URBAN EXPANSION AND ITS ENVIRONMENTAL IMPACT ANALYSIS USING HIGH RESOLUTION REMOTE SENSING DATA: A CASE STUDY IN THE GREATER MANKATO AREA

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ABSTRACT

Land use and land cover change is regarded as the single most important factor of environmental changes. In cities, urbanization and its ramifications require careful consideration by our local and regional land managers in order to make the best decisions. This research investigates the urbanization in the form of spatial expansion and its impact on local environment using high resolution remote sensing data. Results demonstrate (1) urban percent impervious surfaces increased 14.3% at the expanse of similar amount (15.1%) of cropland and grassland for the Greater Mankato Area; (2) The dramatic urbanization caused evident environmental impacts on local runoff and water quality. These findings provide local decision makers the most accurate temporal - spatial inventory of landscape change and quantitatively environmental and economic impacts analysis.

INTRODUCTION

Urbanization refers to the increase in population, density, or extent of cities over time. Urbanization in the form for increase in spatial scale, also called urban expansion, has long been considered a sign of regional economic vitality. Alig (et al., 2004) projected that the total developed area of United States will increase by 79% by 2025 if population increases 35%. Majority of the newly developed land has come and is expected to continually come from the conversion of croplands and forestland, particularly with the movement of residential and commercial land use to rural areas at the periphery of metropolitan area. However, the benefits of urban expansion are increasingly balanced against environmental impacts (Squires, 2002). Compare to any time in the past, the magnitude and perceived significance of environmental effects from urbanization are probably far greater today. The increased amount of urban impervious surface from rapid urban expansion not only causes growing problems of air pollution, water quality degradation, habit fragmentation, irreversible resource, and traffic jams but also affects local climate by modifying energy balance, surface temperature, and precipitation patterns (Carlson and Arthur, 2000; Collinge, 1996; Dougherty et al., 2004; Nikolakaki, 2004; Tilman et al., 2001).

Remote Sensing in the context of geographic information systems provides an effective tool for exploring the range of impacts of land development. Earlier relevant studies using remote sensing have been focused mainly at regional scale in 30 m Landsat imagery due to its synoptic view and effective cost. The advancement of satellite technology, especially the recent availability of high-resolution satellite remote sensing images and Digital Orthophotography Quadrangles (DOQs), provides an improved ability to assess environmental effects of urban expansion at local scales.

This study aims to analyze the environmental change and effects in a regional center – The Greater Mankato Area – in south central Minnesota from 1971 to 2003. In particular, land cover change and patterns are explored in comparison to population change and dynamics. Major environmental and economic impacts in relation to urban expansion are assessed using GIS modeling. The implications for landscape and urban planning from the change and effects are discussed. This research contributes to the larger body of knowledge on urban environmental monitoring and analysis. The data collected and the database built in this research will serve as a solid basis for future practical applications. The integration of remote sensing and GIS method provides comprehensive LULC information in a more effective way.

The study site includes two small "Sister Cities" – Mankato and North Mankato along the Minnesota River, which is located about 80 miles southwest of the Twin Cities of Minneapolis and St. Paul. With a total area about 52 km^2 and a total population about 47,000 in 2005, this regional social and economic center provides an ideal site for local level urban environmental change and assessment. Adams et al. (2003) reported a medium economic and population growth rate for this area from 1970 to 2000. Nevertheless, a more recent study based on 30 m Landsat remote sensing data revealed dramatic urban expansion (50% increase of impervious surface area) from 1990 to 2000 (Bauer et al., 2005). These studies provide a broad and synoptic view of urban dynamics for this area. However, in highly heterogeneous urban environment, only sub 5 m resolution may provide satisfactory results for local studies (Antrop, 2004). Therefore, to provide a suitable direction for policy and decision makers in this area, it is imperative to perform land use and land cover inventory, and assess the dynamics and effects of urbanization using higher resolution data.

