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GIS and Cartography at the University of Toronto Technical Paper Series

Paper No. 1:
A guide for deriving a consolidated built-up urban area for the Toronto metropolitan region using satellite imagery

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Byron Moldofsky, and Jo Ashley

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GCUT - GIS and Cartography at the University of Toronto Technical Paper Series - Paper no. 1
A guide for deriving a consolidated built-up urban area for the Toronto metropolitan region using satellite imagery

Abstract

This paper describes a method for mapping and analysing the built-up urban area of a municipality using Landsat Thematic Mapper (TM) 5 satellite imagery and Geographic Information Systems. The goal was to develop a consistent method for delineating a consolidated built-up urban area using established image processing techniques and specific post-processing rules. It includes a step-by-step description of the image processing method, the statistical assessment of the resulting classification, and the post-processing analysis used to refine the final product.

Keywords: remote sensing, urban form, built-up urban area

Preface

This paper describes a method for deriving a built-up urban area for large urban regions using Landsat Thematic Mapper (TM) 5 satellite imagery. The procedure described here is a work in progress. The paper is the first in a series of methodological papers hosted by the Department of Geography at the University of Toronto that describe the application and use of remote sensing and GIS techniques to examine urban planning and other issues. The work is based on research by Dr. Wayne Forsythe and Baorong (Paul) Du that examined urban growth over time in the Greater Toronto Area. This work was published in Du's master's thesis.[1] Forsythe's work has been presented at many conferences and in various journals.[2]

The Neptis Foundation funded research to adapt and expand the original method to address a larger study area: the Toronto metropolitan region, or Greater Golden Horseshoe, a moniker recently coined by the Province of Ontario. The purpose was to develop a method that could be used to delineate a consolidated built-up urban area in any urban region, using well-established image processing techniques and post-processing rules. Although the method described within is specific to time, place and software, it should be adaptable to other circumstances.

This paper contains few references to the literature, since these references have been well-documented in work by Du and Forsythe. Rather, it includes a step-by-step description of the image processing analysis, the statistical assessment of the land cover classification, and the post-processing analysis used to refine the original land cover classification, including its conversion from an image to a vector data set. This final step allows for the integration of the built-up urban area data set with other geospatial data sets required to estimate intensification. Screen captures from the various software packages used in the analysis (PCI Geomatica v9.x, ERDAS Imagine v8.x, ArcGIS v.9.2) have been included to illustrate the method and its implementation.

The consolidated, built-up urban area data set was to be used to examine residential intensification trends (see "A methodology for estimating the historical rate of residential intensification between 1991 and 2001 for the Toronto Region", paper no. 2 in the *GIS and Cartography at the University of Toronto Technical Paper Series*). After developing the procedure for the Toronto region, the research was then expanded to two other Canadian urban regions: the Greater Vancouver Region and the Calgary census metropolitan area. The method was tailored to account for the unique physical landscape in both regions. The adapted procedures for these cities will be documented in forthcoming papers in this series. A non-technical overview of the process is available on the website the Neptis Foundation. Readers may find it helpful to read the overview first, to get an overall idea of the procedure, before studying the method described in this paper.

1 Du, Paul, "Urban Change Detection and Analysis in the Greater Toronto Area from 1971 to 2004 using Remote Sensing and GIS," Ryerson University: [2005]. The paper was published as part of the requirements for the degree in Master of Spatial Analysis, a joint Masters program between Ryerson University and the University of Toronto. The thesis is available at the Ryerson University library and the Cartography Office at the University of Toronto.

2 See, for example, K.W. Forsythe, Pansharpened Landsat 7 Imagery for Improved Urban Area Classification. *Geomatica* vol. 58, no. 1, March 2004, pp. 23-31.

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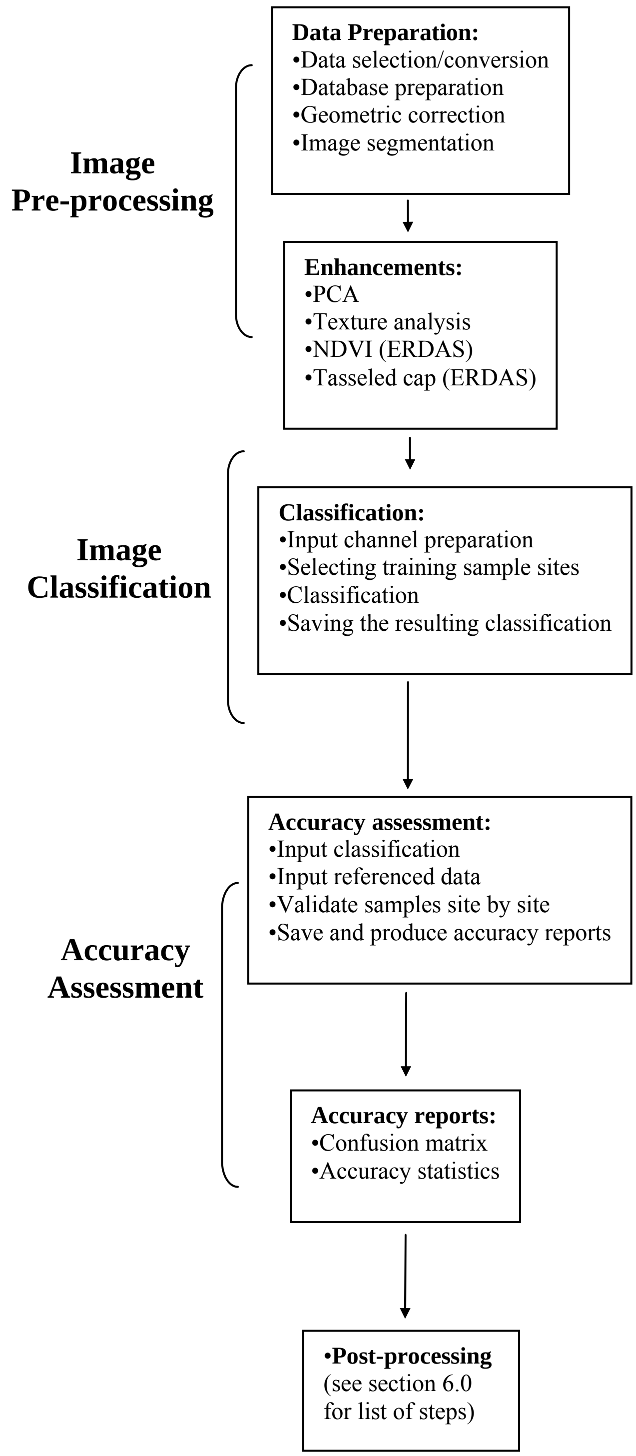
1. Introduction

The Toronto metropolitan region extends over 33,000 km2. Most of the urbanized land centres on the City of Toronto, with satellite cities in the west and north, and smaller communities dotting the landscape. The physical landscape includes large amounts of rural, non-urbanized land, many water bodies both large and small, and a variety of natural heritage or greenland features. The Landsat TM5 satellite imagery required for this study area contains more than 200 million pixels, or bits of information. The challenge of processing this amount of information was overcome by segmenting the study area into smaller, more manageable areas of analysis that contained similar terrain and land cover.

After the initial preparation of the data was complete, the study area was broken down three areas of similar terrain and land cover. Those areas were further subdivided in order to expedite processing time. For each area, a land cover classification data set was derived using a supervised classification algorithm that included six spectral bands, along with several image enhancements, as inputs to the procedure. A statistical assessment of the output data sets was performed for each of three areas and one sub-area. In the post-processing stage, urban category of the classification for each area was isolated and mosaicked (or stitched together) to obtain an urban land cover map for the entire study area. This data set was then converted from its original raster format to a vector format. Finally, the consolidated built-up urban area was determined using a set of iterative rules. The analysis was performed on 1990 and 2001 satellite imagery for the Toronto. In this paper, the 2001 analysis for the Toronto region is described and illustrated. The chart below outlines the work flow for the image processing procedure. The GIS post-processing procedure is outlined in a chart at the beginning of chapter 6.

Figure 1.1: Overview of image processing methods



2. Data Preparation and Pre-processing

2.1 Imagery selection and purchase

Landsat TM5 imagery can be purchased through the United States Geological Survey's (USGS) Earth Explorer (http://edcsns17.cr.usgs.gov/EarthExplorer/). The Earth Explorer web interface allows the analyst to examine available imagery and assess its quality before making a purchase.

The methods employed in this analysis are sensitive to several factors that affect the quality of a single image and consistency between images. These include:

- cloud cover over an area;
- geometric referencing;
- radiance consistency of land covers between images.

Therefore certain considerations should be made when purchasing imagery for a study area.

The images should be greater than 90% cloud-free and acquired during the summer or early fall months when trees are in leaf. If more than one image is required for a study area, the images should be captured at the same time period or during the same season.

Each Landsat TM5 image contains seven bands (six spectral and one thermal); information for each band is stored in a separate file. Only the spectral bands are necessary for this analysis. Imagery can be requested in two file formats: NDF or TIF. The latter is recommended, as it is easily imported into many different image processing and GIS software packages.

2.2 Database preparation and importing imagery

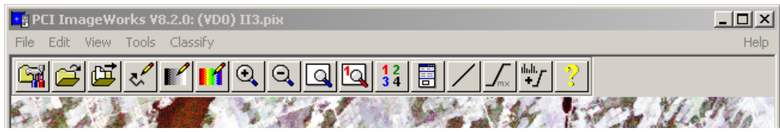
The analysis employed two image processing software packages: PCI Geomatica™ and ERDAS Imagine™. PCI was used for most of the processing, including image classification and accuracy assessment.

To begin the analysis, a PCI database file (.pix) needs to be created for each TM5 image. A PCI database stores the input and output information used and created in the analysis. The information is stored as separate channels within the database. At this point in the analysis, the newly created pix file requires only six channels, one for each spectral band. After the TM5 images have been geocorrected (see section 2.3), and segmented (section 2.4), the segmented pix files require 16 channels, one for each of the spectral bands plus eight enhancements of the spectral bands. Two additional channels will also be needed to store the training sites used as input to the classification procedure and the final results of the land cover classification.

2.2.1 Procedure

1. Open ImageWorks™ in PCI to create a new database

Figure 2.1: PCI Image Works menu

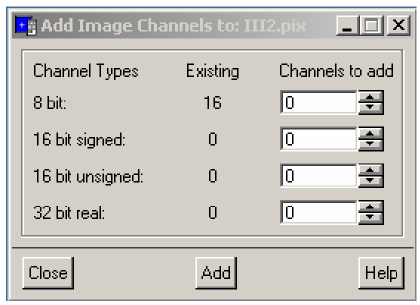


2. Under File menu, go to "Import spectral bands" to import each of the six original geotiff files.

3. Under Edit menu, go to File Utility and select "Add Layers."

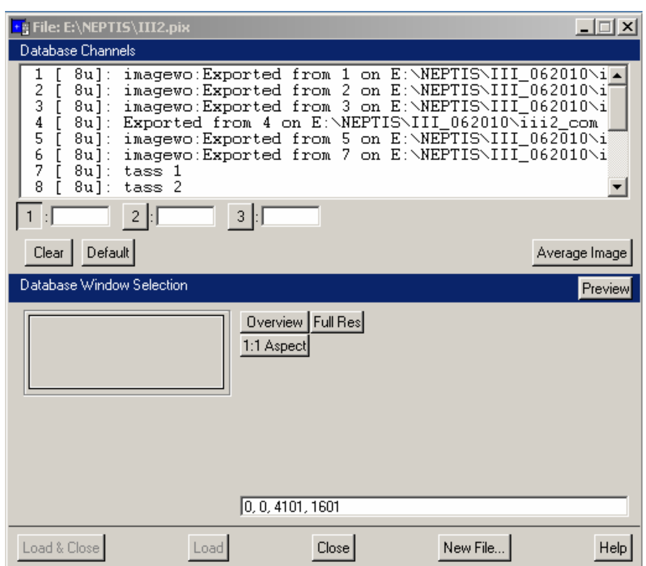
4. Specify (6) 8-bit channels. Click "Add."

Figure 2.2: Add Image Channels dialogue box



5. To see an image in colour, a combination of spectral bands needs to be displayed, so database channels 1, 2 and 3 must be mapped to the image planes 1, 2, and 3. Map these channels and click "Load and Close."

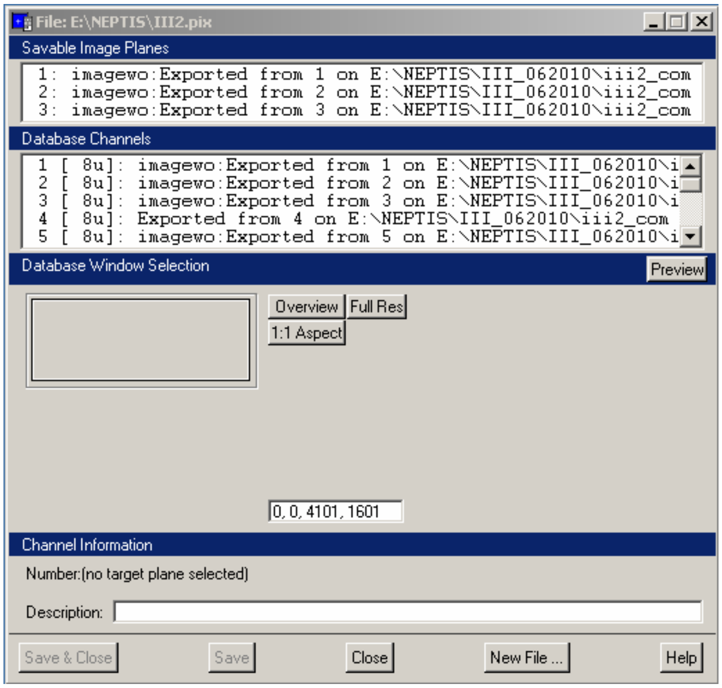
Figure 2.3: Mapping database channels to image planes



6. In the Image Works menu under file, click "Save Image." This will allow all imported geotiff files to be saved in a .pix file or a PCI database. The image planes must be mapped again, but in

this box, a description of each database channel can be entered as an alternative to a default description, which is the pathname of the original image. This will be particularly useful when more database channels are needed to accommodate the image enhancements, classification training site, and results.

Figure 2.4: Save Image dialogue box



2.3 Geometric correction

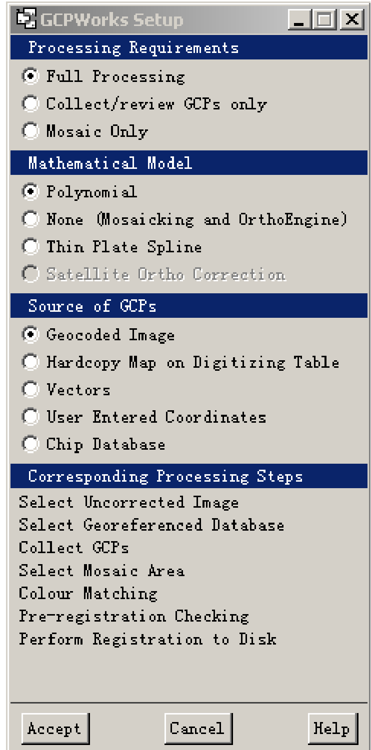
Although imagery is georeferenced by the USGS, a thorough comparison of each image against all overlapping images is necessary, since there may be small shifts between scenes. Typically, street intersections are used to determine whether two scenes are geometrically correct. GCPWorks™ in PCI is the recommended software for geocorrecting images. During this process, ground control points (GCPs) are selected in the image that align to a street network data set and used to correct the misaligned image. The procedure is described below. Further considerations are provided as a guide for the analyst.

2.3.1 Procedure

1. Start GCPWorks.

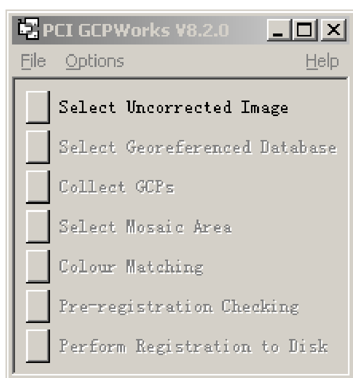
2. Choose GCPWorks Setup, and click “Accept” to the default options of (1) full-processing, (2) a first-order polynomial fit and (3) the geocoded, or georeferenced, image as the source of the GCPs.

Figure 2.5: GCPWorks Setup



3. Check "Select Uncorrected Image" button in PCI GCPWorks dialogue box.

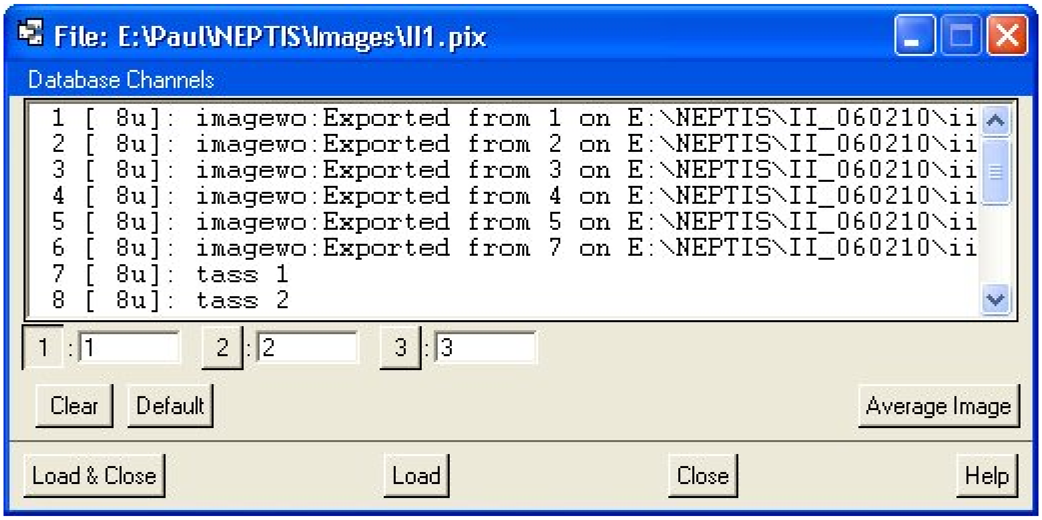
Figure 2.6: GCPWorks dialogue box



4. After selecting the PCI database file containing the uncorrected image, click "Default." This will display the image using spectral bands 1, 2, and 3.

5. Click "Load & Close" to initiate process. These bands will provide a natural colouring of the image during the geometric correction process.

Figure 2.7: Database channels dialogue box



6. At this point, two windows will open: the overview window and the zoom window. The display of the overview window is limited, but the zoom window is based on the image resolution (30 metres for TM5), revealing more detail in the image during the GCP selection process.

Figure 2.8: Overview window

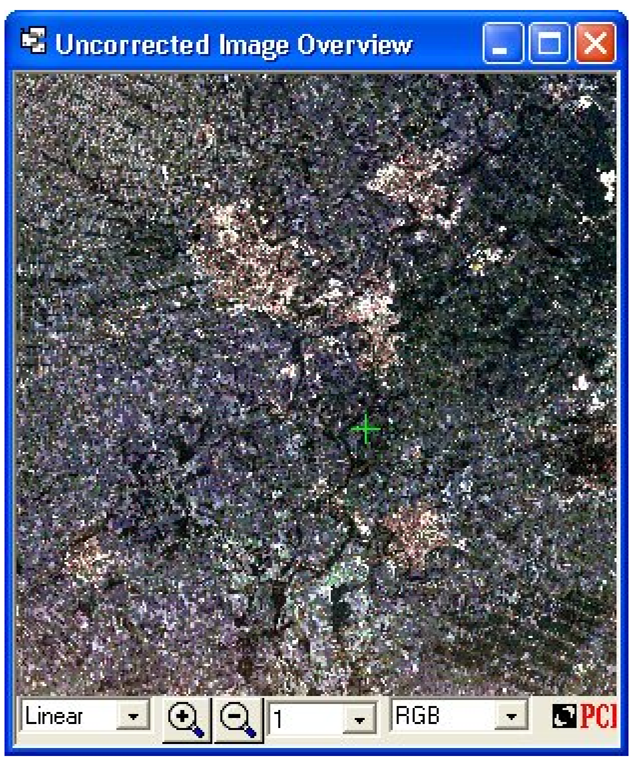
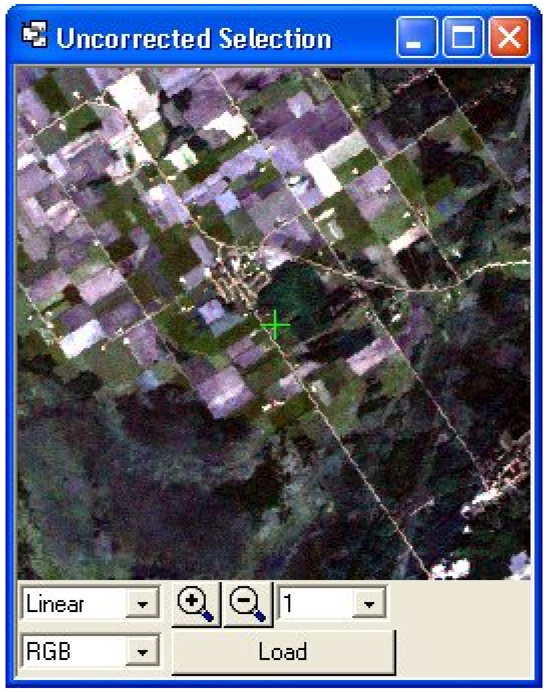


Figure 2.9: Zoom window



7. Go back to GCPWorks dialogue box. Click “Select Georeferenced Database.”

8. Import georeferenced image. Click “Default” and “Load & Close.” As in step 4, this will open the overview and zoom windows.

9. Go back to GCPWorks dialogue box. Click “Collect GCPs” to collect the ground control points.

10. The GCP Selection and Editing dialogue box will open. GCPs must be identified first in the uncorrected image, then in the georeferenced image. The GCP Selection and Editing dialogue box displays an ID for each GCP collected, as well as the coordinates of the GCP from the corrected and uncorrected image. Once a GCP is selected and accepted, the residual error will be displayed in the Selection and Editing window. The residual error is reported in pixels and represents the distance between the location of the point in the uncorrected image, as calculated by the polynomial fit model, and the location of the point in the georeferenced image. This error should be as small as possible, no larger than one pixel in the x and y direction. The overall root mean square (RMS) error is also reported and will change after adding and deleting GCPs. The RMS is the mean or average distance deviation from the GCPs and their associated location points in the georeferenced image.

