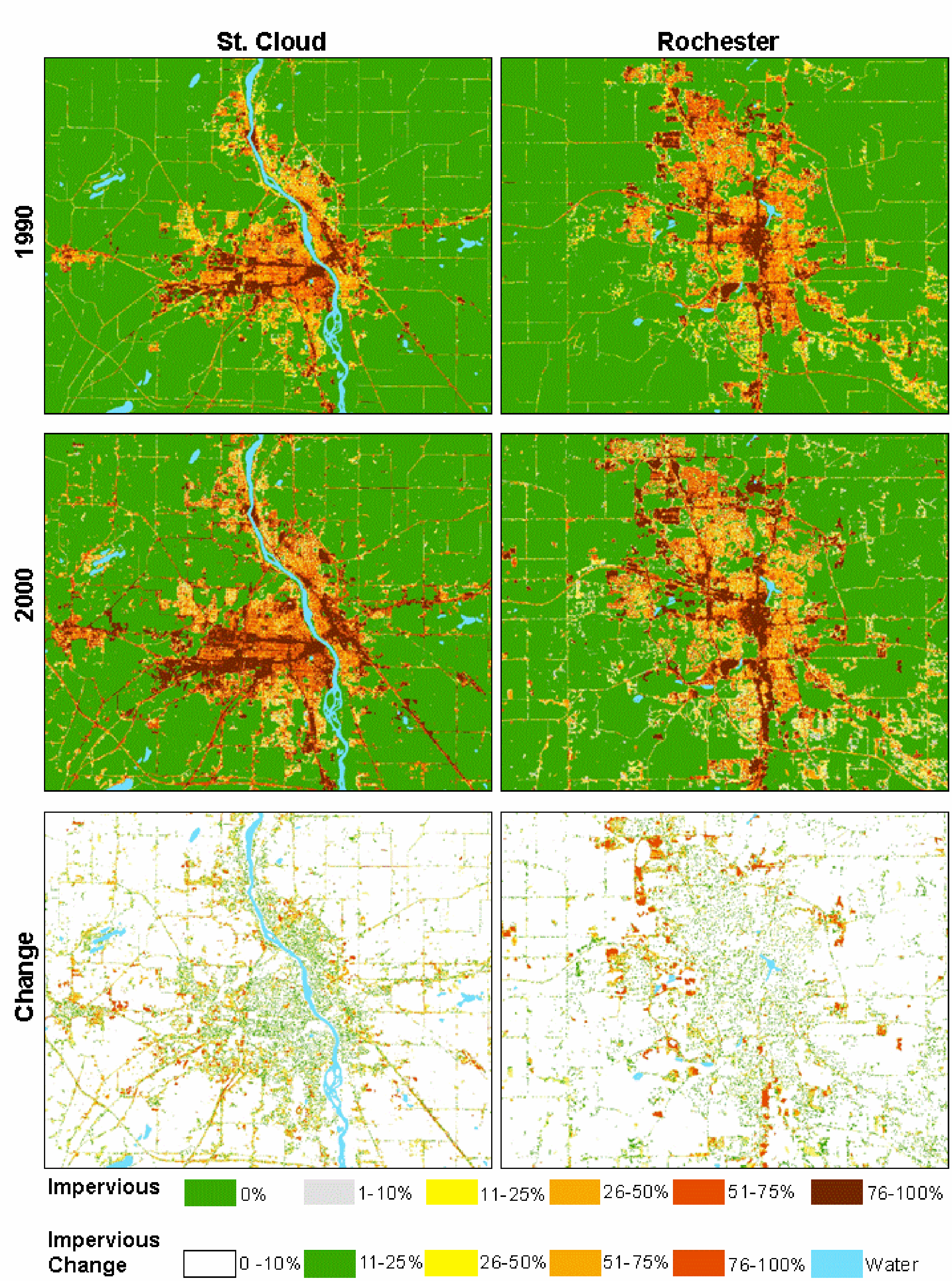


Figure 7. Impervious classifications of St. Cloud and Rochester for 1990 and 2000, and the change maps.

Table 1. Impervious area statistics for selected cities and the state of Minnesota for 1990 and 2000.

	Total Area (ha)	1990 ISA (ha)	2000 ISA (ha)	Change (ha)	1990 % ISA	2000 % ISA	Pct. Change
St Cloud	10,405	2,066	2,894	829	19.9	27.8	40.1
Rochester	11,932	2,405	2,953	548	20.2	24.8	22.8
Bemidji	3,448	625	698	73	18.1	20.2	11.6
Brainerd	2,936	518	575	57	17.6	19.6	10.9
Fergus Falls	3,879	405	634	229	10.4	16.3	56.7
Elk River	11,344	795	1,295	500	7.0	11.4	62.9
Sauk Rapids	1,409	323	499	176	22.9	35.4	54.7
Duluth	22,601	3,055	3,044	-11	13.5	13.5	-0.4
Mankato	4,290	939	1,414	474	21.9	32.9	50.5
Owatonna	3,436	757	990	233	22.0	28.8	30.7
Eagan	8,652	2,212	2,488	276	25.6	28.8	12.5
Plymouth	9,142	1,709	2,170	461	18.7	23.7	27.0
Woodbury	9,216	1,041	1,594	552	11.3	17.3	53.1
State	21,851,634	272,863	418,693	145,830	1.2	1.9	53.4

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