METHODS

Image Preprocessing and Automatic Land Cover Information Extraction Using Feature Analysis

Remote sensing data include (1) 1971 9-inch 0.6-m black and white (B&W) air photographs; (2) 2003 summer 1-m NAIP DOQ mosaic of the Blue Earth County; (3) 2003 Quickbird satellite image bundles with four multispectral bands at 2.4 m resolution and one panchromatic band at 0.6 m resolution acquired on October 6, 2003 (Figure 1). The 1971 photographs were acquired on different dates with varying atmospheric and illumination conditions. They were scanned at 600 dpi and 16 bits-per-pixel color and imported to ERDAS IMAGINETM image files. All the 1971 images were then georectified to UTM zone 15, GRS1980, NAD83 using 2000 Street Map as the reference. The total root-mean-square error of rectification is The 2003 Quickbird data were reprojected from the original WGS projection to UTM and georectified again to match the 2003 NAIP color digital orthophoto. Finally, all the three different datasets were clipped within the limits of our study area.

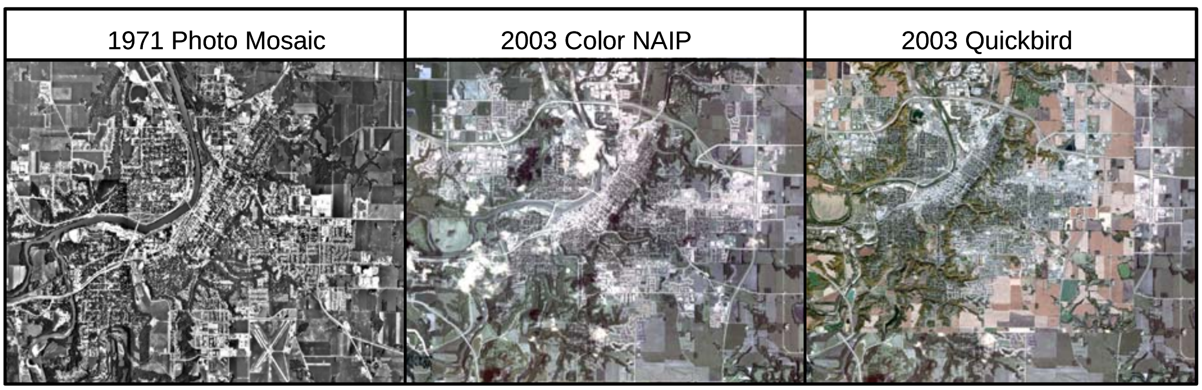

Figure 1. Remote sensing images used in the study.

Comparatively, the single band 1971 photography contains the lowest amount of spectral and radiometric information while the 2003 Quickbird image has the highest quality in terms of spectral and radiometric resolution. The 2003 color NAIP is partially contaminated by clouds and cloud shadows. Given difficulties in radiometric correction and normalization, especially for historical scenes, the 1971 photo mosaic show large amount of uncertainties caused by varying atmospheric and illumination conditions. The low variance of 1971 image makes digital image classification difficult due to similar spectral responses between bare soil and urban impervious, and between some crop fields and forests. To improve classification accuracy, a 3×3 second-order (variance) texture analysis, a measure of heterogeneity which increases when the gray level values differ from their mean, was applied to the 1971 aerial photography.

The resulting texture image was then stacked with the original 1971 aerial photo as an additional layer for land cover extraction. The texture image not only increased the discrimination of land covers since forest and urban impervious surface demonstrate much more heterogeneous textures from the homogenous patterns of crop field (Figure 2), but also helped to minimize classification errors caused by varying atmospheric and illumination conditions.