Figure 2.10: GCP Selection and Editing dialogue box showing uncorrected and georeferenced selections

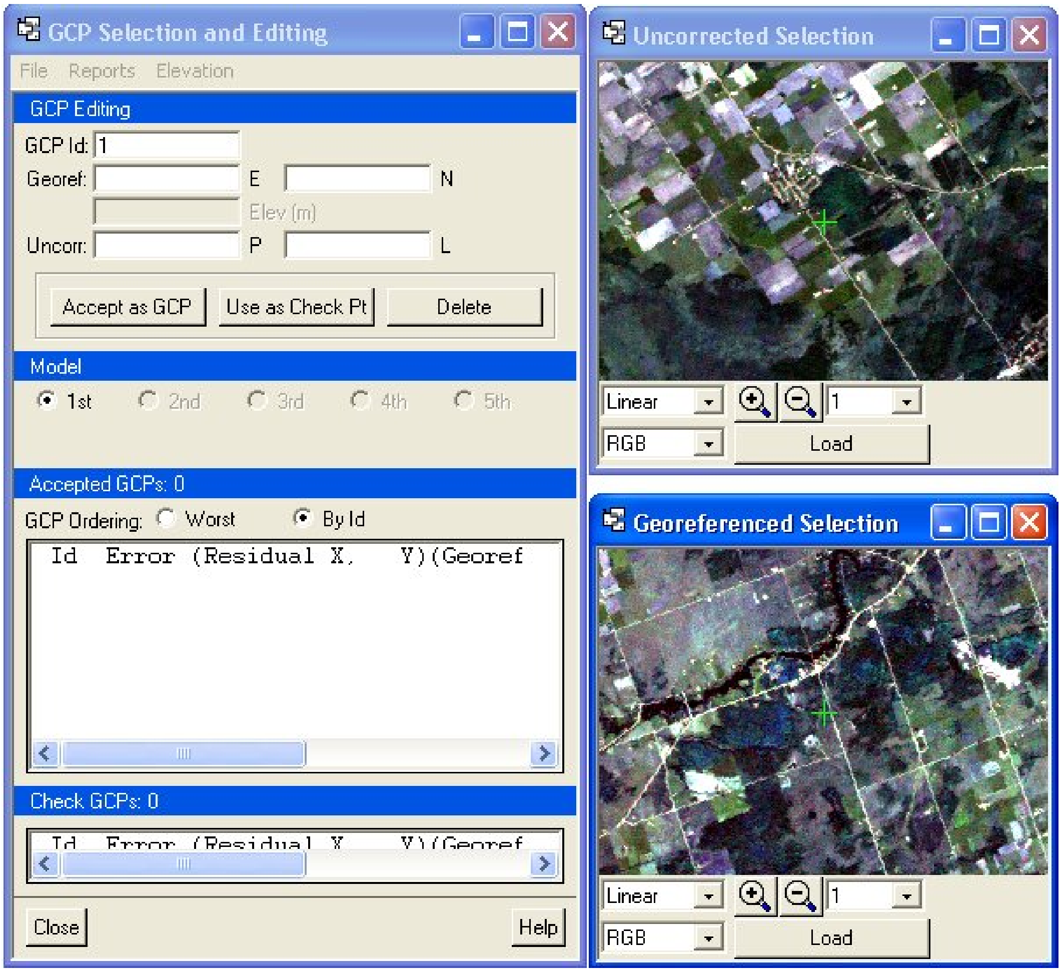
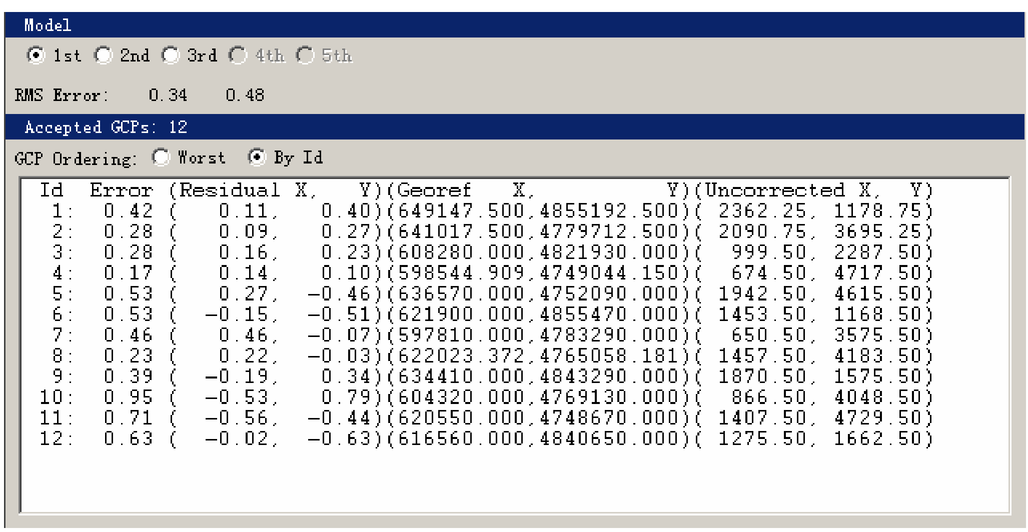


Figure 2.11: Dialogue box showing residual errors


Model

1st 2nd 3rd 4th 5th

RMS Error: 0.34 0.48

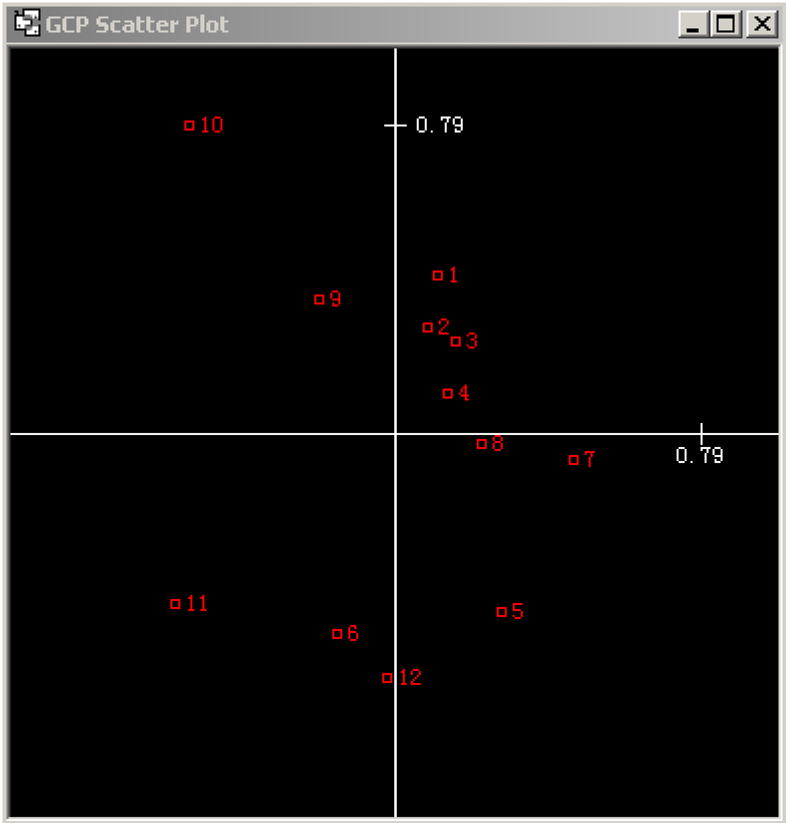
Accepted GCPs: 12

GCP Ordering: Worst By Id

Id	Error	(Residual X,	Y)	(Georef X,	Y)	(Uncorrected X,	Y)
1:	0.42	(0.11,	0.40)	(649147.500,	4855192.500)	(2362.25,	1178.75)
2:	0.28	(0.09,	0.27)	(641017.500,	4779712.500)	(2090.75,	3695.25)
3:	0.28	(0.16,	0.23)	(608280.000,	4821930.000)	(999.50,	2287.50)
4:	0.17	(0.14,	0.10)	(598544.909,	4749044.150)	(674.50,	4717.50)
5:	0.53	(0.27,	-0.46)	(636570.000,	4752090.000)	(1942.50,	4615.50)
6:	0.53	(-0.15,	-0.51)	(621900.000,	4855470.000)	(1453.50,	1168.50)
7:	0.46	(0.46,	-0.07)	(597810.000,	4783290.000)	(650.50,	3575.50)
8:	0.23	(0.22,	-0.03)	(622023.372,	4765058.181)	(1457.50,	4183.50)
9:	0.39	(-0.19,	0.34)	(634410.000,	4843290.000)	(1870.50,	1575.50)
10:	0.95	(-0.53,	0.79)	(604320.000,	4769130.000)	(866.50,	4048.50)
11:	0.71	(-0.56,	-0.44)	(620550.000,	4748670.000)	(1407.50,	4729.50)
12:	0.63	(-0.02,	-0.63)	(616560.000,	4840650.000)	(1275.50,	1662.50)

11. Go to Reports next to File menu in GCP Selection and Editing dialogue. Select "Scatter Plot." This plot shows how the RMS Error is distributed along the X and Y axis and can be used to help refine the GCP selection. The closer the GCPs lie to the x, y origin point, the more accurate the geometric correction will be.

Figure 2.12: GCP Scatter Plot display window



12. Go back to GCPWorks dialogue box. Click "Pre-registration Checking."

13. In the Registration Options dialogue box, select "Nearest Neighbour" resampling mode and "1st" model order. Set background to "0," then click "Registration Overview." The nearest-neighbour resampling algorithm best preserves the original radiance values in the uncorrected image. Using "0" as the background allows for the overlapping area of the uncorrected image to be transparently displayed over the corrected image.

Figure 2.13: Registration Options dialogue box

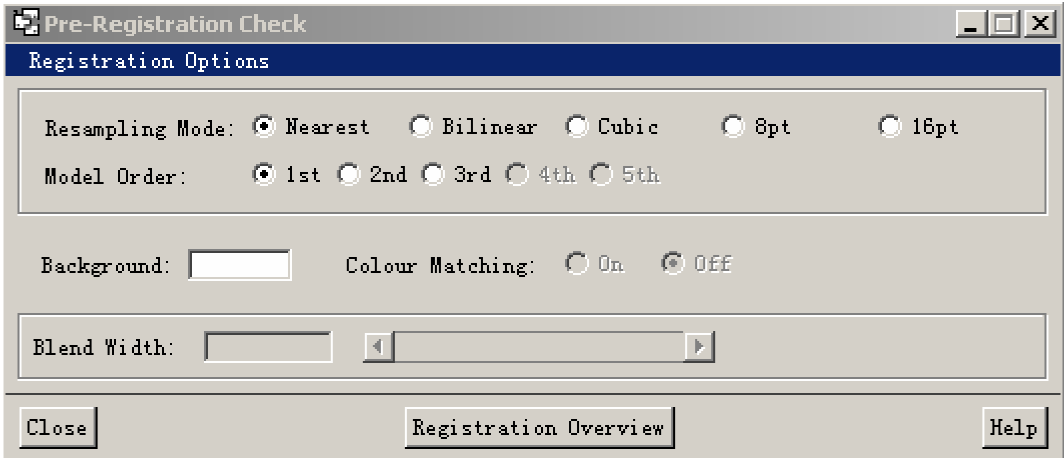
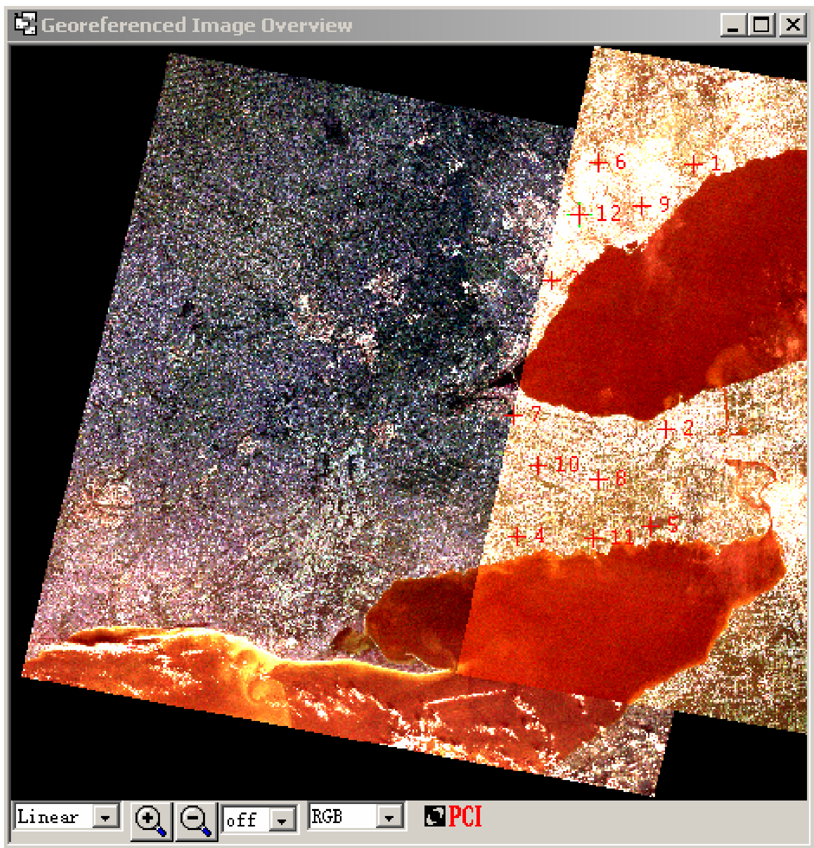
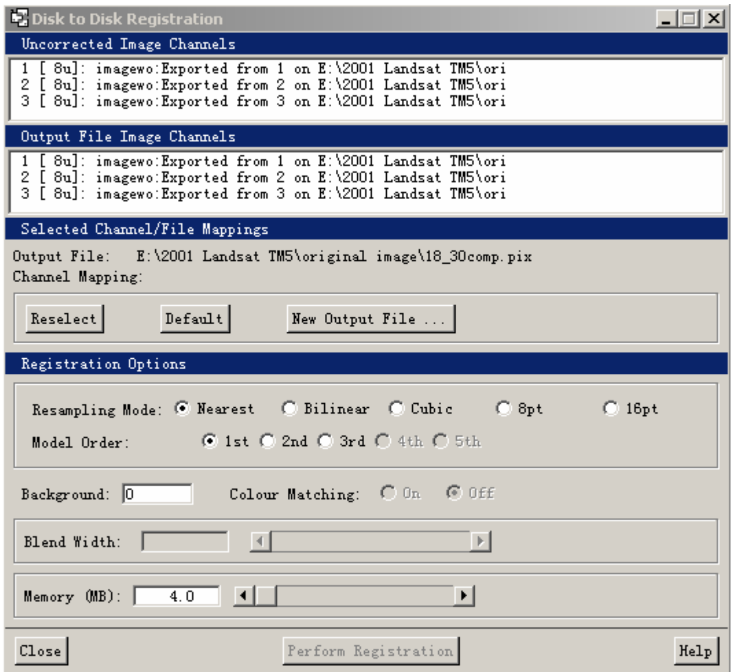


Figure 2.14: Georeferenced Image Overview



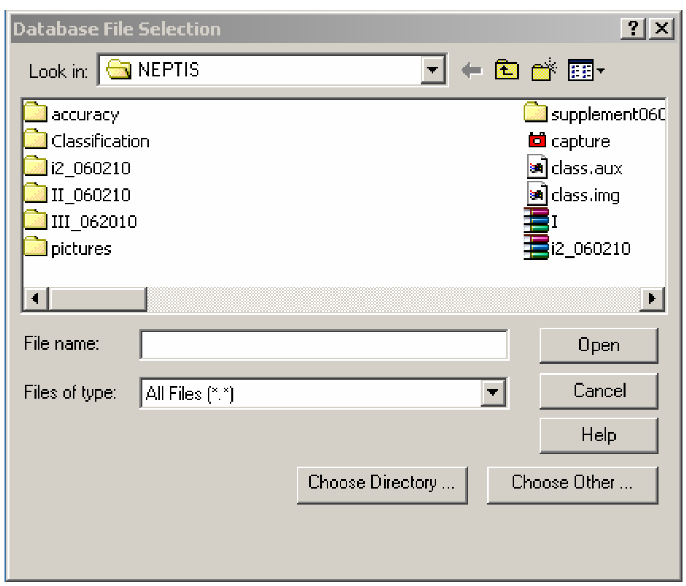
14. Go back to GCPWorks dialogue box. Click "Perform Registration to Disk." Click "New Output File."

Figure 2.15: Disk to Disk Registration dialogue box



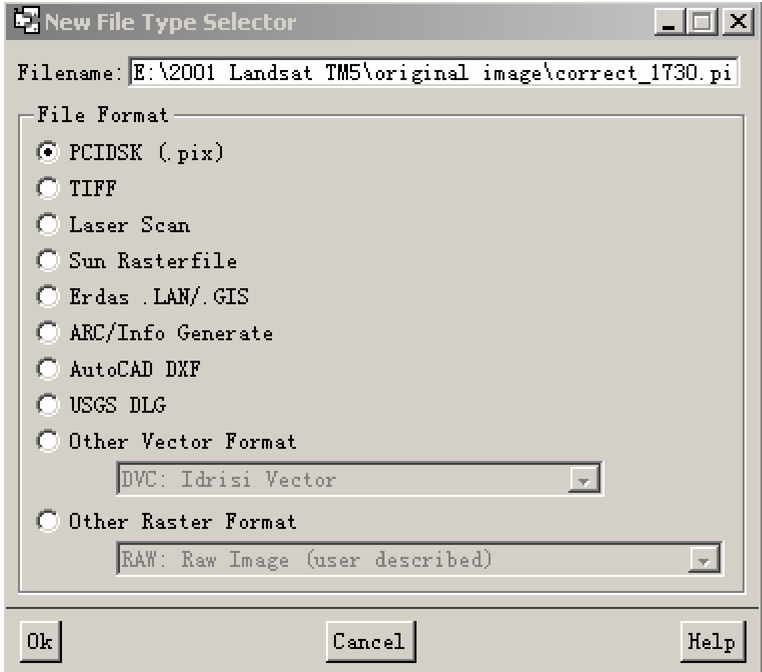
15. Name the output file in Database File Selection window. Click “Open.”

Figure 2.16: Database File Selection window



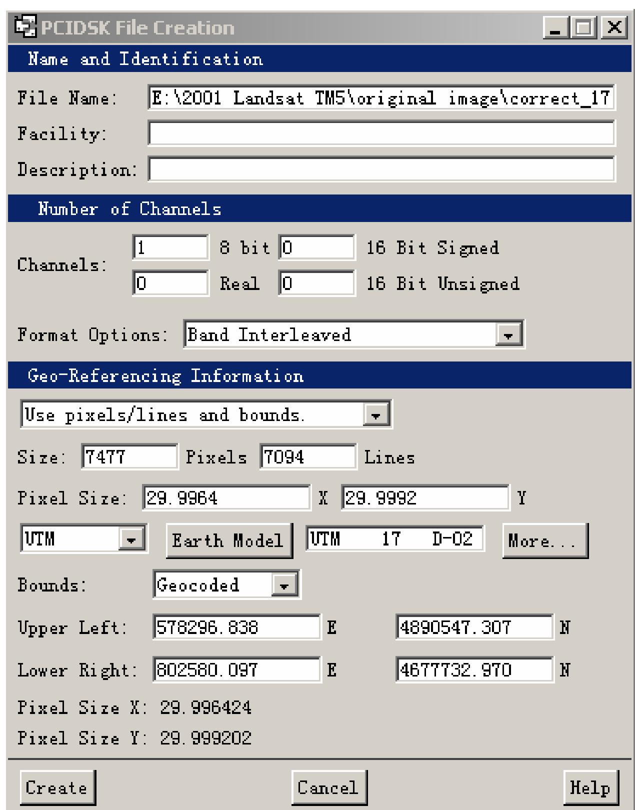
16. Accept “PCIDSK (.pix)” as the file format.

Figure 2.17: New File Type Selector window



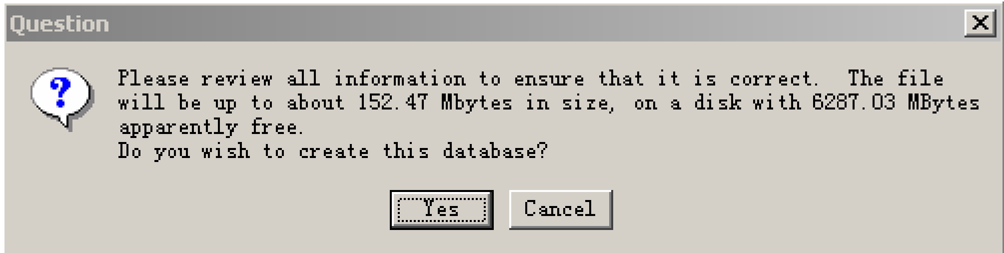
17. Accept all default values, except "Number of Channels." In "8 bit" box, enter 16 for number of database channels. Click "Create."

Figure 2.18: PCIDSK File Creation Window



18. Click "Yes" to create the database.

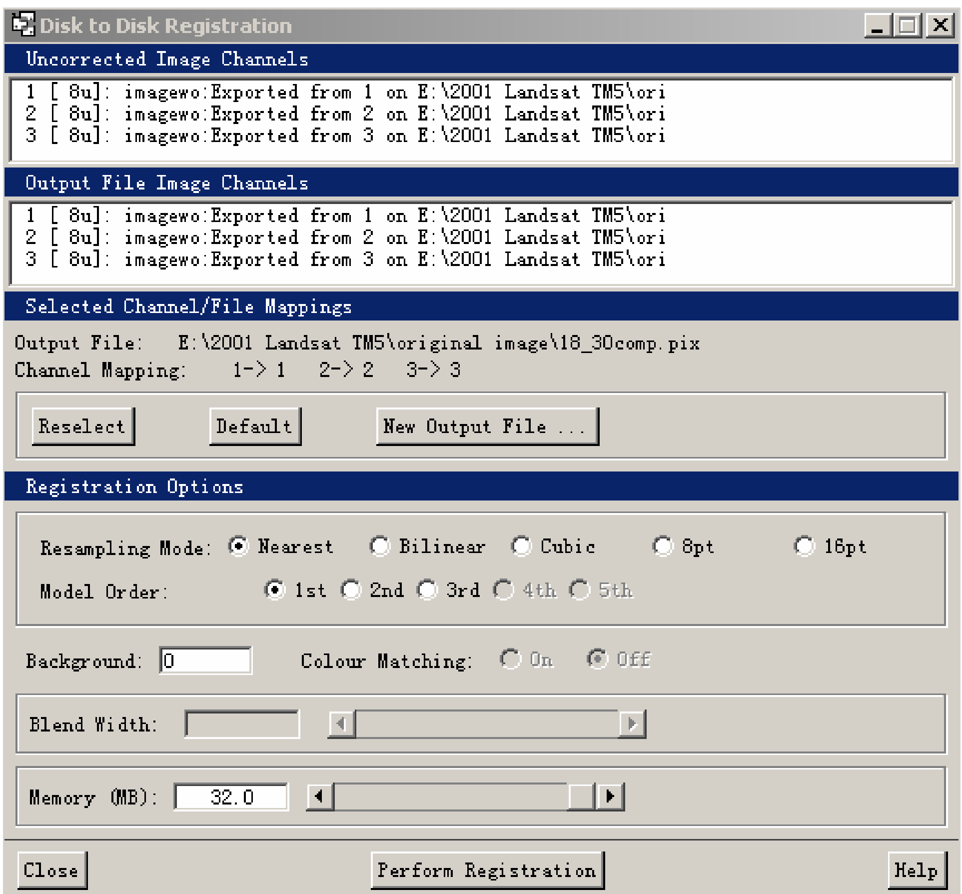
Figure 2.19: Database creation verification



19. Go back to Disk to Disk Registration window opened in step 14. Click "Default." Channels in the newly corrected image will be automatically mapped in the same order as the uncorrected image. In the memory box, enter 32 for 32 MB or the maximum amount of memory allocated for the process. Click "Perform Registration." A progress bar appears.

20.

Figure 2.20: Disk to Disk Registration window



21. To save GCPs into PCI database, go to GCP Editing and Selection window from step 7. Under file menu, click "Save GCPs," then click "Save & Close." The GCPs should be saved in the .pix database so they can be referenced later if necessary.

2.3.2 Geometric Correction Considerations

Evenly distribute Ground Control Points (GCPs) across the overlapping area. Use road intersections as control points.

Zoom to the same scale in the full resolution zoom window.

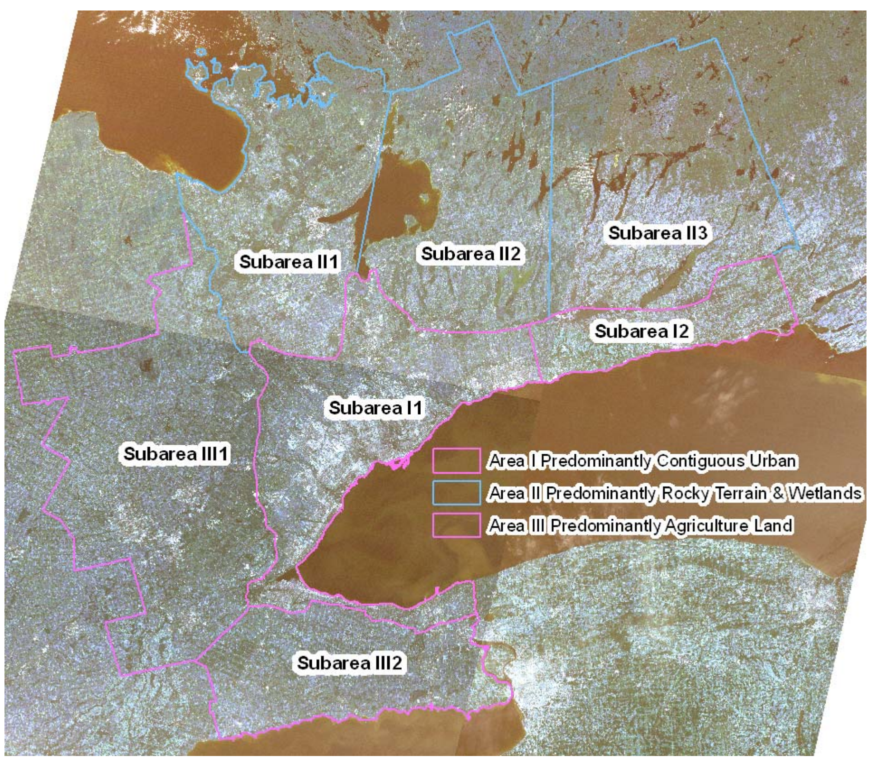
Use display enhancements to make the image more readable. Display enhancement consists of root, linear, equalization, all of which are basic spectral enhancements.

