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Investigation of correlation between remotely sensed impervious surfaces and chloride concentrations

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The main objective of this study is to verify the often assumed correlation between impervious surfaces and chlorides that result from the application of road salts, focusing on a case study in the selected six major watersheds within the Greater Toronto Area. Landsat-5 Thematic Mapper images collected in 1990, 1995, 2000, and 2005 and the unsupervised classification technique were utilized in the estimation of percentage imperviousness for each watershed. Chloride concentrations collected at water quality monitoring stations within the watersheds were then mapped against impervious surface estimates and their spatiotemporal distribution was assessed. The remotely sensed impervious surface maps and chloride maps were overlaid in a geographical information system environment for the investigation of their potential correlation. The main findings of this study indicate an average of 12.9% increase in impervious surface areas as well as a threefold increase in chloride concentrations between 1990 and 2005. Water quality monitoring stations exhibiting the highest amounts of chloride concentration correspond with the most impervious parts of the watersheds. The results also show that the increase in imperviousness does generate higher chloride concentrations. Correspondingly, the higher levels of chloride can potentially degrade the quality of surface waters. Through developing a novel integrated remote-sensing approach, the study was successful in identifying areas most vulnerable to surface water quality degradation by road salts.

1. Introduction

Growing cities often signify a strong economy. However, as they expand, the stress exerted on natural environments and resources becomes greater (Weng 2001). During the past 30 years, the Greater Toronto Area (GTA), Ontario, Canada, has been identified as one of the fastest growing industrial areas of the Great Lakes Basin. Therefore, serious questions are being raised regarding the environmental sustainability of the urban growth around the GTA. Economic development and growth in the GTA continues with each passing year and is characterized by the transformation of rural and agricultural lands into residential and commercial centres.

One of the serious consequences of this growth has been reduced stream water quality and loss of aquatic habitat caused by application of road salts on these paved surfaces. Impervious surfaces prevent precipitation and meltwater from infiltrating soils and are

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likely to generate more runoff during wet seasons and less groundwater discharge to streams during dry seasons (Bowen and Hinton 1998; Barnes, Morgan, and Roberge 2001; Shuster et al. 2005).

It has been well documented that the amount of urban runoff and its impact on surface water quality are strongly correlated with the percentage of impervious surface within a watershed (Schueler 1994; Arnold and Gibbons 1996; Clausen et al. 2003). In the GTA, chloride concentrations have been rising across a majority of urbanized watersheds over the past three decades. Within the GTA, one region that has always been the focus of local and regional planners is the Oak Ridges Moraine. A study by Bowen and Hinton (1998) revealed that upstream areas within the Oak Ridges Moraine dilute chloride concentrations in downstream urban areas (Bowen and Hinton 1998). The rise in chloride levels is attributed mainly to the increase in road salt applications. Road salts, particularly sodium chloride (NaCl), represent the largest chemical loading to the Canadian surface waters (Environment Canada 2001). According to an assessment by Environment Canada, an estimated 6.8 million tonnes of road salts were sold for highway de-icing in 2003. The trouble is, once the salt dissolves, it washes into streams, enters the drainage system or underlying soil, and is forgotten (Kaushal et al. 2005).

In April 2004, Environment Canada released a code of practice for the environmental management of road salts. Since then, the Municipality of Metropolitan Toronto as well as the Regional Municipality of Peel has developed a salt management plan to minimize the amount of salt entering the environment by including best salt handling practices and using new technologies. The code of practice is a voluntary pollution control tool for road authorities using more than 500 tonnes of road salts per year. It is proposed that unless mandatory requirements are put in place by regulatory authorities, no effective method of salt management, storage, application, or disposal could be achieved and no major reduction in usage could be implemented (Hounsell, Lintner, and Mercer 2006).

Geographical information systems (GISs) and satellite remote sensing are valuable tools in mapping and determining the extent of impervious surfaces within urban watersheds. Through the interpretation and analysis of impervious surfaces derived from satellite imagery, the potential impact of road salts on surface waters can be indirectly assessed. A land-use and land-cover (LULC) map, including an impervious surface map, is one of the most important end products of image interpretation that is obtained from a digital image classification process.

Accordingly, the ultimate goal of this study is to make use of satellite remotely sensed data and GIS to develop a fast and reliable solution to estimate the amount of imperviousness with an acceptable level of consistency and accuracy. In this case, the connection between chloride and impervious surfaces could be confirmed, and the most vulnerable areas to water quality degradation could be predicted.

This study contributes to the field of hydrology and water resource management. By using satellite remote-sensing techniques, this work extends the literature on the potential correlation between increased chloride concentrations as a result of increased impervious surfaces and potential water quality impacts in the GTA.

The primary objectives of the study are to

(1) map out chloride concentrations at the selected Provincial Stream Water Quality Monitoring Network stations within six watersheds in the GTA during a 15 year period (1990, 1995, 2000, and 2005) and
(2) generate improved and consistent impervious surface estimates for the four separate dates of image data, and to identify the relationship between increased watershed-based impervious surfaces and decreased water quality over time.

Overall, this study provides a spatiotemporal measure of an important environmental indicator of a rapidly expanding region in Canada by adopting an integrated remote-sensing and GIS approach, which may then be applied to other regions as a preliminary step in water quality monitoring and protection.