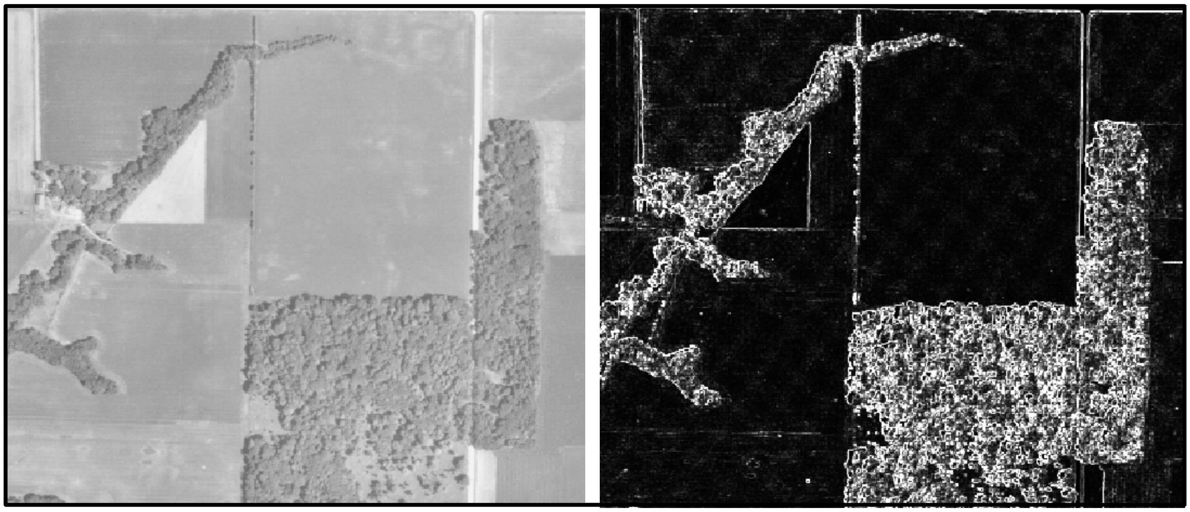

Figure 2. 1971 Aerial photography vs. its texture image.

For 2003 image classification, both the NAIP color air photography and the Quickbird Image were utilized. The multispectral and panchromatic bands of Quickbird data were fused to provide a four-band image with 0.6 m resolution, which was then stacked with the color NAIP to get a seven-band image. The fused image help improve classification accuracy by reducing misclassified class, cloud effects, and shadow problems. In particular, shadow has been a very difficult problem to address in high resolution imagery usually (Yuan and Bauer, 2006), but the stacked 7-band data was able to resolve the shadow problem successfully since many shadows in the Quickbird imagery are not shadowed in the NAIP data and vise versa.

Training polygons for four land cover classes – impervious surface, forest, cropland/grass, and water – were digitized as separate shapefiles for both years. Virtual Learning System's (VLS) Feature Analyst™ was used for the classification. Using spatial context as well as spectral information, this software is designed particularly for classifying high-resolution data. Another advantage of Feature Analyst is it addresses image clutter with a hierarchical approach that allow the Classifier not only to learn from the user input but also to refine classification results by mitigating clutter and retrieving missed features (VLS, 2005). Using Feature Analyst™, each of the four land covers were extracted as vector layers, which then were converted to 1 meter raster images for both years. A 3×3 majority filter was applied finally to remove isolated pixels on the classification maps.

Environmental Impact Assessment Using GIS

The environmental and economic impacts from land use change, especially urban forest and impervious surfaces changes were assessed using CITYgreen™, which is a comprehensive tool that can be used to calculate the environmental benefits provided by urban trees and to model the impacts of various development and planning scenarios. It has four major functions of analyzing air quality, carbon storage and sequestration, stormwater runoff, and water quality changes.

In particular, the Curve Number (CN) that describes how much of the rainfall that falls on a site will run off and how quickly that will happen is determined based on land cover and soil conditions, which the model represents as hydrologic soil group, cover type, and hydrologic condition (USDA, 1985). A hydrological soil group code "A", "B", "C", or "D" is used as a measure of infiltration capacity of water in soils in the model. "A" soil type is very pervious with the highest rate of infiltration. The rate of infiltration is decreasing with the changes of "A" type soil to "D" type soil. In CITYgreen™ , CN for each pixel was first generated based on the standard lookup tables in USDA (1985) and USDA (1986). Next, the mean CN value of each land cover was calculated and then weighted to get a composite value for the entire site.