2.4 Image segmentation

Land cover and terrain vary greatly across the Toronto metropolitan region. Two large, geologic features, the Oak Ridges Moraine and the Niagara Escarpment, bisect the region north-south and east-west. These natural divisions form the basis for segmenting the study area into smaller, more manageable areas of analysis.

To achieve a better result in the final image classification, the region was segmented into three main areas based on the predominance of urbanized land, similarities in physiographic features and predominance of agricultural land. Segmenting the images of a study area reduces the range of the radiance values being analyzed and allows for the differentiation of more subtle variations in land cover types in the classification process. These three areas were further divided to improve the computer processing time. Map 1 shows the segmentation scheme used for the analysis. It is followed by a description of the segmentation areas and procedure.

Figure 2.21: Segmentation scheme for study area



2.4.1 Segmentation Scheme

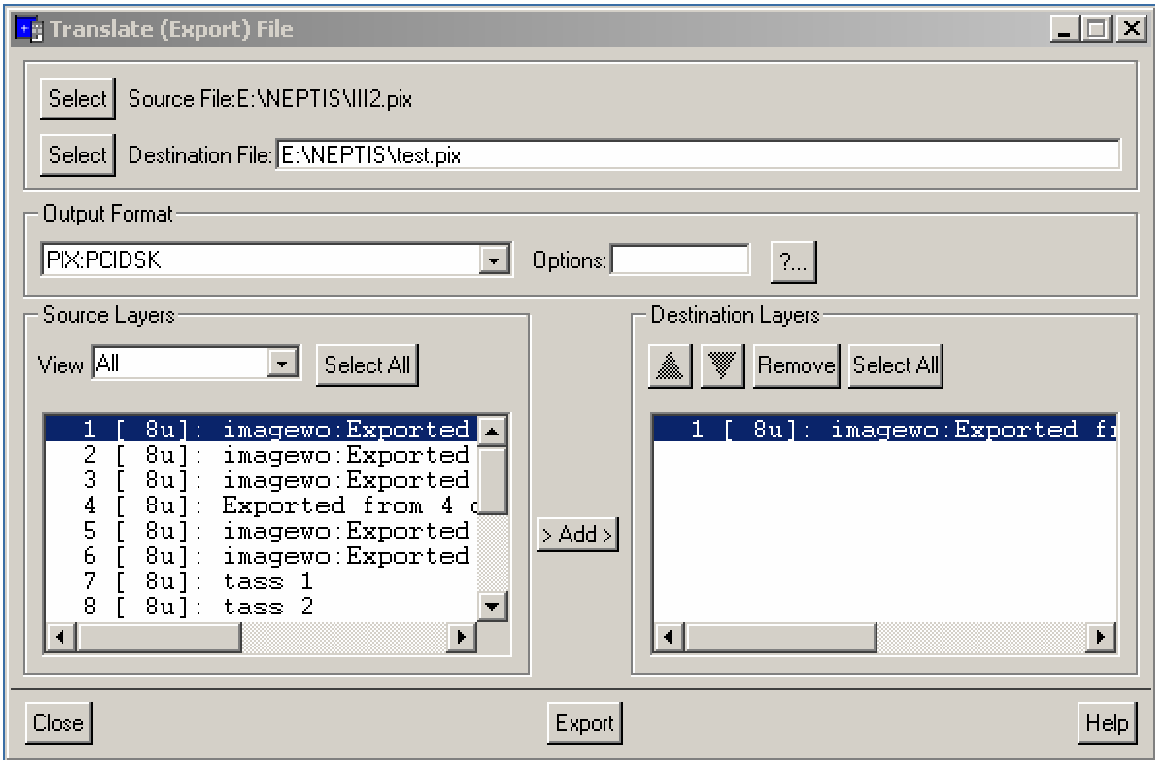
- Area I – predominant land cover: contiguous built-up urban area
  - Subarea I1
  - Subarea I2
- Area II – predominant land cover: rocky terrain and wetland features
  - Subarea II1
  - Subarea II2
  - Subarea II3
- Area III – predominant land cover: agricultural land
  - Subarea III1
  - Subarea III2

2.4.2 Exporting spectral bands from PCI

Each Landsat TM5 image is a rectangular in shape, covering nearly an area of 185 × 172 kilometres. PCI can only segment images based on a regular shape, e.g., a square or rectangle. Any custom segmentation must be done in a GIS software such as ArcGIS™. Therefore, after an image is geocorrected in PCI, each spectral band must be exported from PCI using the .img file format, so it can be imported to ArcGIS for segmentation.

1. Open and display each image in ImageWorks™.
2. Open File Utility under File menu bar. Select “Export.” The source file is the original PCI database file (.pix) and the destination file is the file to be exported.
3. Change output format from pix to img.
4. In Source Layers, select all channels and add them as destination layers.
5. Click “Export” so that all six bands are exported from a .pix file to an .img file.

Figure 2.21: Export window



2.4.3 Segmentation in ArcGIS™

For each subarea, a shapefile[3] needs to be created to be used as a mask in the segmentation process (see Map 1). Existing data sets such as streets, rivers, etc., can be used to define the boundaries of the subareas. Once these shapefiles have been created and spectral bands have been exported as .img files, segmenting can begin.

1. In ArcMap™, open Spatial Analyst in the Toolbox.
2. Select "Extract by Mask."
3. Select an .img file as the "Input Raster."
4. Select subarea shapefile as "Input raster or feature mask data."
5. Provide a name for an "Output Raster."
6. Repeat this process for all TM5 images and for all seven subareas.

3 Shapefile is a proprietary file format used in ESRI GIS software.

Figure 2.22: Extract by Mask window

3. Image Enhancements

The addition of image enhancements in the image classification process has been found to improve the overall accuracy of the land cover classification and significantly improve the delineation of built-up urban land cover features. Image enhancements of the original spectral bands provide extra information in the classification process by isolating components within the multispectral data that are most useful in portraying the essential elements of a particular image.

In the Toronto metropolitan region, image enhancements allow for a better differentiation between built and unbuilt features on the landscape than performing a classification procedure on the spectral bands alone. Four types of enhancements were used in the analysis:

- Principal Component Analysis (PCA);
- Texture analysis;
- Normalized Difference Index (NDVI);
- Tasselled Cap.

3.1 Principal Component Analysis

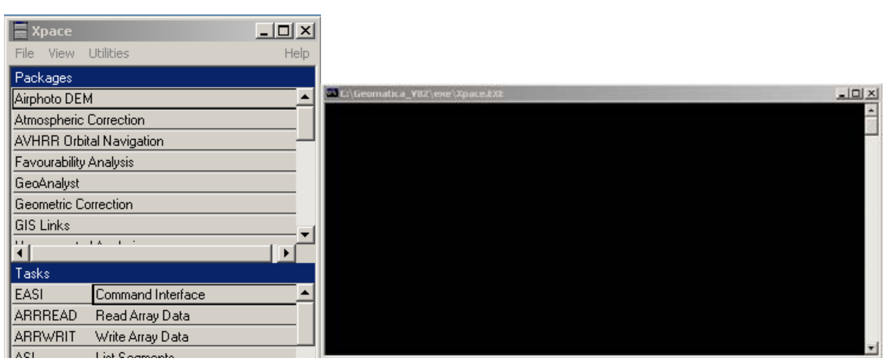
Principal Component Analysis (PCA) is used to simplify the image data by identifying the optimum linear combination of the multispectral data that account for variation in pixel values in an image. Spectral bands 1-5, and 7 in the Landsat TM5 images are used to calculate three principal components (i.e., eigen 1, 2, 3 in PCI).

3.1.1 Procedure

1. Open PCI and select the “Xpace” icon. Xpace and DOS window will appear.

2. Click “Utilities” in Xpace. Select “Locate Task.”

Figure 3.1: Xpace window and DOS window



3. Type in “PCA” in bottom box. Click “Activate.”

Figure 3.2: Task Activation and Search window

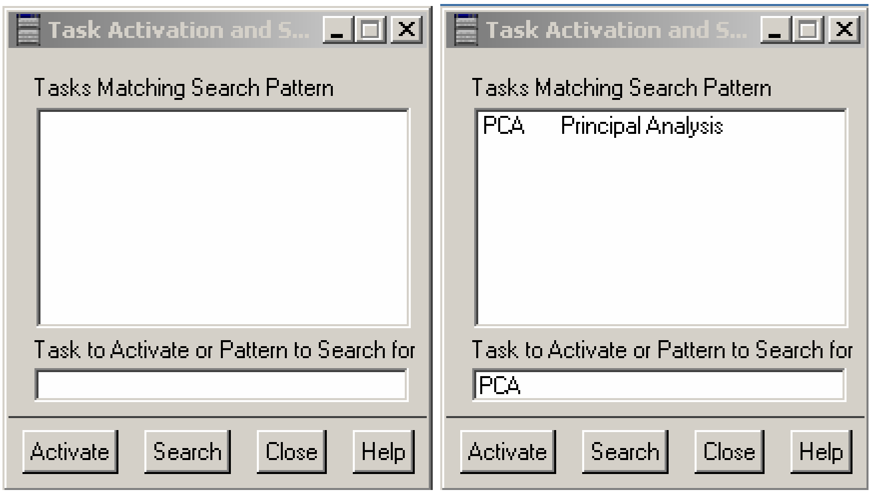
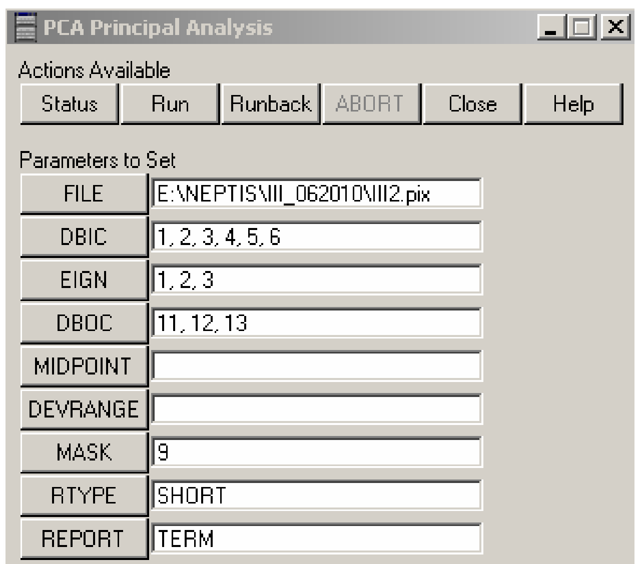


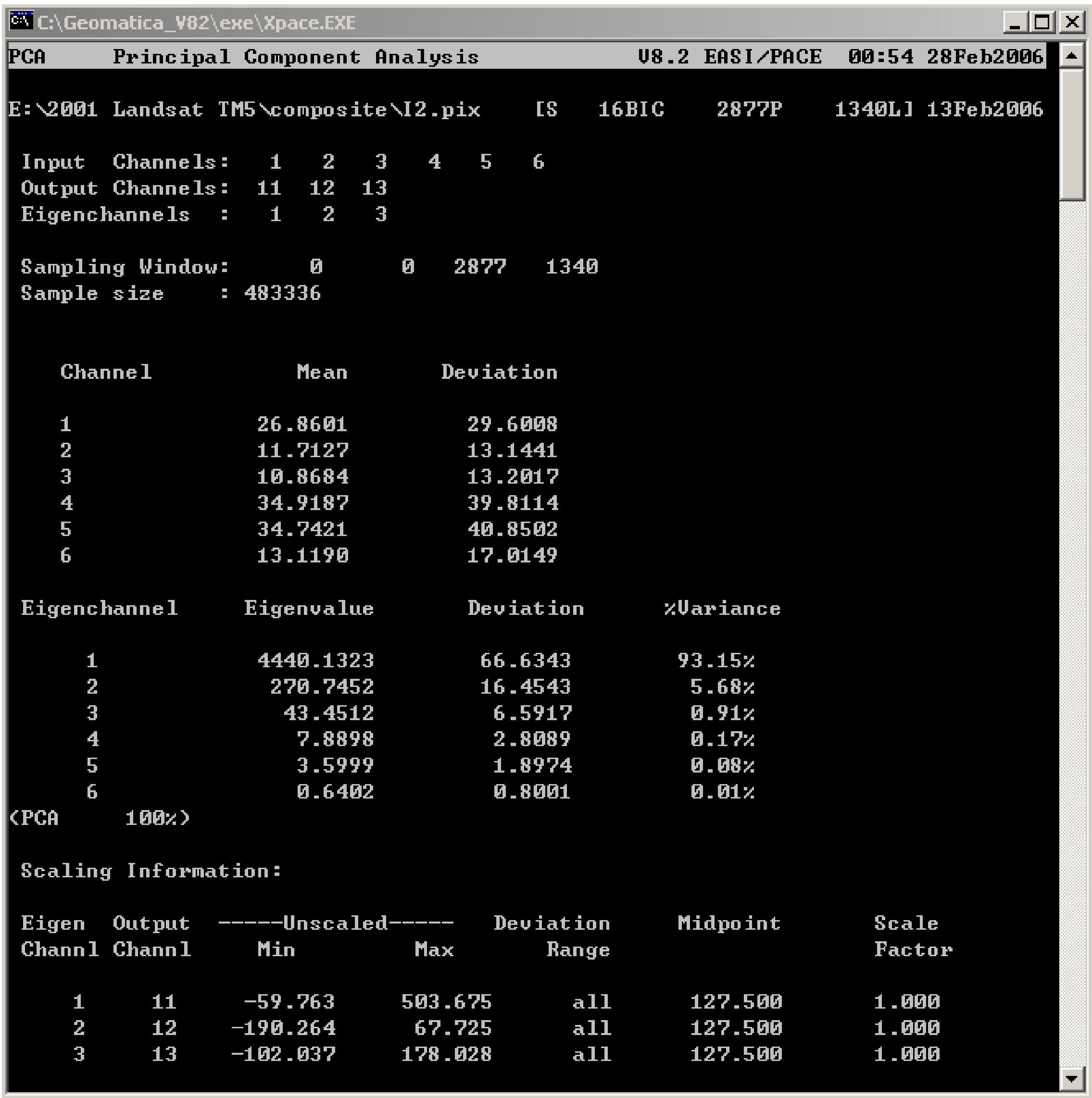
Figure 3.3: PCA Principal Analysis window



4. In PCA Principal Analysis dialogue box, click “File” to import prepared PCI .pix file.
5. Click “DBIC” to select database input channels to be analyzed. In this example, channels 1 to 6 represent spectral bands 1, 2, 3, 4, 5, and 7 in the original TM5 image.
6. Click “EIGN” to select the PCA factors that will be calculated (1, 2, and 3).
7. Click “DBOC” to select database output channel that will contain the results of the PCA. The channels will be used as inputs during the classification process.
8. The remaining text boxes represent parameters or additional output that can be altered in the PCA. Through experimentation, the optimal parameters for the analysis are as shown in Figure 3.3. “Midpoint” and “Devrange” remain blank. Input for “Mask,” “RType,” and “Report” are as shown above. Click “Run” to initiate the processes.

9. The DOS interface displays the output from the PCA including statistics of original spectral bands according displayed as database channels and their extracted eigen values, i.e., the statistics calculated during the PCA, and statistics for final principal components (PC1, 2, and 3).

Figure 3.4: DOS Interface Display showing PCA output



```
C:\Geomatica_V82\exe\Xpace.EXE
PCA      Principal Component Analysis                  V8.2 EASI/PACE   00:54 28Feb2006

E:\2001 Landsat TM5\composite\I2.pix    [S    16BIC     2877P     1340L] 13Feb2006

 Input  Channels:   1   2   3   4   5   6
 Output Channels:  11  12  13
 Eigenchannels  :   1   2   3

 Sampling Window:      0      0   2877   1340
 Sample size    : 483336


    Channel            Mean        Deviation

    1                 26.8601         29.6008
    2                 11.7127         13.1441
    3                 10.8684         13.2017
    4                 34.9187         39.8114
    5                 34.7421         40.8502
    6                 13.1190         17.0149

 Eigenchannel     Eigenvalue        Deviation       %Variance

      1             4440.1323        66.6343         93.15%
      2              270.7452        16.4543          5.68%
      3               43.4512         6.5917          0.91%
      4                7.8898         2.8089          0.17%
      5                3.5999         1.8974          0.08%
      6                0.6402         0.8001          0.01%
<PCA     100%>

 Scaling Information:

 Eigen  Output  -----Unscaled-----   Deviation     Midpoint       Scale
 Channl Channl      Min         Max      Range                    Factor

     1     11    -59.763     503.675      all       127.500       1.000
     2     12   -190.264      67.725      all       127.500       1.000
     3     13   -102.037     178.028      all       127.500       1.000
```

3.2. Texture Analysis

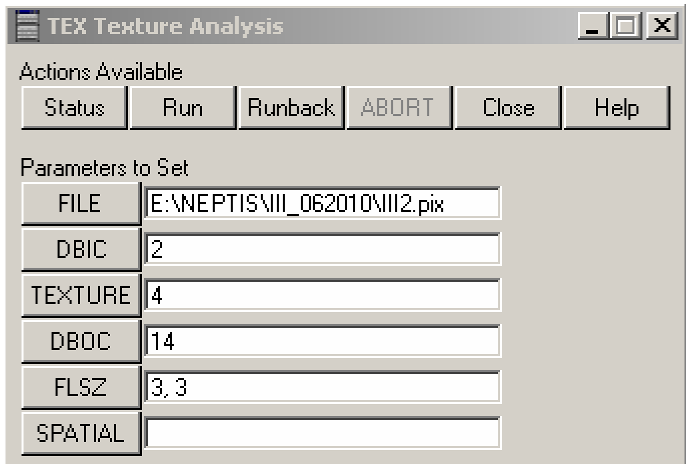
Texture analysis is an image enhancement technique that examines tonal differences in an image and the connectivity or spatial pattern of these differences. Certain land use features, such as a street grid or a ploughed agricultural field, have distinctive and identifiable textural patterns. Including these patterns can greatly improve an image classification. In this analysis, texture was found to improve the delineation between built and unbuilt pixels at edge of an urban area.

Texture analysis does pick up contrasting texture between water and land, which can lead to a misclassification and overestimation of built-up urban land in these areas. These misclassified features were removed during the post-processing analysis.

3.2.1 Procedure

1. Repeat steps 1 to 3 in PCA, but this time, activate texture analysis by typing “Tex” in the box.

Figure 3.5: TEX Texture Analysis dialogue box



2. Click “File” to import PCI .pix file.
3. Click “DBIC” to select database input channels to be analyzed. In this case, band 2 coincides with channel 2 of the database.
4. In the Texture box, type “4” to calculate the mean texture measure.
5. Click “DBOC” to select output channel in database that will house the texture results. This channel will be used as an input to the classification process.
6. Click “FLSZ” and enter “3, 3” to indicate the size of window applied in texture analysis. Leave the spatial parameter blank. Click “Run” to initiate the analysis. Its progress will be displayed in a DOS window.

3.3. Normalized Difference Vegetation Index (NDVI)

Normalized difference vegetation index (NDVI) measures the “greenness” of an image. This index is useful in identifying areas of healthy vegetation. The index is calculated using the following formula:

$$NDVI = 100*((NIR4 - R3)/(NIR4 + R3))$$

where, in a Landsat TM5 image:

- NIR4 is spectral band 4 that captures the infrared range of the full spectral range
- R3 is spectral band 3 which capture the red range of the full spectral range.

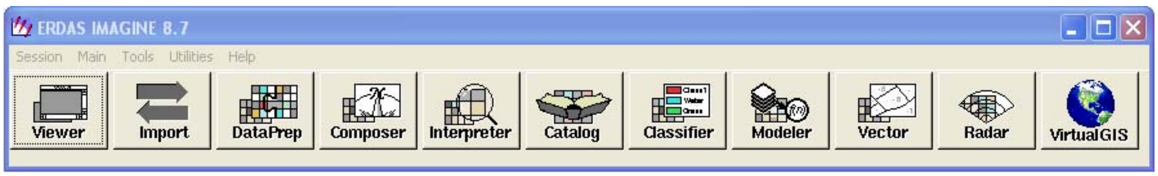
An NDVI calculation is not available in the PCI image processing software version 9.x, although an analyst could develop a customized script. The ERDAS Imagine image processing software provides a function to produce a number of vegetation indices.

This research used the ERDAS function and imported the result to PCI. An .img file of the bands 3 and 4 were exported from PCI for each subarea so they could be analyzed using the NDVI function in the ERDAS software.

3.3.1 Procedure

1. Initiate the ERDAS Imagine program. Select "Interpreter."

Figure 3.6: ERDAS Imagine 8.7 menu

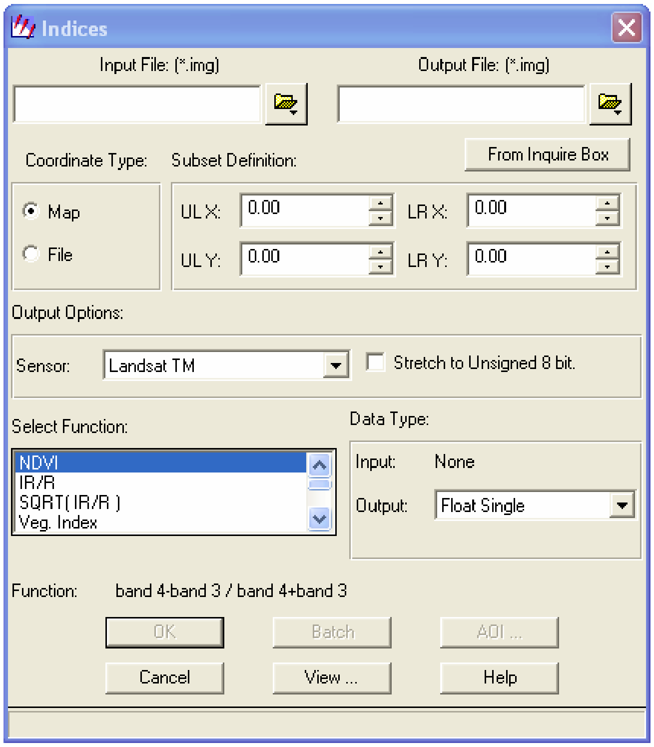


2. In Image Interpreter dialogue box, select "Spectral Enhancement."
3. In Spectral Enhancement dialogue box, select "Indices."

Figure 3.7: Image Interpreter and Spectral Enhancement dialogue boxes

4. In the Indices dialogue box, go to Select Function window. Select "NDVI" to import image.

Figure 3.8: Indices dialogue box



5. Specify location of output image, i.e., NDVI result. Click "OK" to initiate the process. A progress bar will indicate when the process is complete.

3.4 Tasselled Cap Transformation

The application of the Tasselled Cap Transformation was a new component of the research conducted on the Toronto metropolitan area. This image enhancement technique was not applied in Du or Forsythe's original research, because the study area was less varied in its land cover, containing mainly urbanized area and much less agricultural land.

Tasselled Cap Transformation is the process of converting information from multispectral bands (i.e., multiple data sets) that relate to spectral components of vegetation and soil conditions, particularly those under agricultural use, into a single data set. This new information is then used as an input to the image classification process. A Tasselled Cap Transformation produces six spectral components. The first three are used to highlight agricultural and natural heritage features[4] with some components performing this function better than others. The current research found that the fourth and fifth components aid in highlighting urban features.

4 Kauth, R.J. and G.S. Thomas, 1976. "The tasseled cap—a graphic description of the spectral-temporal development of agricultural crops as seen by Landsat." *Proceedings of a symposium on machine processing of remotely sensed data*. West Lafayette, Indiana: Purdue University, Laboratory for Applications of Remote Sensing: 41-51; Crist, E.P. and R.C. Cicone, 1984. "Application of the tasseled cap concept to simulated thematic mapper data." *Photogrammetric Engineering and Remote Sensing* 50: 343-352; Crist, E. P., 1985. "A TM tasseled cap equivalent transformation for reflectance factor data." *Remote Sensing of Environment* 17: 301-306; Crist, E.P. and R.J. Kauth, 1986. "The tasseled cap demystified." *Photogrammetric Engineering and Remote Sensing* 52: 81-86.

3.4.1 Performance and function of Tasselled Cap Transformation

The images below illustrate how the three components of tasselled cap transformation highlight different features in the imagery and compare them with features highlighted by spectral information only. Figure 3.9, the Landsat TM5 image, shows a heavily urbanized area surrounded by rural land uses in the Toronto metropolitan region. The image is displayed using a combination of spectral bands 1, 2, and 3. Although many of the urban features appear very bright in the display, these bands alone are not able to differentiate urban features from bare soil in the rural areas which also appears bright in the imagery.

Figure 3:9: Landsat TM5 Composite Image

Figure 3.10 illustrates the third component of the Tasselled Cap Transformation, which makes it possible to differentiate urban features from rural features in both tone and texture. However, a variety of tones and textures also characterize different field and crop conditions. This component interferes with the distinction between bare soil and land that has been cleared for urban development, a condition that this research was interested in capturing.

Figure 3.10: Tasselled Cap Third Component

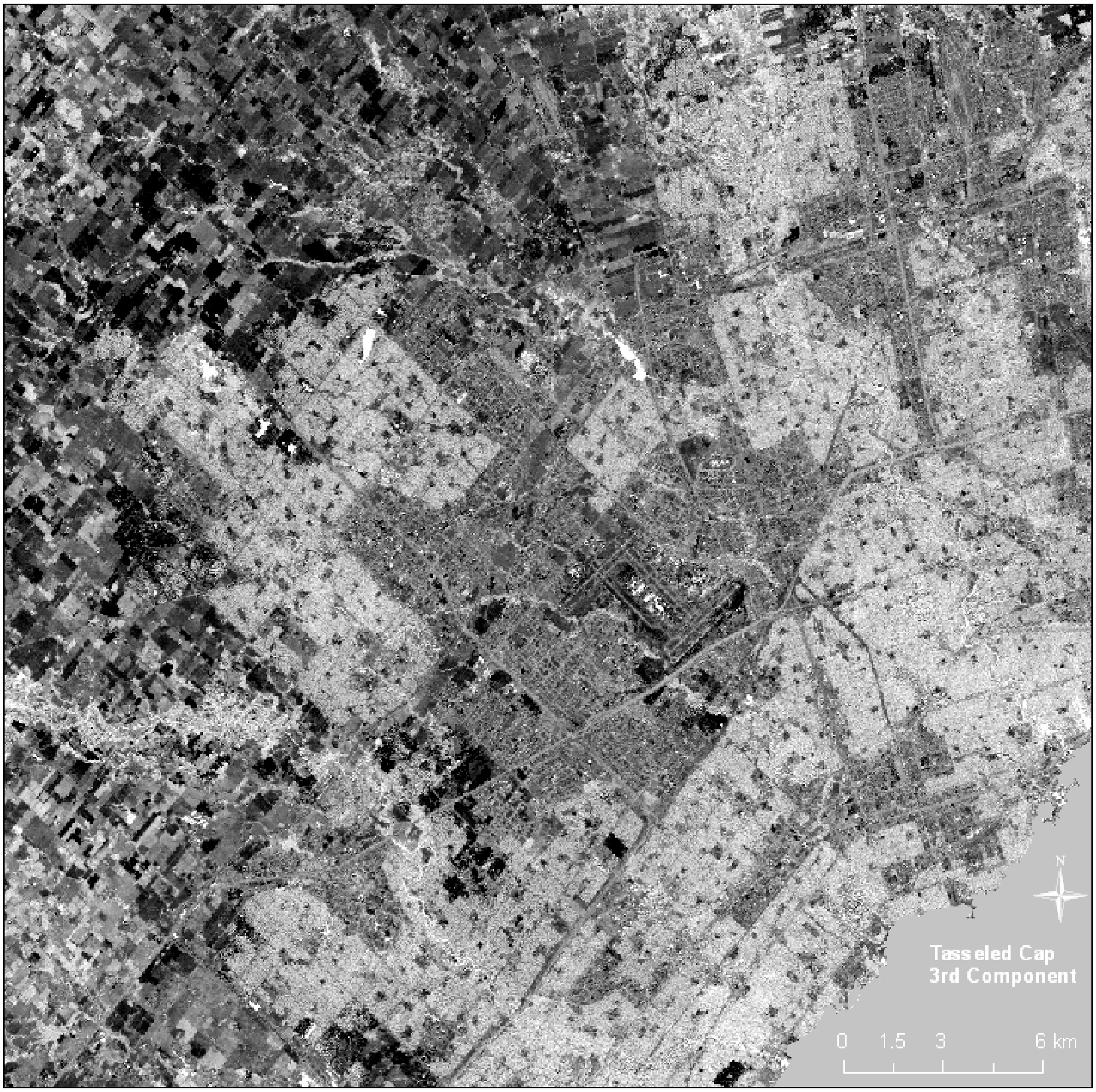
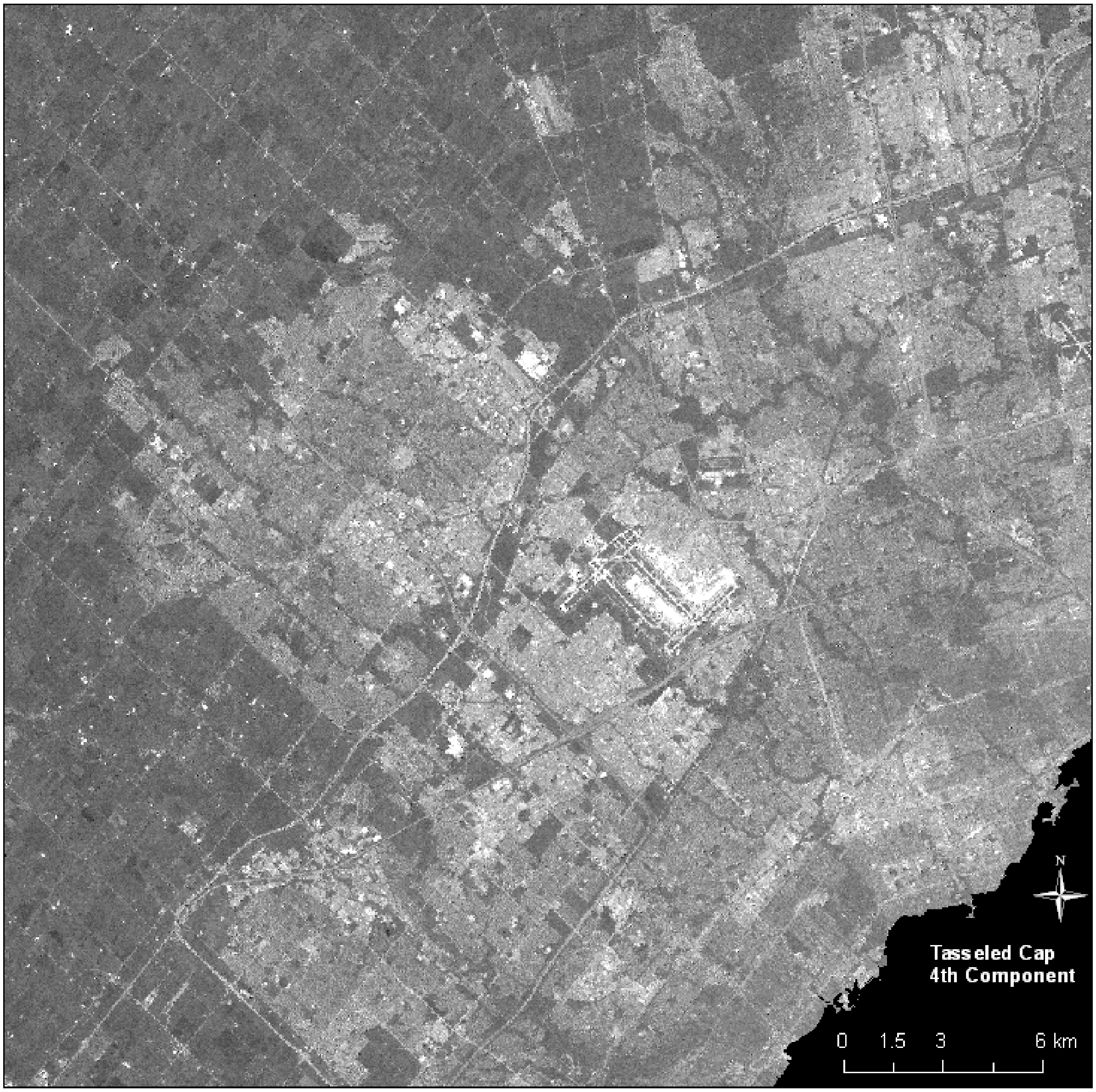


Figure 3.11 illustrates the fourth component of the Tasselled Cap Transformation. The fourth component was found to differentiate urban and rural land uses, and in addition, it was useful in grouping features in these two categories better than the third component.

Figure 3.11: Tasselled Cap Transformation Fourth Component



The fifth component of the Tasselled Cap Transformation, illustrated in Figure 3.12, also differentiates urban and rural land features, but it is more difficult to group features in each category. The fifth component may, however, make it easier to differentiate between residential and employment uses within the built-up urban category. Differentiating the two land uses is not necessary for defining the built-up urban area boundary, but may be useful in future research. Although all three components may not be necessary for classifying an image subarea, if an image has many rural features, the three components provided a better classification result. Ultimately, the number of components used in the analysis will depend on the variability of land cover and environmental features in each image. Some experimentation is required when adding Tasselled Cap Transformation components to the classification process.

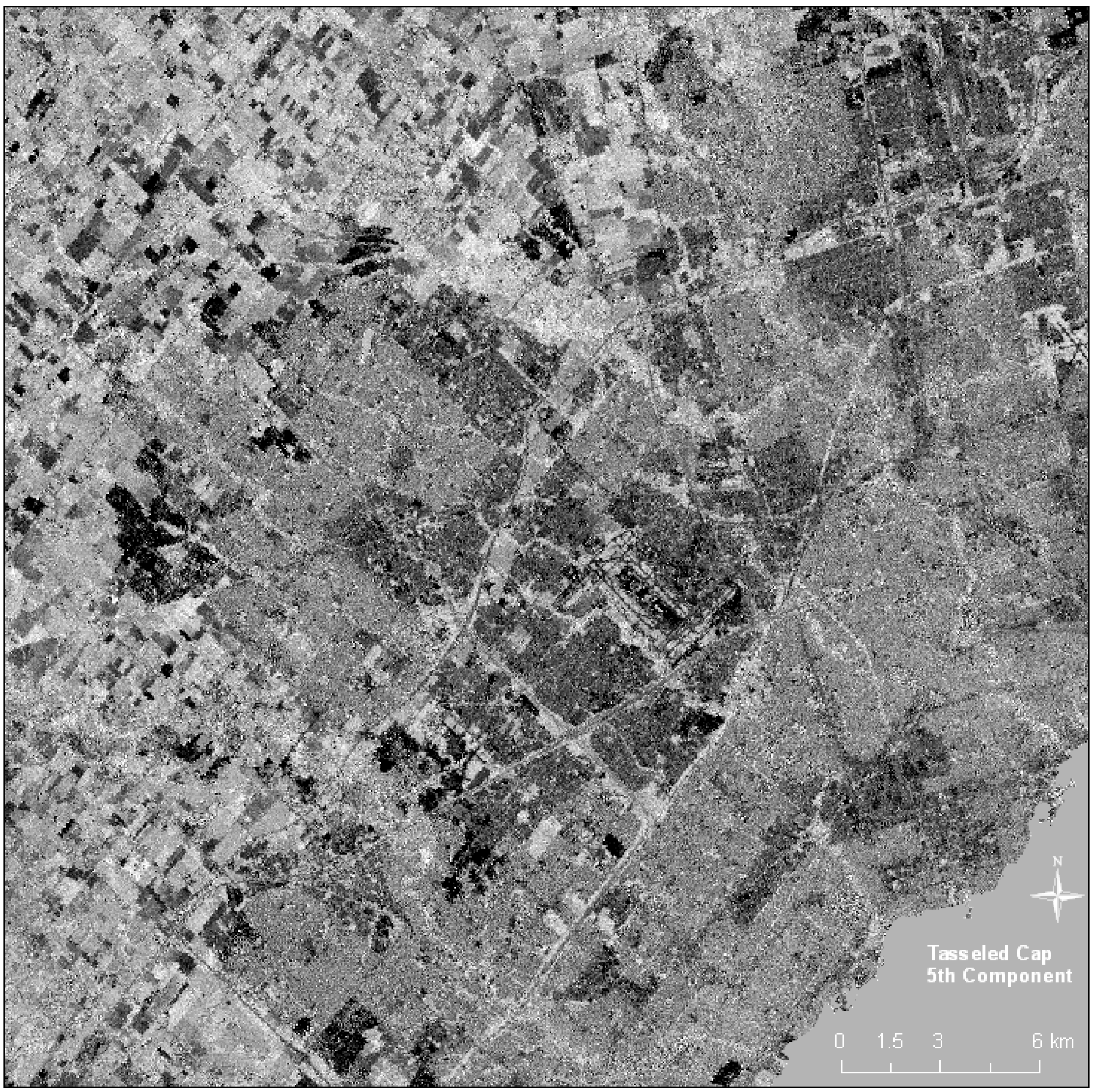
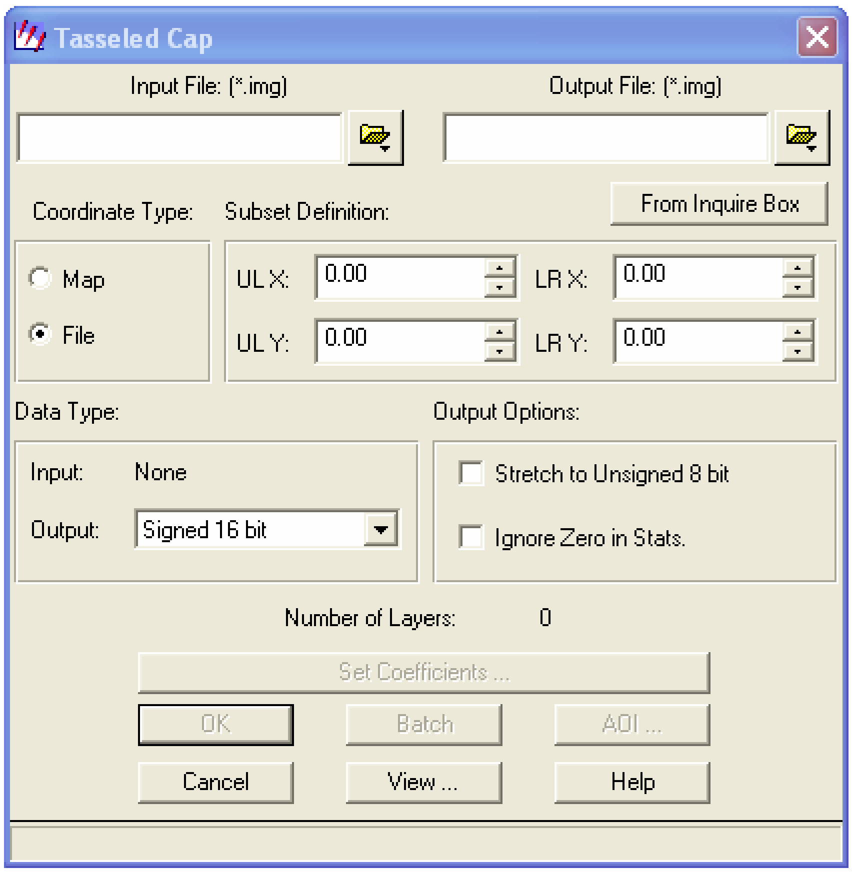


Figure 3.12: Tasselled Cap Transformation Fifth Component

3.4.2 Procedure

1. Export the six spectral bands for each subarea from PCI as an .img and import them into ERDAS.
2. Initiate the ERDAS Imagine program. Select "Interpreter," then "Spectral Enhancement."
3. Select "Tasseled Cap."
4. Select input and output files as in NDVI analysis and check box "Stretch to Unsigned 8 bit." Click "OK" to initiate the process.

Figure 3.13: Tasselled Cap dialogue box



4. Image classification[5]

In the image classification procedure, all spectral data and image enhancement data are analyzed in combination in order to transform an image into a classified map. There are two approaches to image classification: supervised and unsupervised.

An unsupervised approach relies on a computer program to cluster or group pixels in the image according to statistical similarities in pixel values. These groupings are then assigned to a classification category by an analyst.

In the supervised approach, an analyst "trains" the computer program to recognize categories in the data by identifying sites in the image as representatives of a category. The computer program then takes the range of pixel values represented by the categories and identifies other pixels as members of those categories.

In Du's research, it was found that a supervised approach using a maximum-likelihood probability algorithm best captured built-up urban land cover in the Greater Toronto Area, particularly when more than spectral information is used in the image classification process.

Image classification, whether supervised or unsupervised, requires experimentation by the analyst. Classification algorithms perform differently, depending on the variability of pixel values in an image, information used as input to the analysis, and, in the case of the supervised approach, the training sites chosen by the analyst. The process requires educated choices on the part of the analyst.

4.1 Classification preparation

In order to conduct the supervised image classification, the PCI database must contain the original spectral bands and image enhancements as inputs to the analysis. The analyst needs to import the image enhancements created in ERDAS Imagine™ to the PCI database (see Section 2.2 for instructions on preparing the PCI database).

The processing speed of the image classification is significantly affected by the volume of data used in the analysis. Since up to 14 channels of information are required as input, the study area size must be segmented into smaller areas, as described in Section 2.4. Finally, two additional database channels must be created to store the training sites used to classify the images and the results of the classification.

The database channels required for classification are:

5 N.B. When the screen captures were created, the authors did not define a set of consistent terminology for the land cover classes. In some case, "green" or "greenspace" is used to refer to the unbuilt category.

- Channels 1 to 6 – 6 original spectral bands (exclude band 6, thermal band)
- Channels 7 to 9 – 3 PCAs (Components 1, 2, 3)
- Channels 10 – Texture analysis
- Channels 11 – NDVI enhancement
- Channels 12 to 14 – 3 Tasselled Cap enhancements
- Channel 15 – Training sites
- Channel 16 – Classification results.

4.2 Selection of training sites

Training sites must be selected with care, since they greatly affect the outcome of any supervised classification. The analyst must also determine the number of desired categories in the land cover classification. Since the goal of the research is the delineation of the built-up urban area, a limited number of general land cover categories are required. Training sites were collected for three categories: built-up urban, unbuilt land and water. Unbuilt land includes natural heritage and agricultural features, e.g., forest stands and field crops. Each of these land cover categories can be spectrally separated by using a probability algorithm that compares the pixel values of the training site categories to the pixel values in the rest of the image.

The choice of training sites can be subjective exercise, but the subjectivity can be minimized by using other data sources to verify a training site such as fine-resolution aerial photographs, orthophotography, or land use data sets and choosing training sites that maintain a distinct spectral signature for each category. The number of training sites is less important than the selection of the sites; more training sites will not necessarily yield a better classification result.

The following considerations for choosing training sites may be helpful:

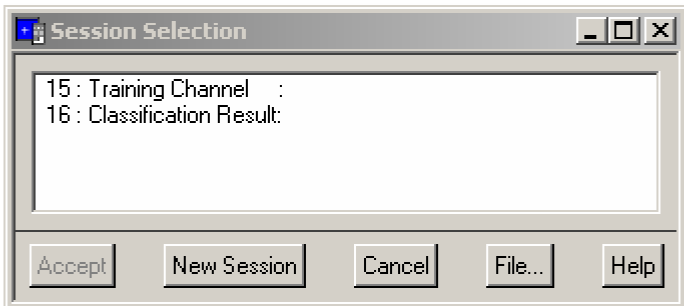
- As more training sites are collected for each category, the cumulative pixel values must be distinct among the different land cover categories. By examining the range, mean, and variance of the pixels reported for training sites of each category, the analyst can maintain this distinction.
- Nominate common feature-types that have characteristic patterns. For example, urban features in a metropolitan area constitute at least two types of patterns in Landsat TM imagery. Large, white, or bright tones typify non-residential land uses such as large industrial, commercial, and institutional buildings or extensive paved areas. Residential areas have fairly distinct textural patterns, given their association with grid or curvilinear road patterns, but their spectral signature may be mixed, i.e., characterized by features that have different spectral signatures such paved streets lined by trees.
- Unlike other image processing software, a preview window is available in PCI. This allows the analyst to assess the effects each training site has on the classification. Each training site should be evaluated using this tool.
- As more training sites are collected, the cumulative effect of the training sites should be assessed by revisiting the training sites that were chosen earlier in the classification process to determine whether their classification category has changed by the addition of new training sites.

Although visual inspection of the classification results may guide an analyst, a statistical report of the accuracy of the classification is necessary to assess the results. Therefore the training sites should be saved in a database channel in case future adjustments need to be made after this assessment.

4.3 Procedure for capturing training sites and classifying images

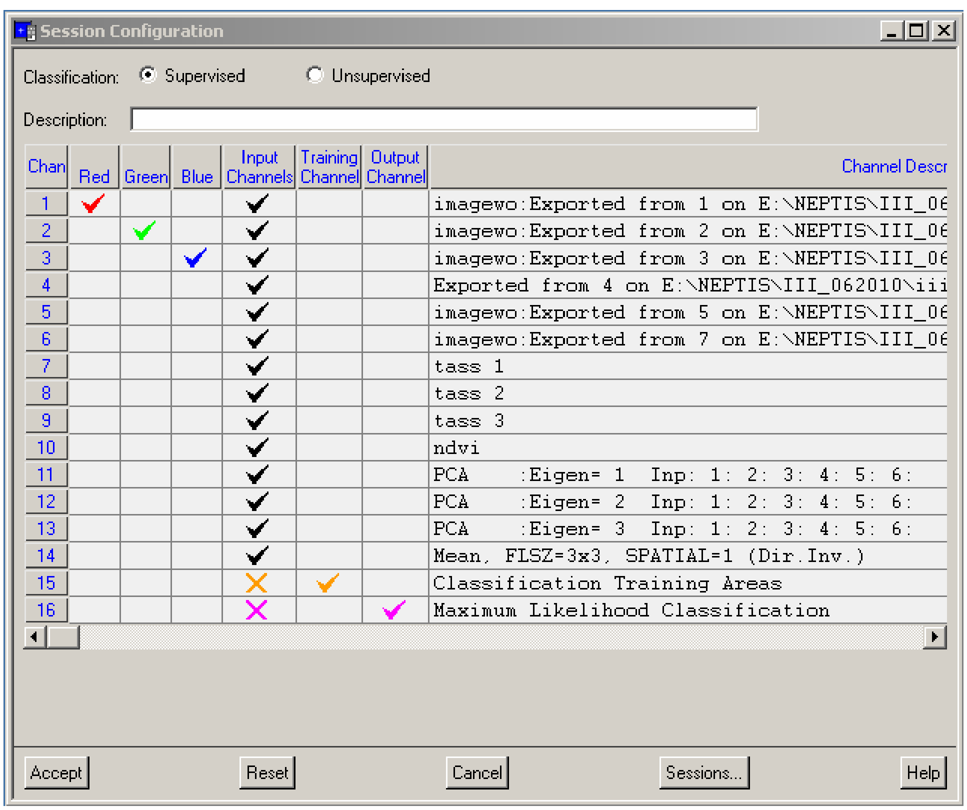
1. In ImageWorks, go to the Classify menu. Select the sessions. Click "New Session."