Next, CITYgreen assesses how land cover, soil type, and precipitation affect stormwater runoff volume use the TR-55 model, which is based on curve number. Curve numbers range from 30 to 100. The higher the curve number the more runoff will occur. The volume of runoff in a 2-year 24-hour storm event that would need to be contained by stormwater facilities if the trees were removed was calculated first. This volume was then multiplied by local construction costs to calculate the dollars saved by the tree canopy. Finally, the relationship between the amount of pollutants present in the nearby water bodies and the composition of land cover was also modeled. More specifically, changes in concentrations of Nitrogen, Phosphorus, Suspended Solids, Zinc, Lead, Copper, Cadmium, Chromium, Chemical Oxygen Demand (COD), and Biological Oxygen Demand (BOD) in runoff during a 24-hour storm event were estimated.

RESULTS AND DISSCUSSION

Urban Expansion Derived from the Land Cover Classifications

Land cover classification maps for both years are displayed in Figure 3. An accuracy assessment based on 300 randomly digitized sample points on both year's images were implemented. The overall Kappa statistics are 0.87 and 0.9 respectively for 1971 and 2003. The slightly higher accuracy of 2003 classification is reasonable since the fused 7-band image contains much more spectral information than the B&W aerial photography of 1971.

In Figure 3, striking suburban expansions can be identified for the Greater Mankato Area. The largest cluster of urban growth at the expense of the vast expanse of cropland is located in the northeastern region. This area is the current business and commercial centre of Mankato, where highway 22 located in a north-south direction intersects with highway 14 running in east-west direction. Dramatic rural to urban conversions in the north, northwest, and south areas are also apparent. Specifically, the newly developments in the north are mainly industries and commercials, while growths in the south are dominated by new residential houses. The northwest rural area of Northern Mankato converted dramatically to residential and commercial land uses.

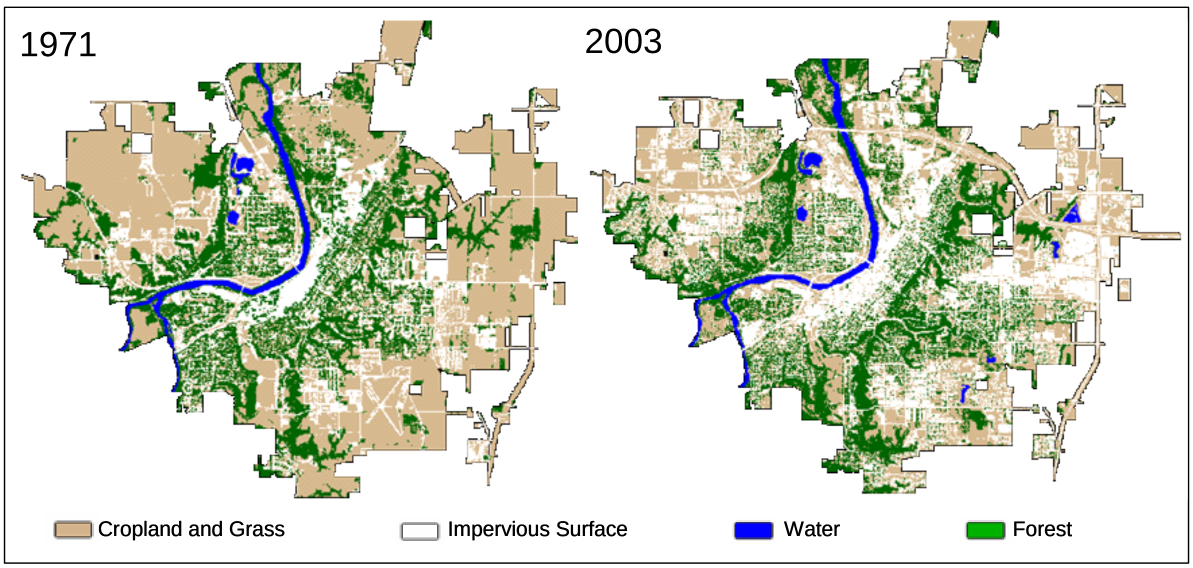

Figure 3. Land cover classification maps.