Figure 4.1: Session Selection dialogue box



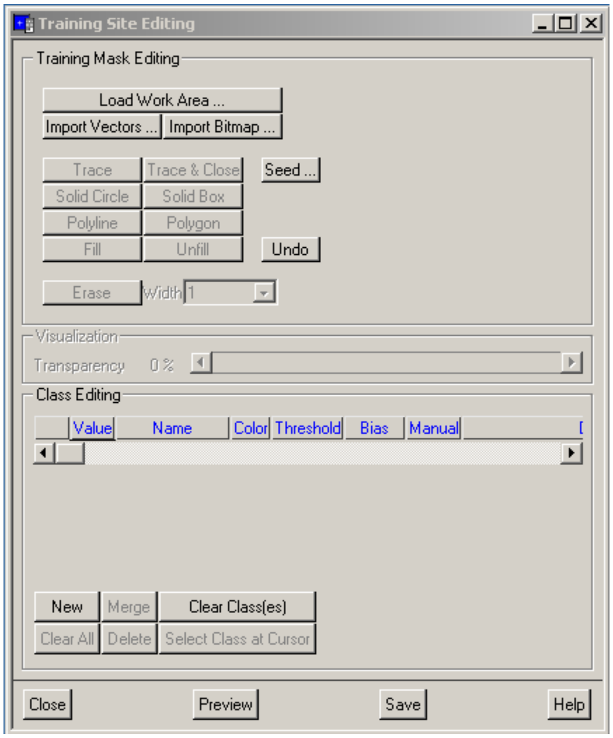
2. In the Session Configuration window, select the "Supervised" classification option. Select the input channels to be used in the classification. Indicate the channel where the training sites will be stored. Finally, select "Output Channel" for the classification results. Click "Accept."

Figure 4.2: Session Configuration dialogue box



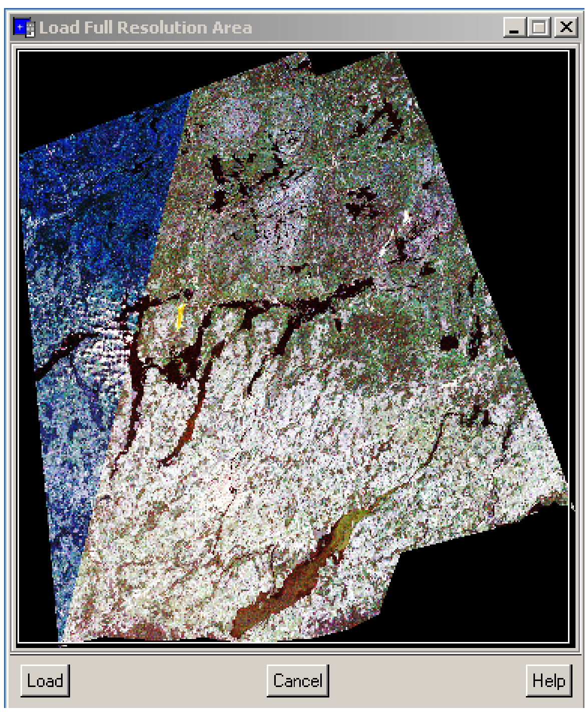
3. In Training Site Editing dialogue box, click "Load Work Area."

Figure 4.3: Training Site Editing dialogue box



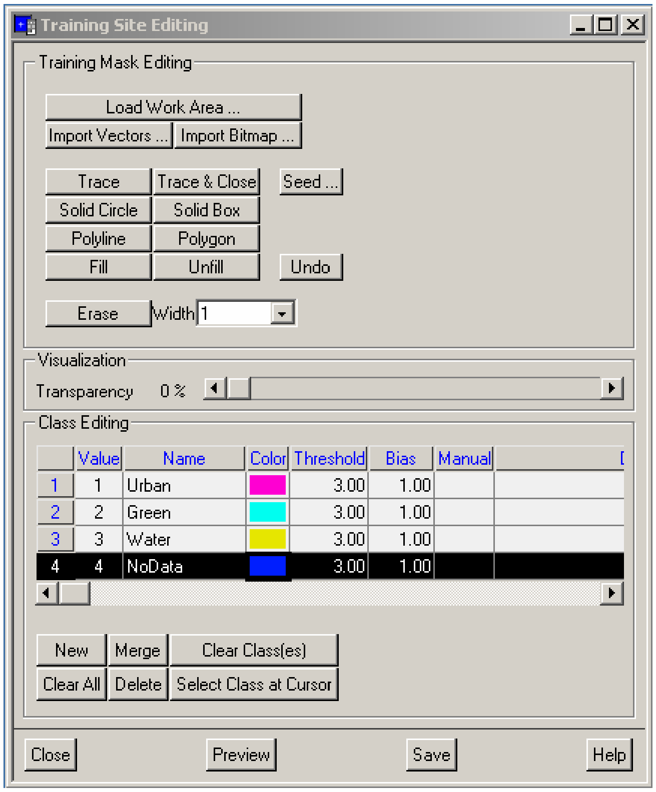
4. Click "Load."

Figure 4.4: Load Full Resolution Area window



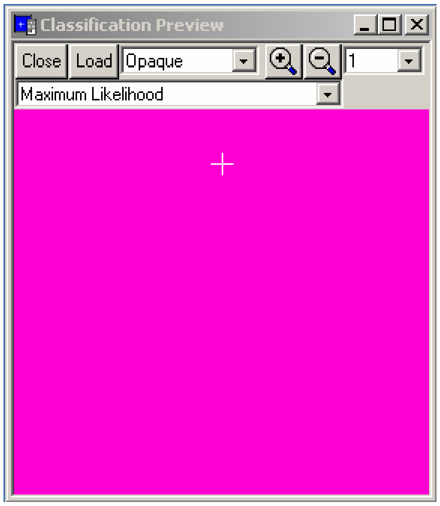
5. Click "New" to create each category. The name and colour of each category can be altered. When all categories have been entered, click "Preview."

Figure 4.5: Training Site Editing dialogue box showing entered categories



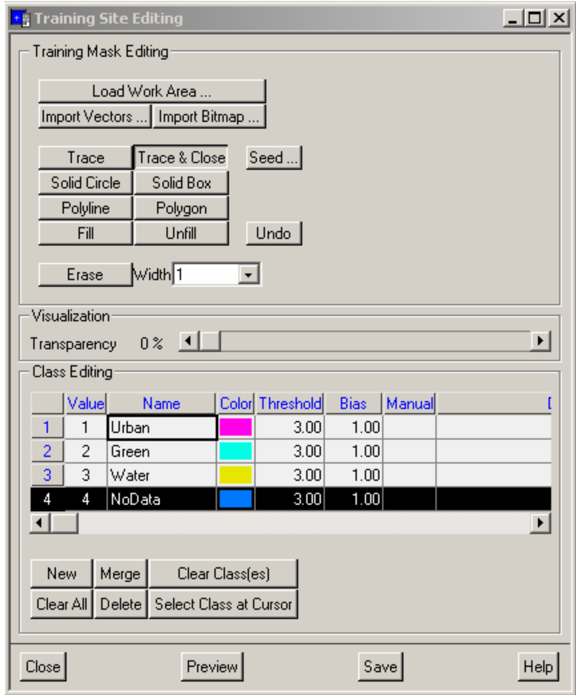
6. The classification preview window allows the analyst to work within a smaller area of the image when choosing training sites. Wherever the cursor is placed in the ImageWorks window, that zoomed-in area will appear in the preview window. The classification algorithm is also chosen in this window.

Figure 4.6: Classification Preview window



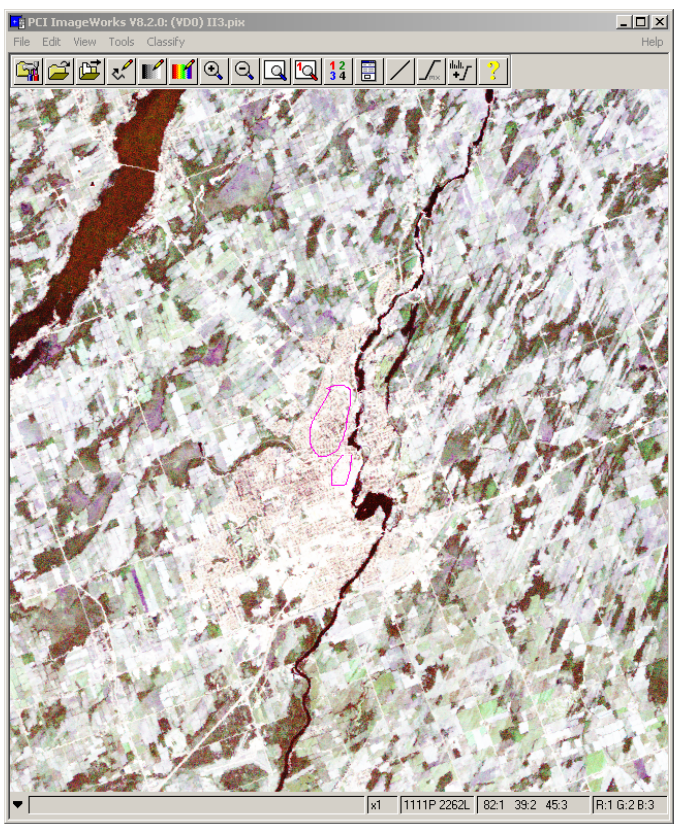
7. In the Training Site Editing window, place cursor in the category. Click "Trace & Close."

Figure 4.7: Training Site Editing window showing "Trace and Close" command



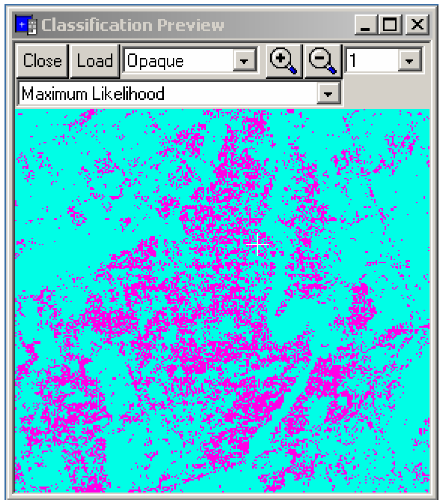
8. Go to the ImageWorks window and use the trace tool to capture training sites.

Figure 4.8: ImageWorks window showing training sites



9. Click "Preview" in the Training Site Editing window to evaluate the training site.

Figure 4.9: Classification Preview window

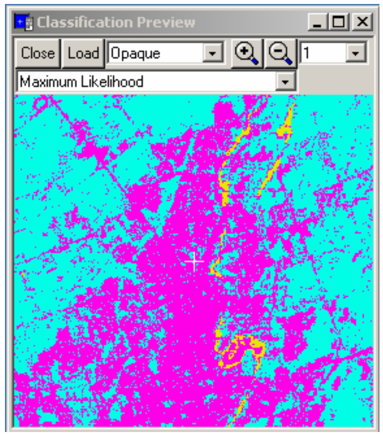


10. Add other training sites for other categories.

Figure 4.10: ImageWorks window showing additional training sites

11. The results of the classification will change as more training sites are added for each category.

Figure 4.11: Classification preview window showing modified results



Identifying training sites and classifying an image is an iterative process. It requires trial and error on the part of the analyst. The achievement of an "accurate" result will depend on the requirements of the analysis. Since the aim of this research is to delineate an built-up urban area boundary, the analyst should concentrate on assessing the accuracy of the built-up urban category, particularly in sub-areas containing a large amount of contiguous built-up urban area. Below is an example of the training sites used to classify the image for subarea I1, an area with a high concentration of built-up urban area.

Table 4.1: Number of training sites used in analysis

Area	Sub-area	Built-up urban	Unbuilt land	Water	Total Sub-area	Total Area
I	I1	24	49	2	75	94
	I2	5	12	2	19	
II	II1	8	28	4	40	99
	II2	4	40	4	48	
	II3	1	8	2	11	
III	III1	17	23	2	42	69
	III2	9	16	2	27	

Figure 4.12: Location of training sites in Subarea I1

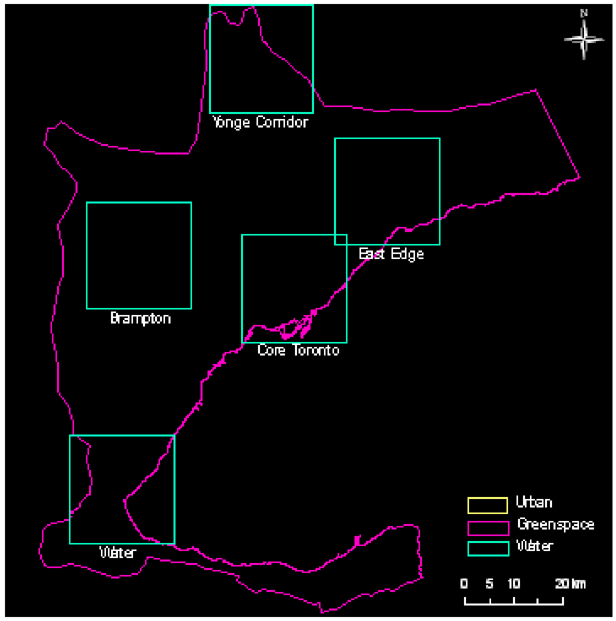


Figure 4.13: Training sites for downtown Toronto

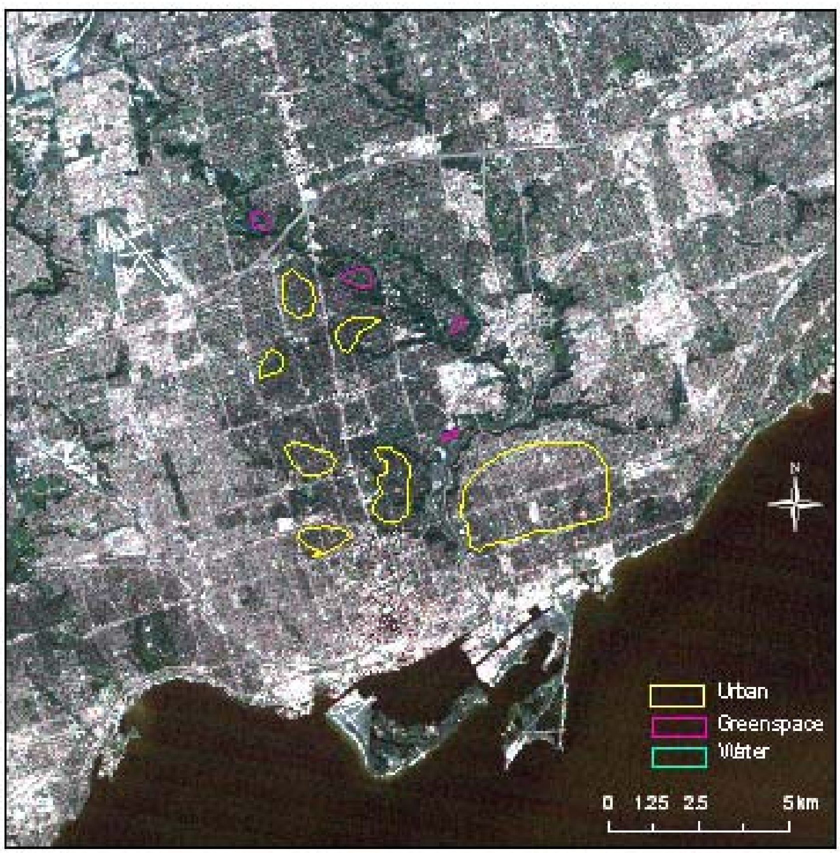


Figure 4.14: Training sites in Brampton

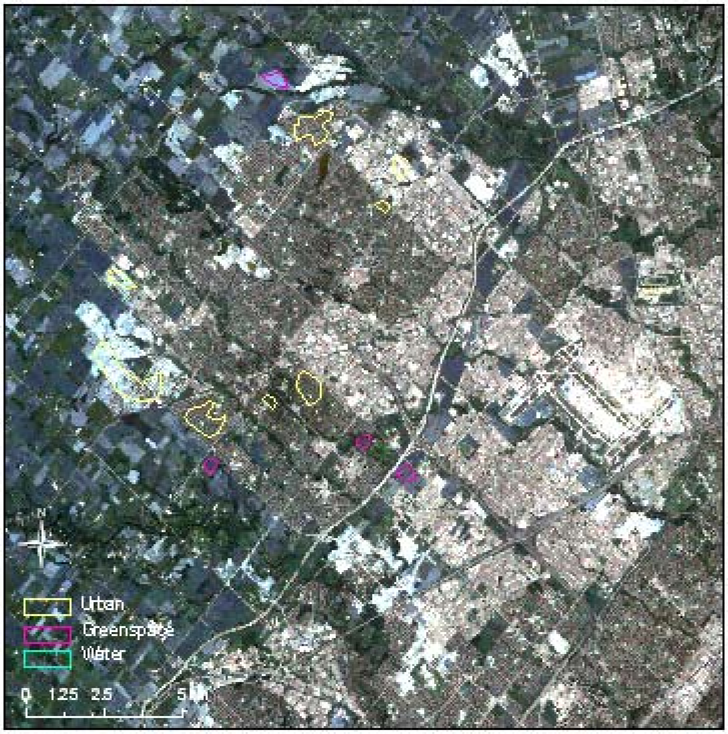


Figure 4.15: Training sites for areas east of Toronto

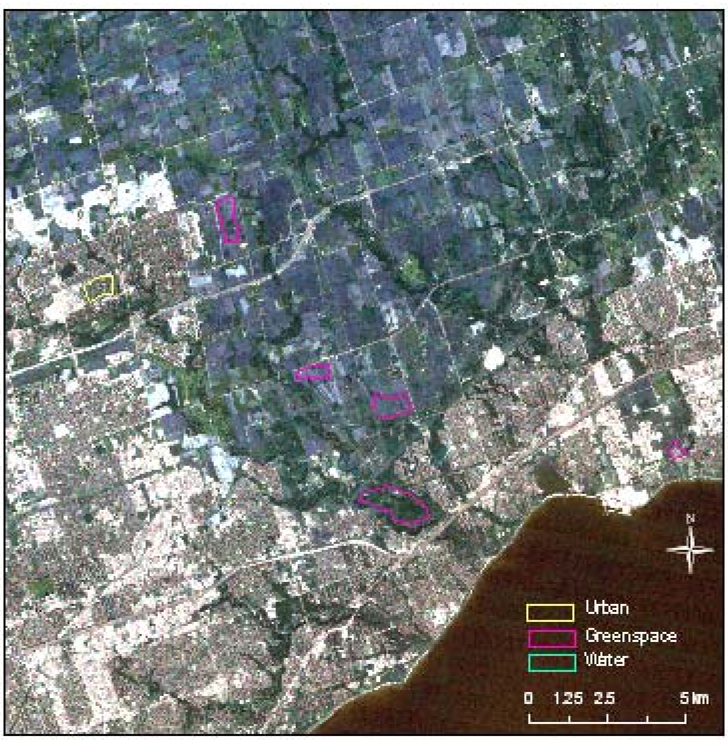


Figure 4.16: Training sites showing areas of water

Figure 4.17: Training sites along Yonge Street corridor

5. Classification Accuracy Assessment

The results of any land cover classification will never be a perfect representation of reality. In order to understand the relative accuracy of a land cover classification and its subsequent uses as mapped data, the analyst must design and implement an accuracy assessment.

One common approach is to create a sampling strategy, i.e., collect sample locations throughout the classification, verify them against another source of data, and create a confusion matrix to calculate the number of samples classified as the correct category and the number classified as the incorrect category. This approach will yield an assessment of the overall classification and the accuracy of an individual category.

5.1 Sampling Design

Since the research focus is the delineation of the built-up urban area boundary, an accuracy assessment was not performed on the land cover classification for the larger study area.

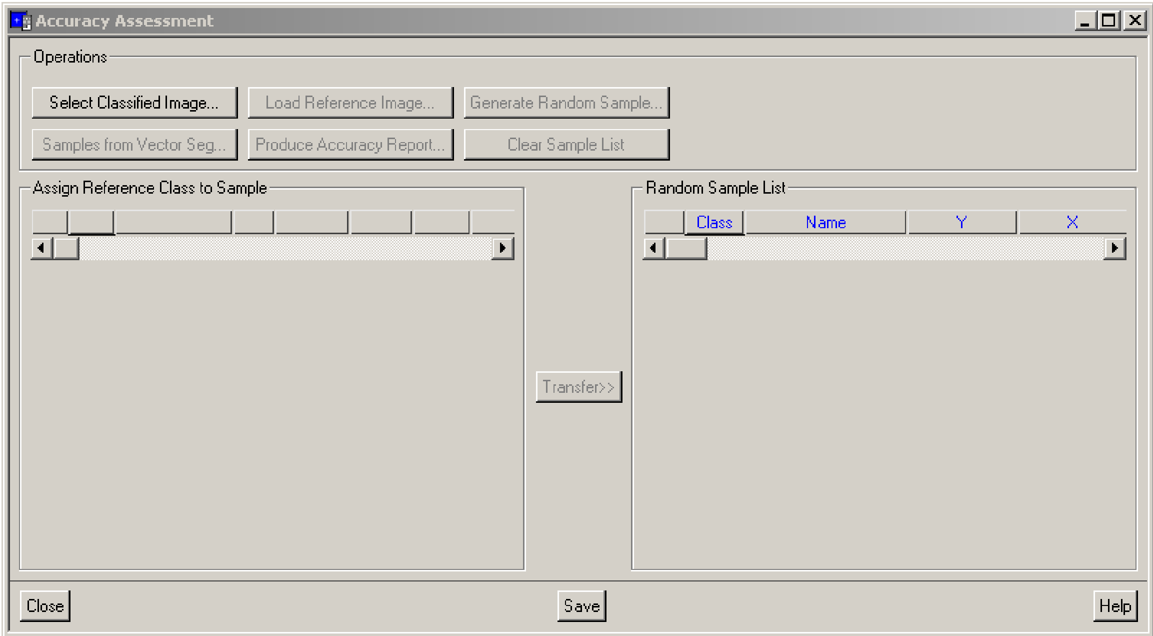
The classification was stratified according to the three main areas, Area I, II, and III. An accuracy assessment was performed for these areas and subarea I1, an area that contains the greatest amount of contiguous built-up urban area and is equivalent to the Greater Toronto Area, the City of Hamilton, and development north of the Escarpment in the Niagara Region.

The size of the sample collected for each area depends on the total number of pixels in an area and the number of pixels for each category in a classified area. The random samples are automatically generated by the PCI image processing software. Each sample point in the classification is verified by the analyst against reference data to compare the classified category and the correct category. In this case, the reference data used was the original TM imagery supplemented by high-resolution aerial photography. In order to perform the accuracy assessment, all pixels containing no data need to be classified in a category called “no data.” This can be done in ArcMap™.

5.2 Procedure

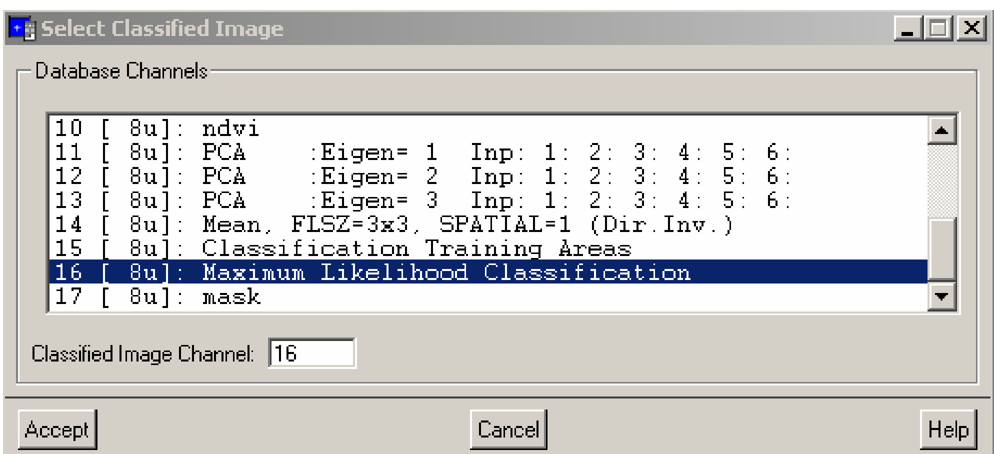
1. Go to Accuracy Assessment under Classify in ImageWorks and click “Select Classified Image.”

Figure 5.1: Accuracy Assessment dialogue box



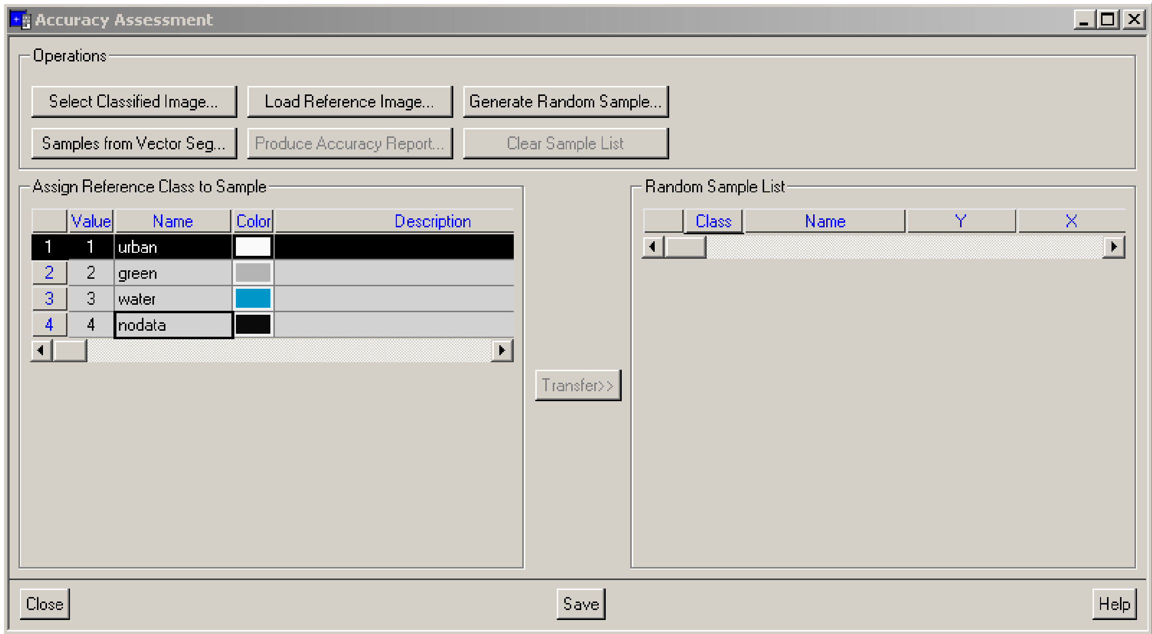
2. Select the channel for saving the results of classification.

Figure 5.2: Select Classified Image dialogue box



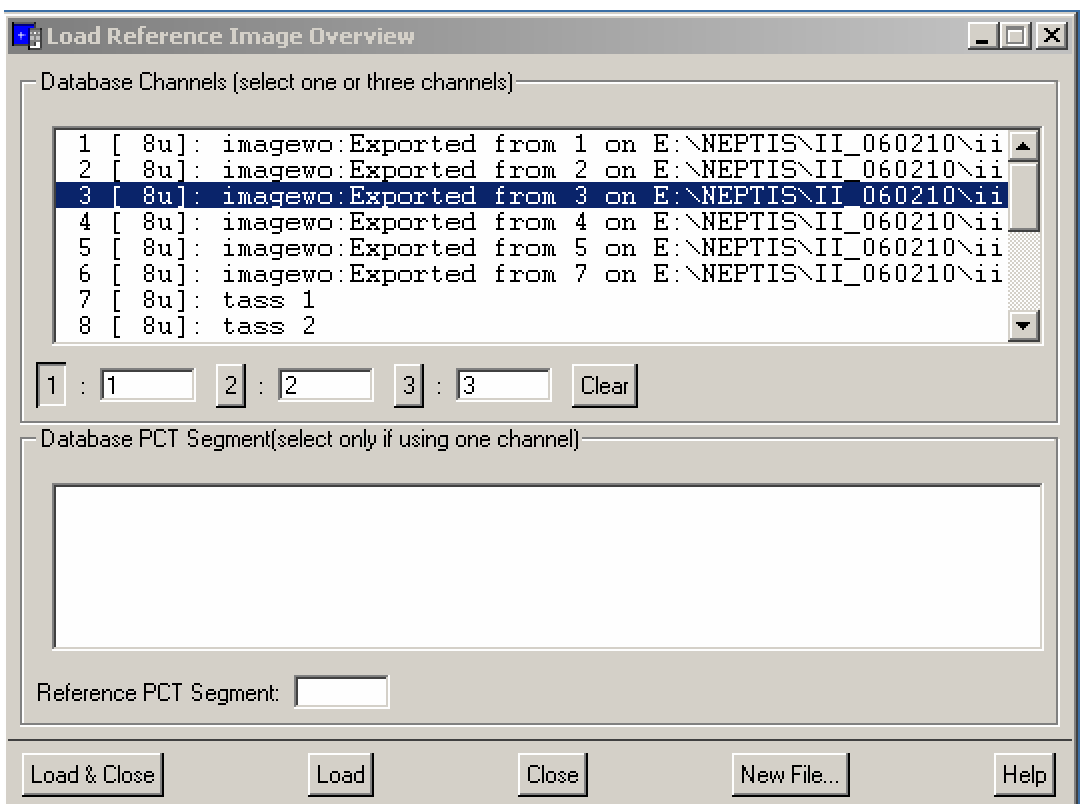
3. Click "Load Reference Image."

Figure 5.3: Accuracy Assessment dialogue box showing loaded reference image



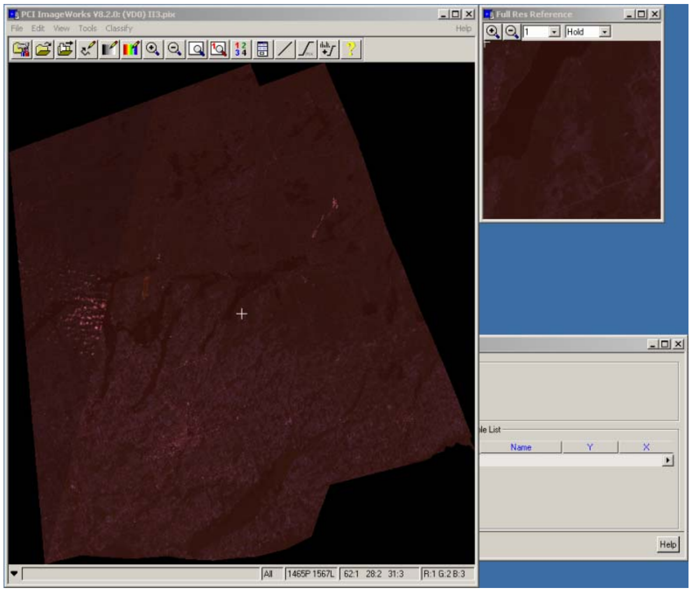
4. Click first 3 channels into 3 image planes (visible spectral bands). Click "Load & Close."

Figure 5.4: Load Reference Image Overview dialogue box



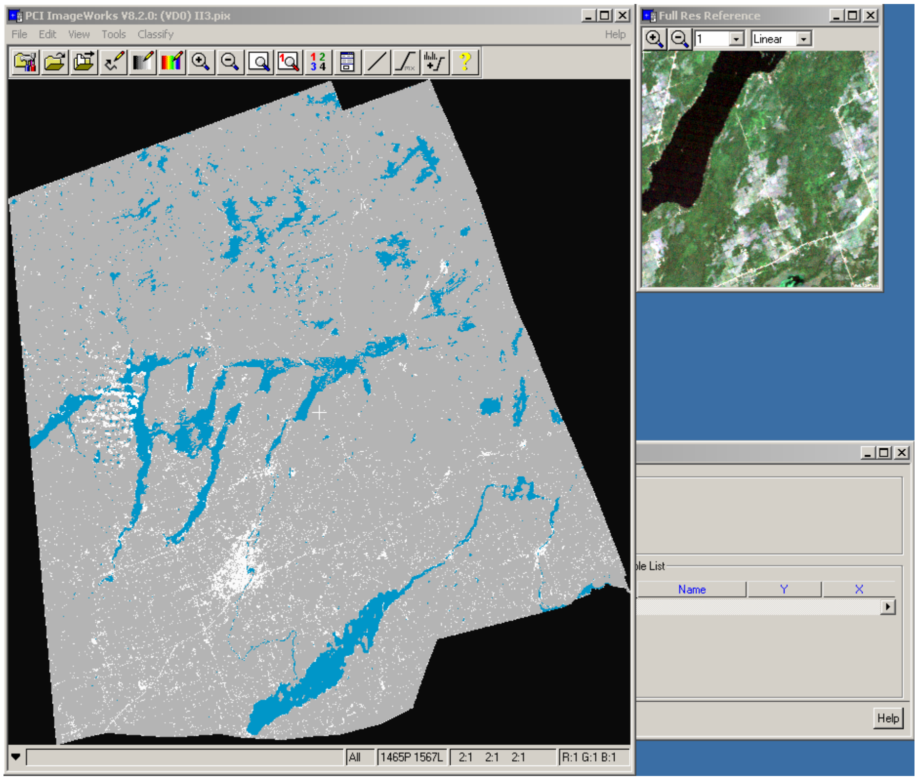
5. Referenced image appears on both full resolution window and ImageWorks window.

Figure 5.5: Full resolution window and ImageWorks window



6. Go to ImageWorks to load classification again. Make enhancement in Full Resolution Reference window as "Linear."

Figure 5.6: Full resolution window and ImageWorks window showing results



7. Click "Generate Random Sample." Specify the number of samples or use the sliding scale bar to gather a low, medium or high number of samples. Click "Accept."

Figure 5.7: Generate Random Sample dialogue box

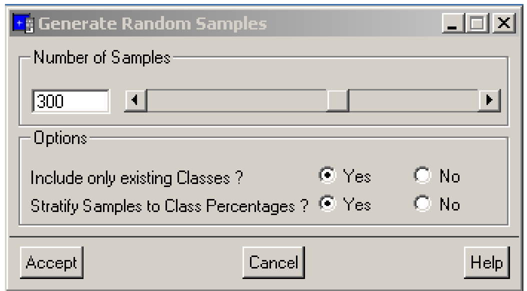
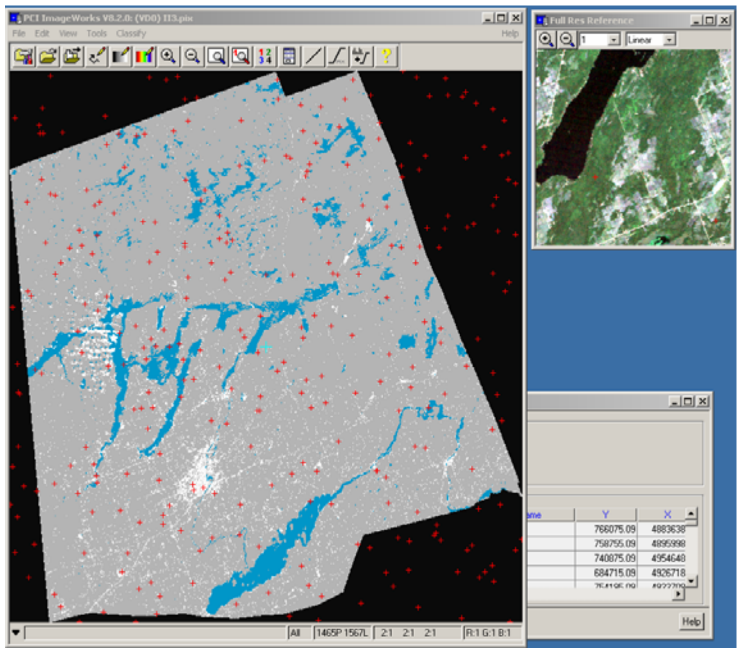


Figure 5.8: Full resolution window and ImageWorks window showing samples



8. Start the validation process by selecting a category or class under "Assign Reference Class to Sample." The sample sites will appear in both windows. Zoom into each sample site and assign a class to each site. For example, the majority of sample sites that occur in the grey area of the map in the window below would be classed as "green" or "unbuilt." The sample sites in the black area on the map would be classed as "no data." Repeat class assignment until all sample sites have been assigned.

Figure 5.9: Full resolution window and ImageWorks window zoomed in

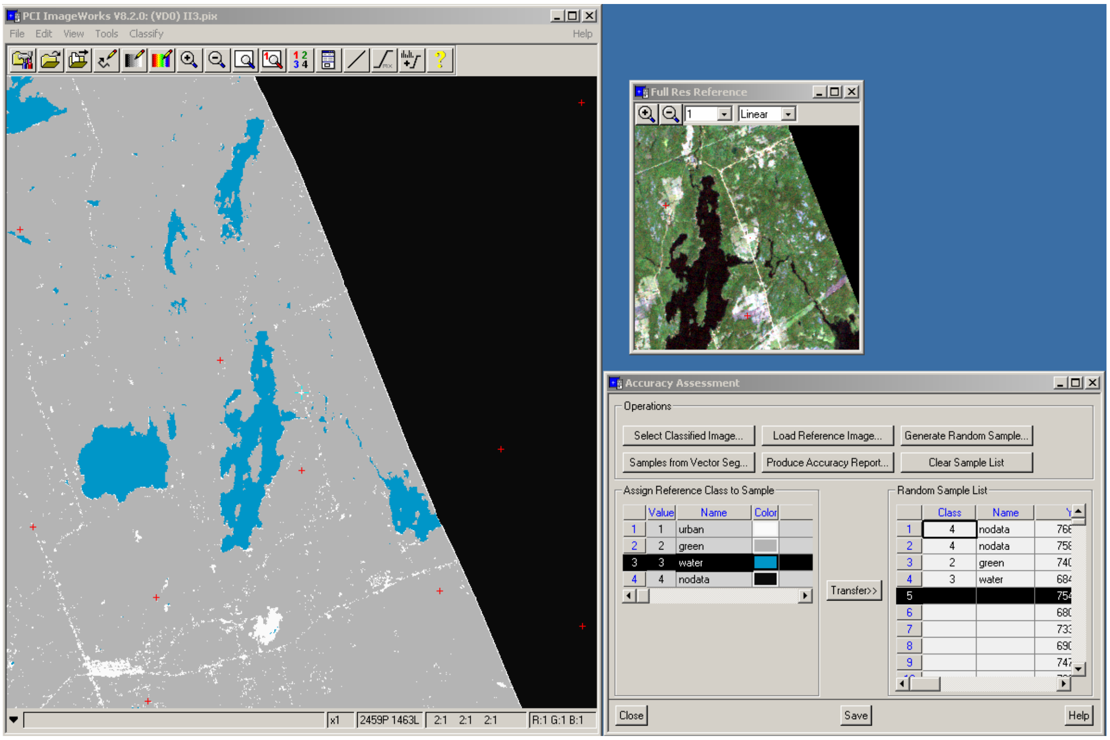
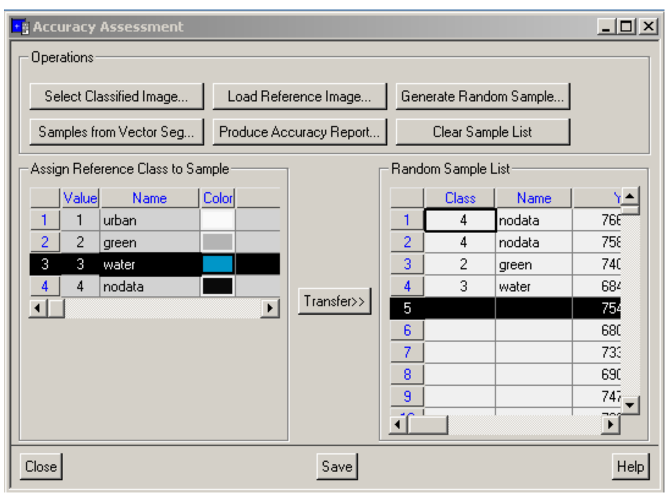


Figure 5.10: Accuracy Assessment dialogue box showing sample list



9. Once all sample sites have been assigned, click “Save” to save the sample sites to the database. Go to “Produce Accuracy Report.” Click “Generate Report.”

10. Assign a name to the report. Click “Append” to add sample sites for each area or subarea for which a report is needed. It is not necessary to complete the assessment of all sample sites in one session. A new accuracy assessment session can be started and the sample assignment can be added to an existing report.

Figure 5.11: Save Text Report dialogue box

5.3 Interpreting the accuracy assessment

After the samples have been gathered and checked, an accuracy report will be generated that consists of three tables:

- a list of verified samples;
- an error (or confusion) matrix;
- accuracy statistics for the overall and categorical accuracy assessment.

Only the latter two tables are included in this report.

The error matrix indicates the number of samples that were correctly and incorrectly classified for each category.

Accuracy statistics report the performance of a classification in percentages:

- The overall accuracy is a measure of how the classification performed in all classes.
- The Kappa statistic is used to compare two contingency matrices, and was not used in this analysis.
- The producer’s accuracy is a reference-based accuracy and describes errors of omission. An error of omission is a measure of category discrimination and occurs when one category on the ground is misidentified as another category(ies) by the observing sensor and/or the classifier.
- The user’s accuracy is a map-based accuracy and describes errors of commission. An error of commission is a measure of the ability to discriminate within a category and occurs when the classifier incorrectly commits pixels of the category being sought to other categories.

Accuracy statistics are highly dependent on the proportion of pixels classified as a particular category. These statistics are less reliable indicators of the performance of a particular category in a classification when a very low percentage of pixels are attributed to that category. Therefore it is important to carry out a visual inspection of the built-up urban category in areas dominated by unbuilt categories.

Accuracy statistics and an error matrix are shown below for each of the three main segmented areas and for subarea I1, the core built-up urban area. The overall accuracy of the classification of each area and the selected subarea is greater than 95%. The accuracy of each category in the classification varies depending on area being assessed and the proportion of that category in an area’s classification.

In areas where the accuracy of the built-up urban category is below 80%, the analyst must reassess the classification results or re-evaluate those areas in the post-processing steps. Since the amount of built-up urban land cover is proportionately much lower than the unbuilt land cover in areas II and III, it was decided to re-evaluate the built-up urban category in the post-processing steps.

Figure 5.12: Map showing subareas

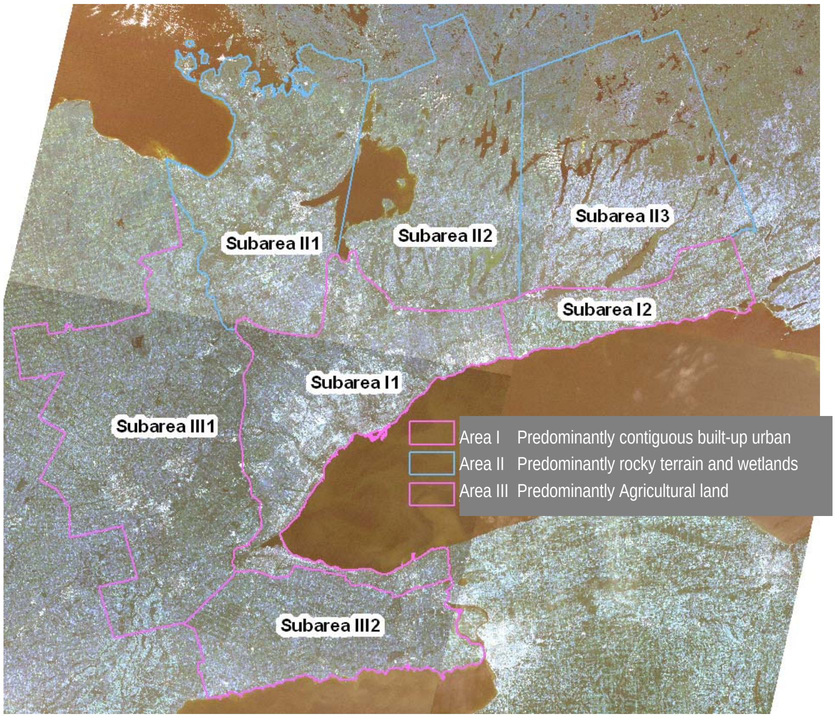


Table 5.1: Accuracy Statistics (Area I: Predominantly contiguous built-up urban)

Overall Accuracy: 95.667% 95% Confidence Interval (93.196% 98.137%)					
Overall Kappa Statistic: 0.882% Overall Kappa Variance: 0.001%					
Class Name	Producer's Accuracy	95% Confidence Interval	User's Accuracy	95% Confidence Interval	Kappa Statistic
Water	100.000%	(75.000% 125.000%)	100.000%	(75.000% 125.000%)	1.0000
Unbuilt	98.230%	(96.290% 100.170%)	96.104%	(93.392% 98.816%)	0.8420
Built	89.500%	(80.166% 95.834%)	94.030%	(87.610% 100.450%)	0.9214

Table 5.2: Error (Confusion) Matrix (Area I: Predominantly contiguous built-up urban)

Classified	Referenced Data			
Data	Water	Unbuilt	Built	Totals
Water	2	0	0	2
Unbuilt	0	222	9	231
Built	0	4	63	67
Unknown	0	0	0	0
Totals	2	226	72	300

Table 5.3: Accuracy Statistics (Area II: Predominantly Rocky Terrain and Wetlands)

Overall Accuracy: 96.750% 95% Confidence Interval (94.887% 98.613%)					
Overall Kappa Statistic: 0.850% Overall Kappa Variance: 0.002%					
Class Name	Producer's Accuracy	95% Confidence Interval	User's Accuracy	95% Confidence Interval	Kappa Statistic
Water	100.000%	(98.276% 101.724%)	100.000%	(98.276% 101.724%)	1.0000
Unbuilt	98.017%	(96.421% 99.613%)	98.295%	(96.801% 99.790%)	0.8549
Built	66.667%	(42.111% 91.222%)	63.158%	(38.836% 87.480%)	0.6142

Table 5.4: Error (Confusion) Matrix (Area II: Predominantly Rocky Terrain and Wetlands)

Classified	Referenced Data			
Data	Water	Unbuilt	Built	Totals
Water	29	0	0	29
Unbuilt	0	346	6	352
Built	0	7	12	19
Unknown	0	0	0	0
Totals	29	353	18	400

Table 5.5: Accuracy Statistics (Area III: Predominantly Agricultural land)

Overall Accuracy: 96.000% 95% Confidence Interval (93.804% 98.196%)					
Overall Kappa Statistic: 0.721% Overall Kappa Variance: 0.007%					
Class Name	Producer's Accuracy	95% Confidence Interval	User's Accuracy	95% Confidence Interval	Kappa Statistic
Water	100.000%	(75.000% 125.000%)	100.000%	(75.000% 125.000%)	1.0000
Un-built	98.137%	(96.504% 99.769%)	97.531%	(95.687% 99.375%)	0.6914
Built	70.231%	(49.567% 88.895%)	75.000%	(55.593% 94.407%)	0.7299

Table 5.6: Error (Confusion) Matrix (Area III: Predominantly Agricultural Land)

Classified	Referenced Data			
Data	Water	Green	Urban	Totals
Water	2	0	0	2
Unbuilt	0	316	8	324
Built	0	6	18	24
Unknown	0	0	0	0
Totals	2	322	26	350

Table 5.7: Accuracy Statistics (Subarea I1: Core urban area)

Overall Accuracy: 96.000% 95% Confidence Interval (93.616% 98.384%)					
Overall Kappa Statistic: 0.913% Overall Kappa Variance: 0.014%					
Class Name	Producer's Accuracy	95% Confidence Interval	User's Accuracy	95% Confidence Interval	Kappa Statistic
Water	100.000%	(75.000% 125.000%)	100.000%	(75.000% 125.000%)	1.0000
Un-built	96.429%	(93.575% 99.282%)	97.423%	(94.935% 99.910%)	0.9257
Built	95.098%	(90.418% 99.778%)	93.269%	(87.973% 98.565%)	0.8980

Table 5.8: Error (Confusion) Matrix (Subarea I1: Core urban area)

Classified	Referenced Data			
Data	Water	Green	Urban	Totals
Water	2	0	0	2
Unbuilt	0	189	5	194
Built	0	7	97	104
Unknown	0	0	0	0
Totals	2	196	102	300

6. Post-processing in GIS software

In the previous section, we described the image processing steps required to derive land cover data from satellite imagery. This process was used to produce a three-category land cover classification for each of the seven subareas in the Toronto region. The seven data sets were combined to form one data set for the study area using a mosaic procedure in ERDAS Imagine software package (see Figure 6.2).