The individual class area and change statistics for both years are summarized in Table 1, which demonstrates urban impervious area increased 721 ha (about 83.2%) 2003 while cropland and grassland decreased 734 ha from 1991 to 2003, implying dramatic expansion for this area.

Table 1. Land Cover Classification Statistics for 1971 and 2003.

Land Cover Class	1971		2003	
	ha	%	ha	%
Impervious Surface	867	18.3%	1588	32.6%
Forest	1229	25.3%	1250	25.7%
cropland	2638	54.2%	1904	39.1%
Water	108	2.2%	123	2.5%

Environmental Effects from the Urban Expansion

The two land cover maps were then imported in GIS and utilized along with other input layers including the 10-m digital elevation model, and soil map by CITYgreen^{TM} to model the effects of urban expansion. CITYgreen^{TM} estimates the carbon storage capacity was about 130 thousand tons and the carbon sequestration rate of trees was one thousand tons per year for both 1971 and 2003 due to the consistent amount of urban forest for both years.

Urban trees also perform a vital air cleaning service by absorbing and filtering out air pollutants. Table 2 presents the annual air pollution removal rate of trees and the dollar values of the pollutants in Mankato and North Mankato. O3, NO2, and PM10 take up more than 98% of the total pollution. The actual externality costs of each air pollutant used in CITYgreen to calculate the dollar values is set by the each state's Public Services Commission.

Table 2. Annual air pollution removal rate of trees and the dollar values of the pollutants in Mankato and North Mankato.

(a) Mankato

	1971		2003	
Air Pollutant	Lbs. Removed/yr	Dollar Value ($)	Lbs. Removed/yr	Dollar Value ($)
CO	6,103	2,605	6,141	2,621
O_3	63,064	193,746	63,458	194,957
NO_2	30,515	93,748	30,706	94,334
PM	22,378	45,900	22,517	46,187
SO_2	4,069	3,053	4,094	3,072
Totals	***126,128***	***339,053***	***126,916***	***341,172***

(b) North Mankato

	1971		2003	
Air Pollutant	Lbs. Removed/yr	Dollar Value ($)	Lbs. Removed/yr	Dollar Value ($)
CO	2,001	854	2,100	896
O_3	20,679	63,531	21,705	66,681
NO_2	10,006	30,741	10,502	32,265
PM	7,338	15,051	7,702	15,797
SO_2	1,334	1,001	1,400	1,051
Totals	***41,359***	***111,178***	***43,409***	***116,691***

The CN numbers in which reflect existing land cover and soil conditions increased from 1971's 83 to 2003's 86, implying a 0.2 inch increase of surface runoff from 1971 to 2003. The total stormwater savings are more than $30 million. Modeling results of the change in the concentration of the pollutants in runoff during a typical storm event also show that the Event Mean Concentrations (EMC) of nitrogen, phosphorus, suspended Solids, copper, cadmium, chromium, chemical oxygen demand, and biological oxygen demand all increase more than 20%, given the scenario of replacing all the trees with impervious surface.

CONCLUSIONS

This research investigates the urbanization in the form of spatial expansion and its impact on local environment using high resolution remote sensing data through digital image processing and GIS modeling. Dramatic urban expansion was found with similar degree of cropland decrease. Urban expansion caused evident environmental impacts on local runoff and water quality. The study also demonstrated reliable land over features can be extracted effectively from high-resolution imagery with the help of various digital image processing techniques such as texture analysis, image fusion, and the hierarchical machine-learning Feature Analyst classifier. By providing the most accurate temporal - spatial inventory of land use and land cover information and precise environmental and economic impacts analysis, this study allows decision makers to make informed decisions on environmental and resource management issues.

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