Yet the combined data set is only the first product of the analysis, that is, a first cut at delineating the extent of the consolidated built-up urban area. In order for the data set to be integrated with other geospatial data sets, the urban data set must be converted from a raster to a vector format and generalized appropriately to include only consolidated urban areas of significant size and location.

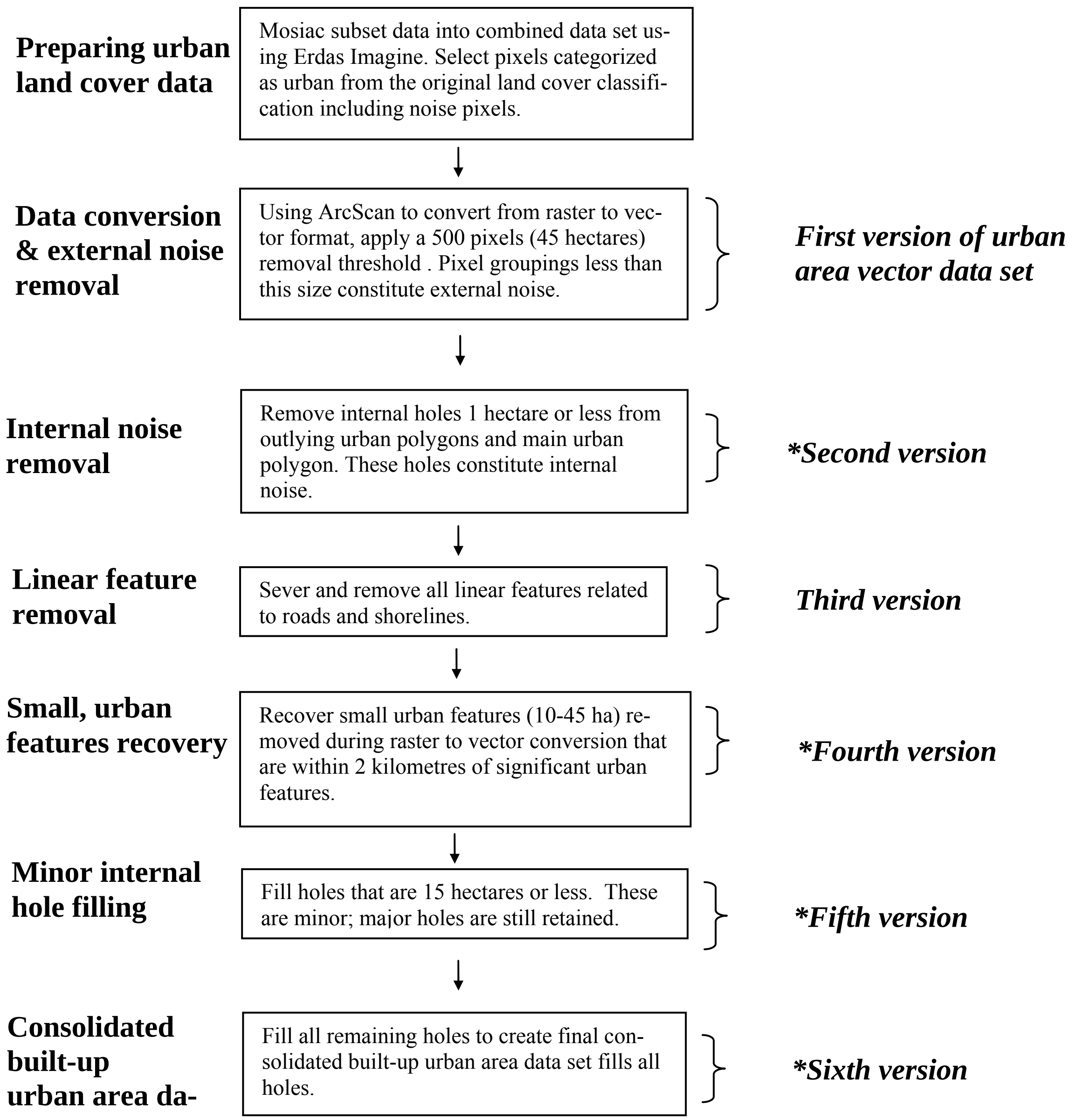
Although the conversion process is relatively straightforward, developing a set of generalization rules required extensive testing before a series of iterative steps could be identified. It should be noted that in any raster to vector conversion, and further processing of vector files, one must be cautious of the creation of slivers. Slivers are very, small polygons created during a spatial overlay procedure. They can either be merged into surrounding polygons or deleted, but they must be treated in a consistent manner, particularly when analyzing the consolidated, built-up urban area for more than one time period.

After the mosaic procedure, the urban land cover category had to be isolated and turned into a binary file (see figure 6.1 for flowchart of post-processing steps).The next step involved the conversion of the data set, from raster to vector, while "cleaning up the noise." For the purposes of our study, individual urban pixels (which represent 30-by-30 metre squares) or small, clusters of pixels located far way from large, urban pixel groupings were suspected to be "noise." To further investigate this assumption, the noise pixels were assessed using a number of spatial metrics that have been developed in the fields of landscape ecology and econometrics. These measures were used as a proxy to describe the shape and contiguity of pixels and pixel clusters. Following this period of testing, a method was developed to convert and generalize the urban land cover data set.

It should be noted that the vector files created during the post-processing procedure may be very large in size depending on the size of the study area.

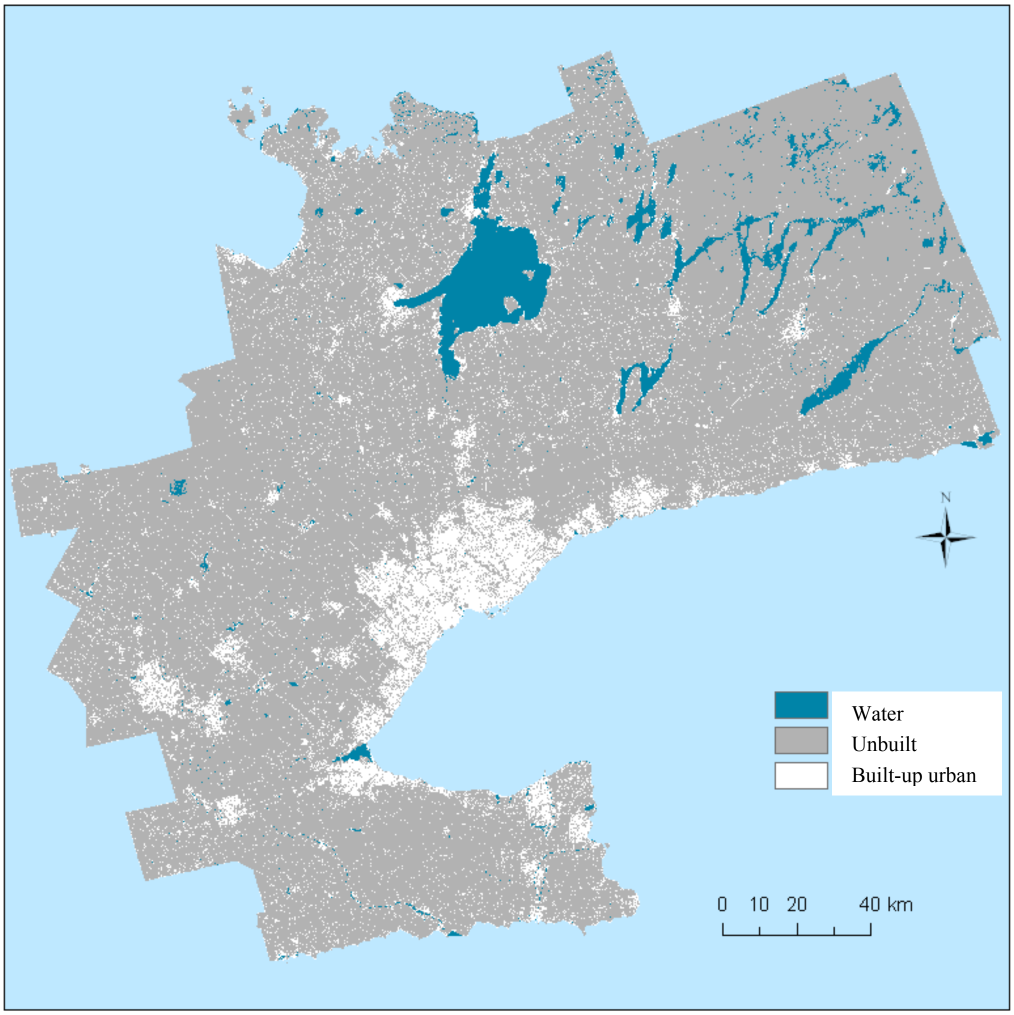
As noted in figure 6.1, a number of intermediate versions of the urban area vector data set were created during the post-processing stage. Several of these versions are useful for subsequent analysis: version 2 which retains most of the internal holes, but fills small holes that are one hectare or less, which we are calling "internal noise"; version 4 which recovers any small urban features within two kilometres of large urban polygons that was removed during the noise removal process; version 5 which retains major internal holes and version 6, the consolidated, built-up urban area with no internal holes. In order to ensure consistency between versions, a series of topological checks should be undertaken as each version is created. See Section 7 for discussion on the use of each version.

Figure 6.1: Post-processing steps



*These are vector data sets varying by the size and types of holes within the urban area which may be useful for subsequent analysis.

Figure 6.2: Map of the Toronto region produced using ERDAS Imagine software



6.1 Data conversion and noise removal

Since the original land cover data is derived from a set of imagery, its format is the same as an image, a raster or grid structure in which the smallest unit is the 30-by-30-metre-square pixel. This format is not conducive to data integration with vector format data sets. A vector format allows for a more realistic and smoother portrayal of the features the data set is representing.

Using the ArcScan module in ESRI's ArcGIS software, the built-up urban category of the land cover classification was isolated and converted to a vector data structure. The parameters set during this process also allow one to remove "noise" at the same time.

After some testing and assessment of results, a set of parameters were chosen for the conversion process. These are described below. One parameter requires the specification of a threshold for connected cells or pixels. During the conversion process, this parameter retains all pixel groupings above the threshold and removes all pixels below the threshold. This is the first step in removing "noise," i.e. the noise pixels that are external to significant urban features. A second noise removal occurs after the ArcScan procedure that removes internal noise, i.e. all internal holes of 1 hectare or less. This is done in two stages and described below.

6.1.1 Procedure

1. Using the Spatial Analyst tool bar in ArcMap, make sure that the raster data set representing the 1990 built-up urban area has been reclassified to a binary format (0 = non-urban, 1 = urban) format using. Use the "Reclassify" menu option and ensure it has been saved/exported to an ESRI GRID file. Right click in the table of contents, select the "Data" option, and click "Export Data."

2. Under the Tools menu, select "Extensions." Select the "ArcScan extension." Right-click the main menu bar of ArcMap. Select the ArcScan toolbar.

3. Create an empty polygon and polyline shapefile in ArcCatalog that covers the same study area. Add them to the ArcMap document. At this stage, there should be a GRID file, a blank polygon, and polyline file within the ArcMap document.

4. Start an edit session for the blank polygon file. Activate the ArcScan toolbar for the mosaic GRID selected.

5. To reduce pixel noise, under the Raster Cleanup menu option, select "Start Cleanup." Make sure foreground is being selected (1 = urban). Under the Cell Selection menu option, select "Connected Cells." Apply the following parameters:

    - Total area of connected cells
    - Foreground
    - Less than or equal to 500 pixels (~45 hectares)

    Under the Raster Cleanup menu option, select "Erase Selected Cells."

6. Export the result to a new GRID.

7. Make any manual edits to the most recent GRID version as needed. In this case, the roads needed to be manually broken using the "Erase" button of the ArcScan toolbar.

8. Export the result to a new GRID.

9. Under the Vectorization menu, select "Vectorization Settings." Click "Styles" and select the outline style. Clicking "OK." Choose the following parameter settings:

    - Intersection Solution: None
    - Maximum Line Width: 20
    - Compression Tolerance: 0.001
    - Smoothing Weight: 1
    - Gap Closure Tolerance: 0
    - Fan Angle: 0
    - Hole Size: 0

Apply the new settings.

10. From the Vectorization menu, select “Options.” In the Raster Colors window, click “Toggle Colors,” so that the foreground represents urban and the background represents unbuilt.

11. From the Vectorization menu, select “Show Preview” to check the polygons and polylines that will be produced. Make sure that the resolution is sufficient for the application. Keep changing the vectorization settings until the optimal vectorization is achieved.

12. From the Vectorization menu, select “Generate Features.” Make sure the appropriate polygon and polyline shapefile are chosen (the empty files created in step 3) to house the vectorized version of the GRID.

13. In the ArcScan procedure if the main urban polygon of the study area is a relatively uncomplicated polygon with a minimal amount of vertices, then the result will be a polygon file instead of a polyline file. Since the Toronto region is so extensive, the ArcScan procedure produces a polygon file for the outlying urban areas and a polyline file for the main urban area adjacent to the Lake Ontario. This is the ***first version*** of the urban area vector data set where all external noise has been removed.

Figure 6.3: Polygon data set: outlying urban areas

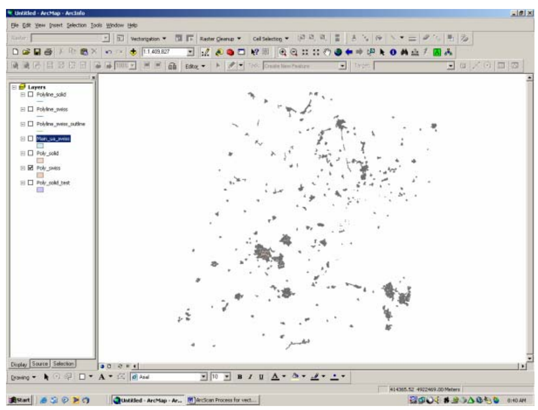
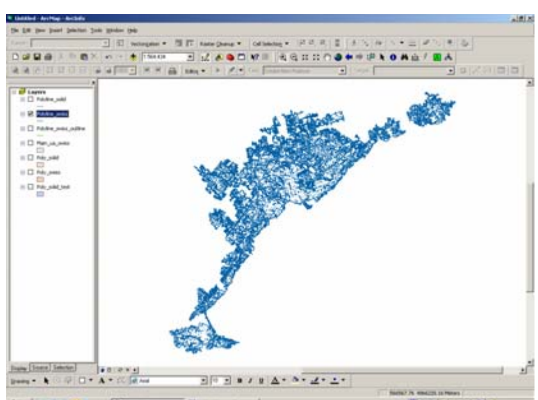


Figure 6.4: Polyline data set: main urban area



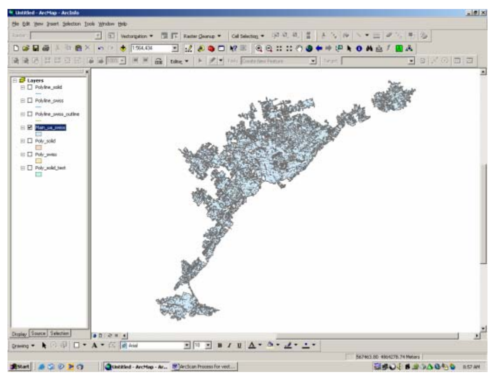
14. Figure 6.3 shows the outlying urban features displayed in a polygon format. In order to remove the internal noise or internal holes that are 1 hectare of less, the file must be converted to a polyline file using the "Feature to Line" tool. After this is done, both the outlying urban features and the main urban area are in polyline format.

15. Next, the integer 'class' field must be added to the table of each polyline data set. Calculate the class field to '9' which will label the urban features in the polyline data set and not internal holes.

16. Convert these polyline data sets into polygon data sets using the Feature to Polygon tool in ArcToolbox. The result produces an urban area data set with all of the internal holes filled but urban features classed as 9 and holes classed as 0.

17. In an edit session, select "internal hole" polygons with a 'class' field value of 0 and an area of 1 hectare or less and merge them with class 9. Depending on the file size, this process may have to be repeated using small sections of the file. Figure 6.5 shows the result for the main urban area.

Figure 6.5: Example for the main urban area



18. Merge/Union main urban area polygon file with outlying urban areas polygon file. The last step produces the ***second version*** of the urban area vector data set where internal noise has been removed.

19. After the ArcScan conversion process, all polygons should be disaggregated using the "explode multi-part polygons" tool in an edit session so that the area measurement is updated for each polygon. This should be done every time the "dissolve" tool is used throughout the analysis.

6.2 Data generalization

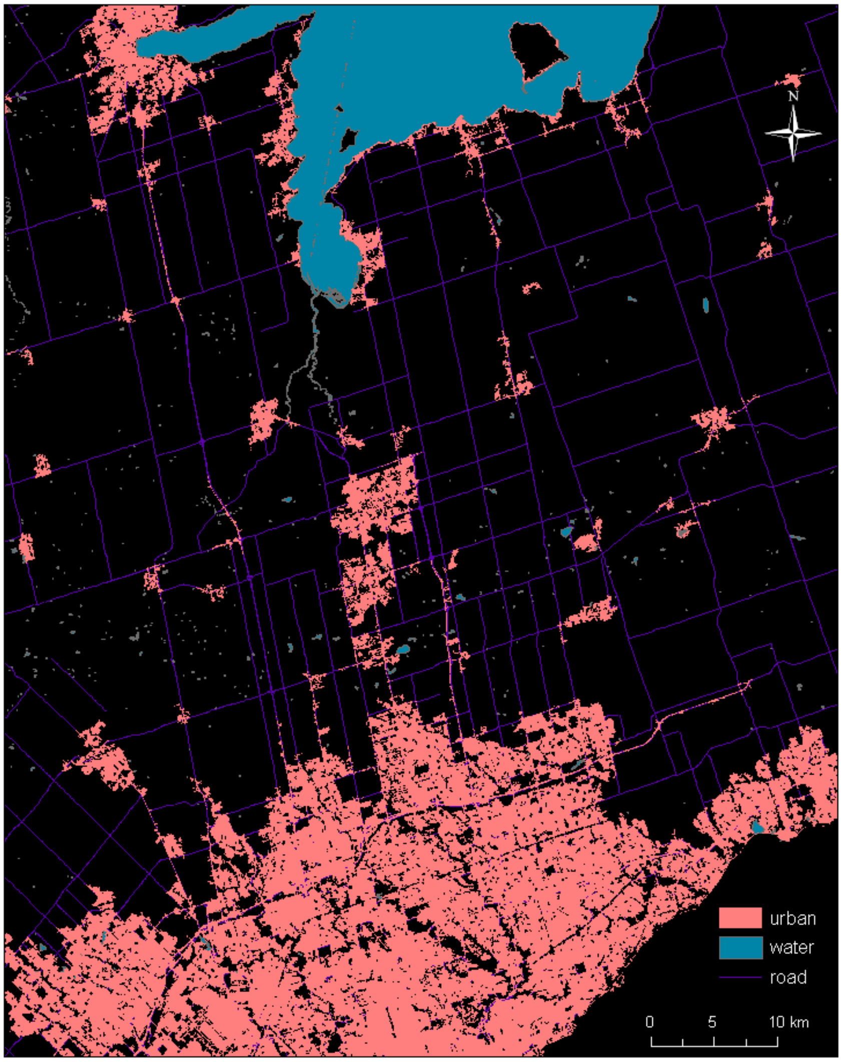
Generalization began during the conversion process, when all pixel groupings with less than 500 connecting pixels were removed from the vector data set. Although most of these pixels were determined to be noise, a close examination of these features is required. The next step of the generalization process involved removing what was deemed "linear noise," spurious, linear urban features generated from roads or shorelines.

Wide roads outside the built-up urban fabric are often detected in Landsat TM imagery and classified as urban due to the spectral reflectance of the road surface and its contrasting pattern with surrounding unbuilt features. Depending on the condition of the imagery, the width of the road and the pervasiveness of vegetation surrounding a road, the full length of a road may not be captured in the land cover classification. In other words, isolated roads may not be consistently captured, especially year to year. Although roads may be considered an urban feature, the occurrence of these features in isolation and far away from other urban land was considered inconsistent with the definition of the consolidated built-up urban area.

In addition to linear noise from roads, it was also identified in association with some shorelines in the study area. During the classification process, an error of commission was introduced from the texture enhancement. The textural measure detected a stark contrast between water and shoreline and mistakenly attributed it the same textural pattern associated with the juxtaposition of urban and some unbuilt features. In the final land cover data set, this type of error shows up as slim linear features that outline water bodies and is easily identifiable.

Figure 6.6 illustrates the urban vector file after the conversion process. The water data set from the land cover classification is mapped as well as an external data source for roads (DMTI 2005). Both data sets are used to generalize the urban data set and remove these insignificant linear features.

Figure 6.6: Urban Vector File after conversion process



6.3 Removal of "linear noise" features

A series of buffer and overlay analyses was used to remove linear noise features. First, a 100-metre buffer is applied on either side of a roads centreline data set [6] (see Figure 6.7). As a word of caution, it is best to use a limited selection of roads that corresponds to the linear road features that are deemed noise. It is very difficult to automate the selection process, so to reduce the number of roads in the analysis, a selection of roads based on an edge buffer of the built-up urban area in combination with a selection based on road type may be the most efficient method for optimizing the road selection.

6 The original source of the centreline data set used for this analysis was DMTI Spatial, 2005. As noted in section 6.3, the dataset contained ramps which could not be isolated and therefore complicated the analysis. In subsequent analyses, we suggest using a centreline data set where ramps can be isolated and removed from the analysis. In Ontario, the Ontario Road Network proved more useful in subsequent analyses.

After the roads have been selected and a 100-metre buffer has been created for the roads, the buffered area is then erased from the version 2 of the built-up urban area data set (see Figure 6.8).

This step removes more than just the unwanted roads. Urban features that are incidentally removed during this step are then replaced by a second buffering process of the urban area data, resulting from erasure (see Figure 6.9). Although this step replaces urban features that have been incidentally removed, it also creates additional urban features at the edge (see Figure 6.10). These urban features are then "trimmed" by intersect overlay with the original urban data set which removes any new urban area beyond the original urban features in that data set (see Figure 6.11).

Figure 6.7: 100m road buffer from centreline and original urban data set with linear noise

Figure 6.8: 100m road buffer erased from urban area

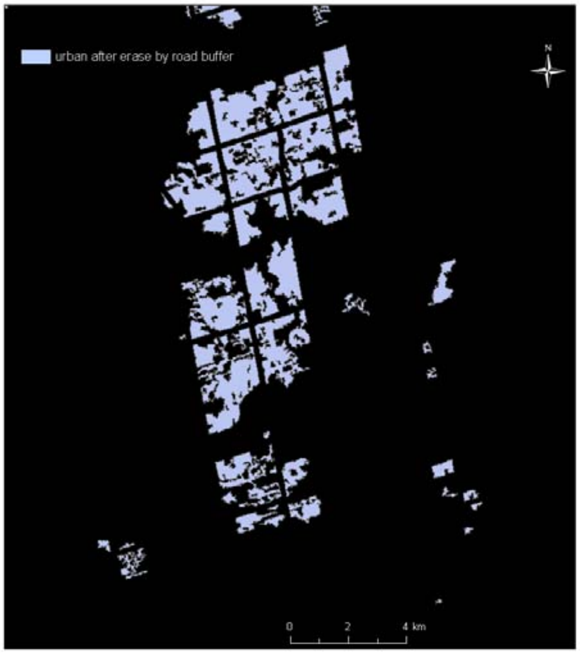


Figure 6.9: 100 m buffer around erased urban data set

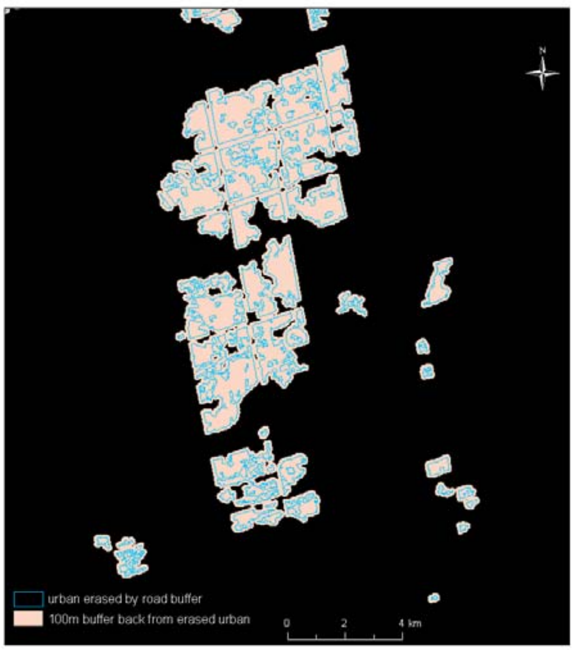


Figure 6.10: Overlay between buffered erased urban and original urban.

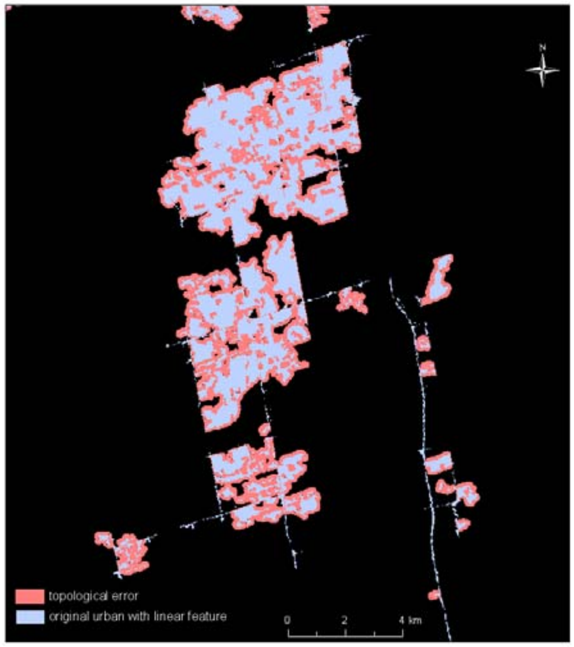


Figure 6.11: Original urban area compared to final result of roads linear removal

A couple of problems have been identified with the above procedure and can be avoided based on the initial roads selection used in the analysis. Where a roads data set contains lines that are closer together than the buffer distance, unwanted holes may be created. This also occur where roads intersects at an acute angle, such as highway ramps. In effect, selecting fewer roads to perform the analyses should help to limit problems that arise during the linear noise removal process.

To fill the unwanted holes introduced this way, a final 100-metre buffer was applied to the generalized urban area and intersected with the original urban area. Figure 6.12 shows the original urban in blue, generalized urban in pink and the boundary of the buffer around the generalized urban as a green line. The yellow box indicates where changes are made after the final buffer and intersect operations have been performed. Figure 6.13 shows the results in which the unwanted holes are filled.

Figure 6.12: Final buffer and intersect operations

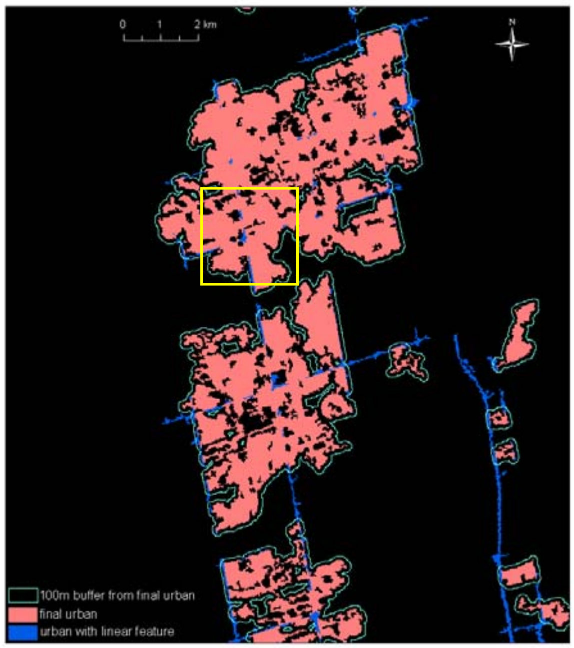


Figure 6.13: Results comparing the final generalized urban area to the original

To remove linear noise resulting from shoreline features, a vector data set is generated from the water land cover class. The same linear removal procedure described above is then performed on the generalized urban area data set but using the linear shoreline features instead of the roads.

6.4 Small urban features recovery

At this point in the analysis, most urban features of significant size have been captured as part of the urban area vector data set. But the small urban features that were removed during the conversion process should be analyzed for their significance.

In the Toronto region, suburban development is planned within a grid of concession roads. Concession roads are typically two kilometres apart. Our assumption is that new development should occur within two kilometres of an existing urban feature. Since urban polygons representing new development may be less than 45 hectares (our maximum noise threshold) at the beginning stages of construction, we wanted to be able to capture this development in the final urban area data set. So we examined noise features that were within two kilometers of significant urban features. We used a 45 hectare threshold to select significant urban features.

Figure 6.14: Areas of significant built-up urban features

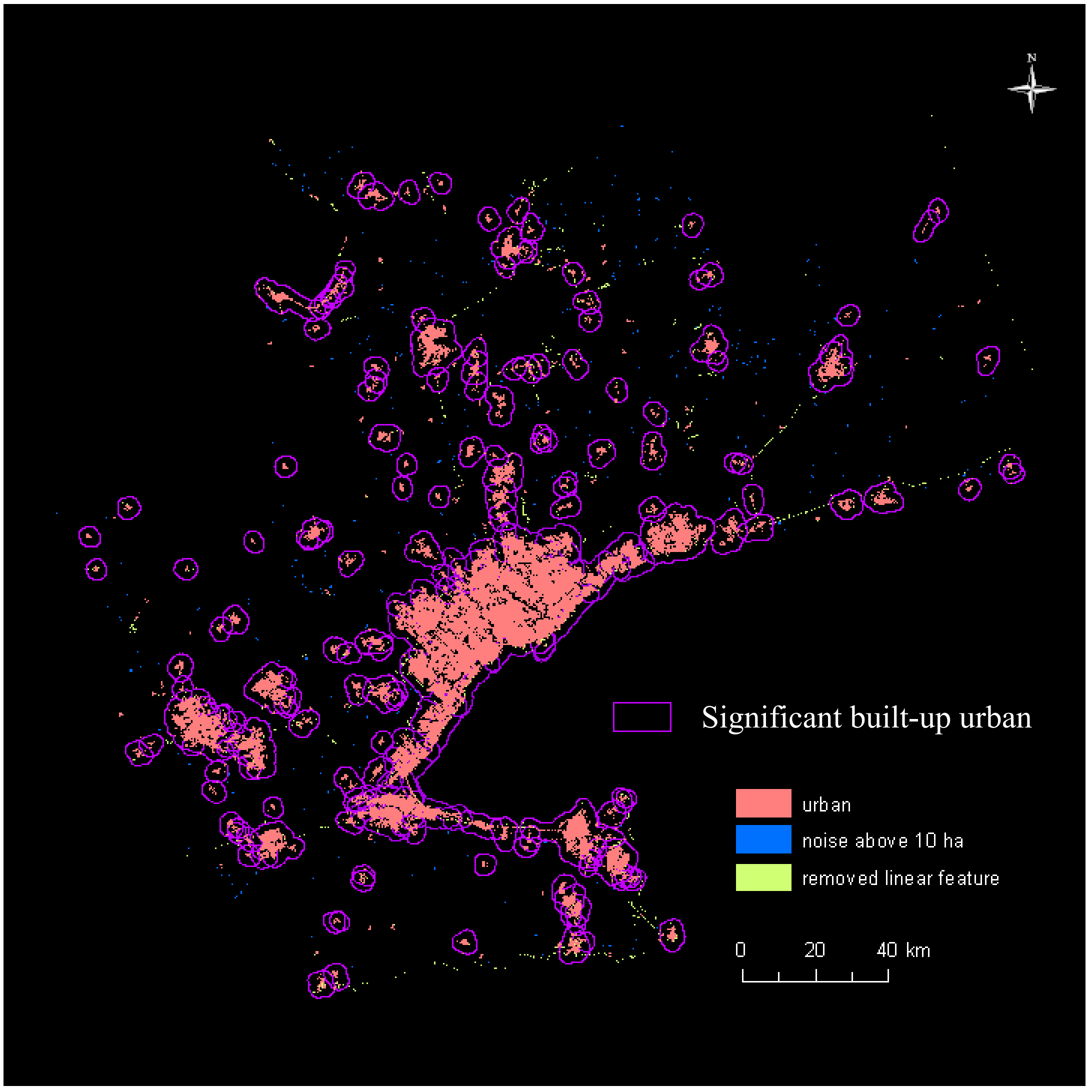


Figure 6.14 shows a 2-kilometre buffer around all urban features that are 45 hectares or greater. We examined the noise pixels removed during the conversion process but were located within this buffer. All urban pixels removed during the conversion process were converted to a vector data set. The area of each feature was calculated, and a frequency distribution of the size of these features was analyzed (see Figure 6.15). The majority of the features were below 10 hectares with an overwhelming majority below 2 hectares (see Figure 6.16).

Figure 6.15: Frequency distribution of urban features removed during conversion (<=45 ha)

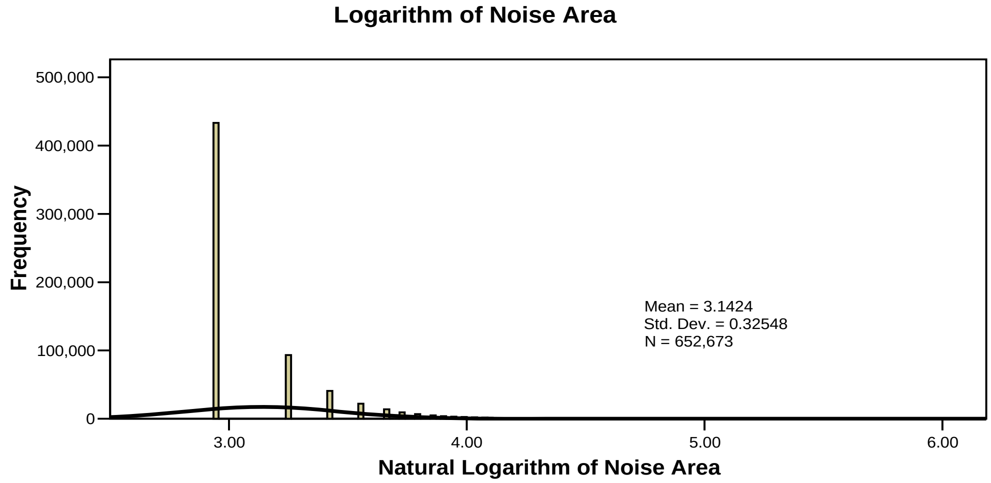
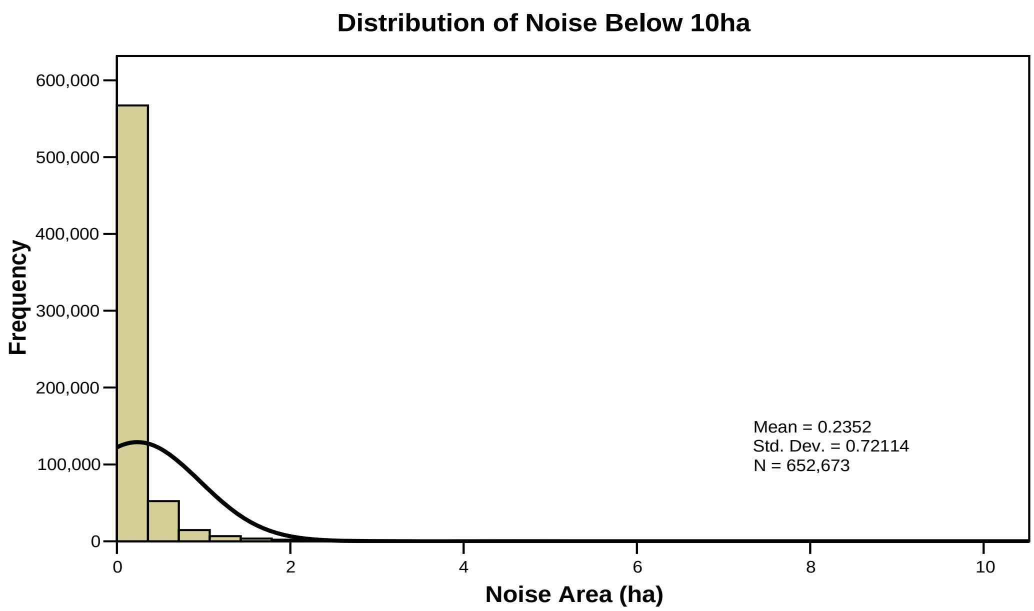
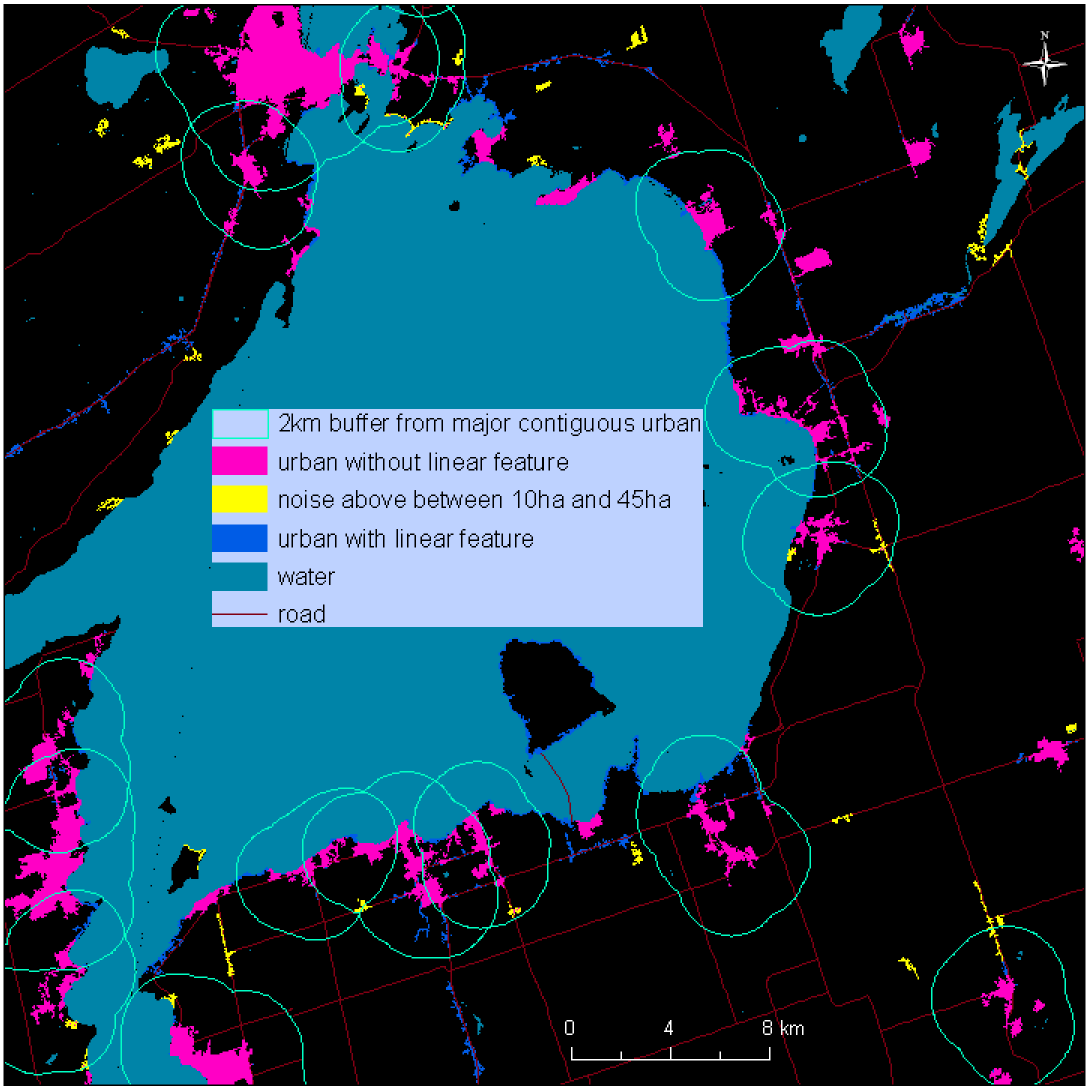


Figure 6.16: Frequency distribution of urban features removed during conversion (<=10 ha)



Therefore we determined that all noise features over 10 hectares and have their centres, or centroid, in the 2-kilometre buffer should be recovered. However, during the feature recovery step, we found that some linear noise was recovered as well (see Figure 6.17) because these noise features were not included in the linear feature removal process. Once the linear noise was removed, the urban features from the noise data set were captured if they were 10 hectares or above and within two kilometres of urban features with an area of 45 hectares. Finally all holes in the returned noise data set that were less than or equal to one hectare were filled in. At this point, the ***fourth version*** of the urban area vector data set is created.

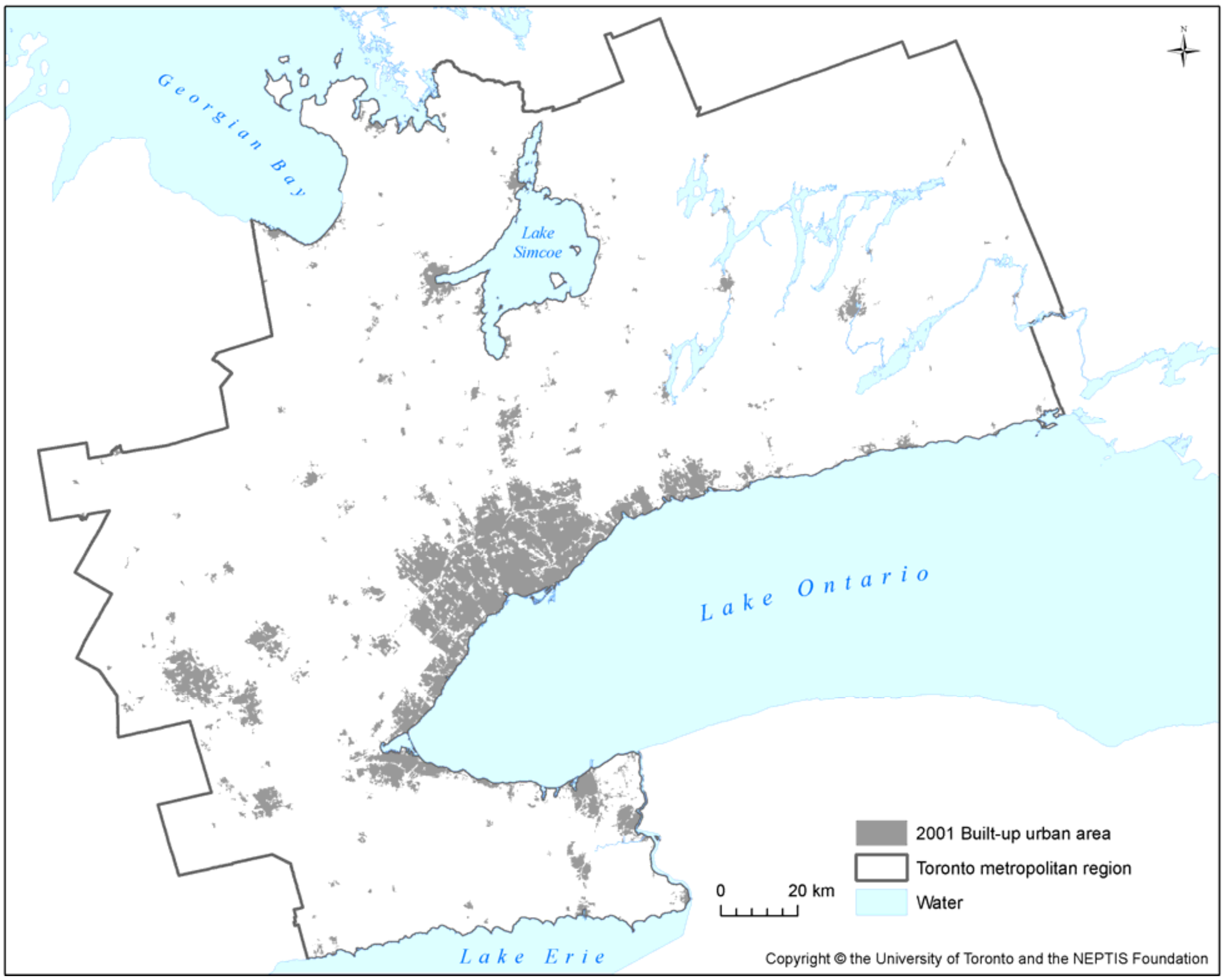
Figure 6.17: Removed noise includes some linear features



6.5 Minor, internal hole removal

To create the ***fifth version*** of the urban area vector data set, minor, internal holes are removed. These are thought to be small, green spaces such as large lawns or small parks that could be deemed an urban use. In the Toronto region, 15 hectare was thought to be a cut-off threshold to create a manageable file that did not enclose significantly-sized holes relate to large greenland areas. Major holes larger than this were retained. The threshold was developed during a process of testing and comparison to aerial photography. This threshold may be different depending on the study area being analyzed. Figure 6.18 illustrates the resulting consolidated built-up urban area for 2001.

Figure 6.18: Version 5 of the consolidated built-up urban area derived from 2001 Landsat TM5 imagery



6.6 Final consolidated built-up urban area

To create the ***sixth version*** of the urban area vector data set, all remaining internal holes are filled. This is done in order to integrate the built-up urban area data set with other geospatial data sets.

7.0 Discussion

The procedure described and illustrated in this guide has been used to delineate the extent of the consolidated built-up urban area for the Toronto metropolitan region. Six versions of the built-up urban area were created using this procedure. Some data sets are considered intermediate files while other are deemed useful for subsequent analysis. It is the sixth version, built-up urban area with all internal holes filled, that formed part of the Neptis Foundation and the Cartography Office's research into rates of residential intensification in the Toronto region for the 1991-2001 period. This is described in "A methodology for estimating the historical rate of residential intensification between 1991 and 2001 for the Toronto Region" (2007), paper no. 2 in the *GIS and Cartography at the University of Toronto Technical Paper Series* and referenced in "The Ins and Outs of Effective Growth Management" (forthcoming from the Neptis Foundation). This procedure has also been applied to Calgary and Vancouver, to delineate their respective urban areas in order to estimate their residential intensification rates for the same period.

Defining the built-up area for an urban region, large or small, is a complex task. One's approach must consider the nature of the existing urban fabric and the planning and development process of a region (see discussion in forthcoming Neptis paper examining urban form and residential intensification in Toronto, Calgary and Vancouver). Given these facts, final decisions on rules for refining a data set must also consider the end use of the data set. For example, internal holes within the urban fabric make integration of the built-up urban area with other continuous GIS data sets a difficult task unless a set of rules is created to fill holes in a manner that will not impact the results of one's analysis. We found that the internal holes, representing things such as parks, golf courses and small greenland features, would not significantly affect an estimate of intensification. However using the urban extent to determine the amount of urban area growth between two dates would require a closer examination of the internal holes, as would a comparison of urban densities between years.

The value of the procedure described in this document lies in its potential to produce repeatable, reproducible results for a variety of urban regions, and thereby allow for comparisons between urban regions.

8.0 Bibliography

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