The following specific tasks are conducted in this study:

(1) map out chloride concentrations of impervious surfaces using multitemporal Landsat-5 Thematic Mapper (TM) data by means of a post-classification approach for four separate dates spanning a 15 year period (1990, 1995, 2000, and 2005);
(2) identify the two land-cover types of ‘green’ and ‘impervious’ surface and calculate the percentage of imperviousness and determine areas of increased impervious surfaces through change detection between each two consecutive pair of land-cover maps;
(3) relate historical chloride information for selected water quality monitoring stations across the study area to the impervious surface estimates for the four dates to determine, preliminarily, whether a relationship between increased impervious surfaces and increased chloride contamination can be identified over time; and
(4) integrate maps of chloride concentrations and impervious surfaces in a GIS environment to validate further the adverse effect of impervious surfaces on water quality.

2. Methodology

2.1. Study area

The GTA in southern Ontario is Canada’s largest metropolitan area, with a population of over 5 million (City of Toronto 2007). In this study, the investigation of chloride levels in relation to impervious surfaces has focused on six watersheds located in a hydrologically sensitive area: five of these are administered by the Credit Valley Conservation (CVC) and one (Don River) is managed by the Toronto and Region Conservation Authority (TRCA). The CVC watersheds are Credit River, Etobicoke Creek, Mimico Creek, West Humber River, and Main Humber River (Figure 1).

The study area includes a diversity of land-cover classes and reflects a range of land use, geology, and soil settings. High-density urban development characterizes the southern half, while several rural land uses, including agricultural fields, wetlands, and forests, are dispersed across the upper (north) portion of the region. The diversity of land-cover types, combined with the urbanization of the GTA, makes it a near-ideal area to evaluate the potential of Landsat TM data for monitoring land change dynamics with respect to water quality.

2.2. Data sets

Four cloud-free Landsat-5 TM images covering the GTA were selected and used in this study (see Table 1). These Landsat images were acquired in late summer and early fall, when the land is fully covered by vegetation, as this is the preferred season for LULC analysis. In order to avoid radiometric differences, an attempt was made to select the acquisition dates as close to each other as possible. Surface water quality data in Ontario are collected by individual conservation authorities and are the property of the Ontario Ministry of the Environment. At each Provincial Water Quality Monitoring Network (PWQMN) station, a standard set of water quality indicators are collected once a month on the major tributaries

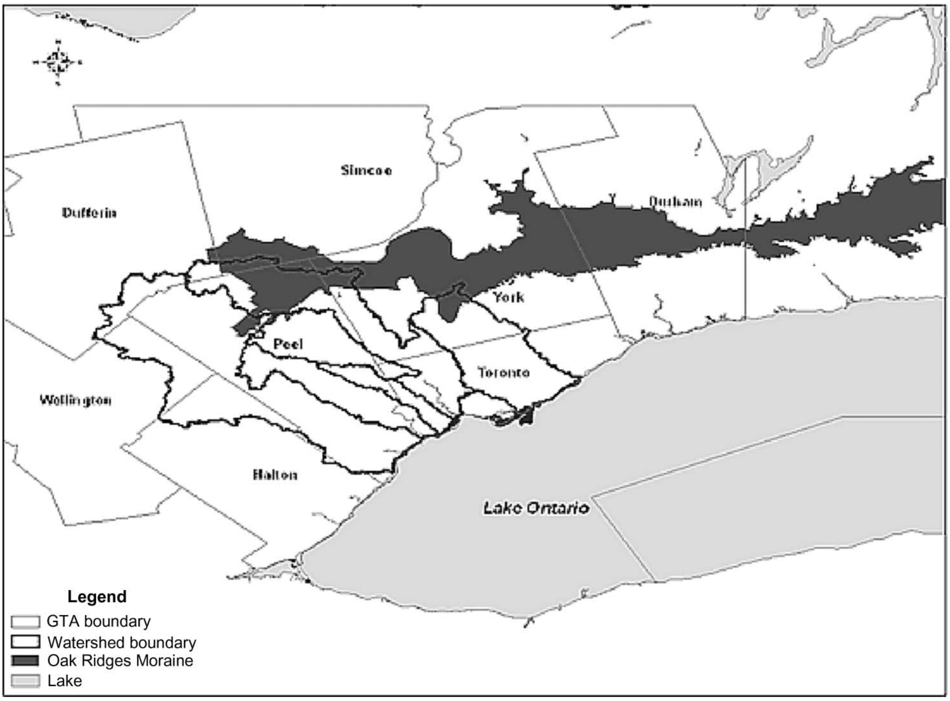

Figure 1. Selected watersheds in the study area. GTA stands for the Greater Toronto Area. It combines the regions of the City of Toronto, York, Durham, Peel and Halton.

Table 1. Selected Landsat TM images used in this study.

Sensor	Date	Georeference	Resolution	Bands
Landsat-5 TM	5 August 1990 19 July 1995 20 August 2000 3 September 2005	UTM, zone 18, WGS84	30 m	1–5, 7

of watersheds. These indicators include chloride, nutrients, suspended solids, trace metals, and other general chemistry parameters (Ontario Ministry of Environment 2007). Basically, data from near the mouth of each watershed are used to provide estimates of the concentration for the entire watershed. Figure 2 shows the location of water quality monitoring stations within the Peel and Toronto Region. The amount of data is varied, ranging from many stations with a monthly sampling interval to some watersheds with only intermittent samples. In each watershed, only a handful of water quality monitoring stations contained continuous historic data, and these stations have been selected for analysis.

2.3. Research methodology

The objective of this part of the study is to distinguish changes of two land-cover types, namely ‘impervious surface’ and ‘green’, and, thereafter, to assess the quality of water at the selected monitoring stations by means of integration with GIS techniques. The classical

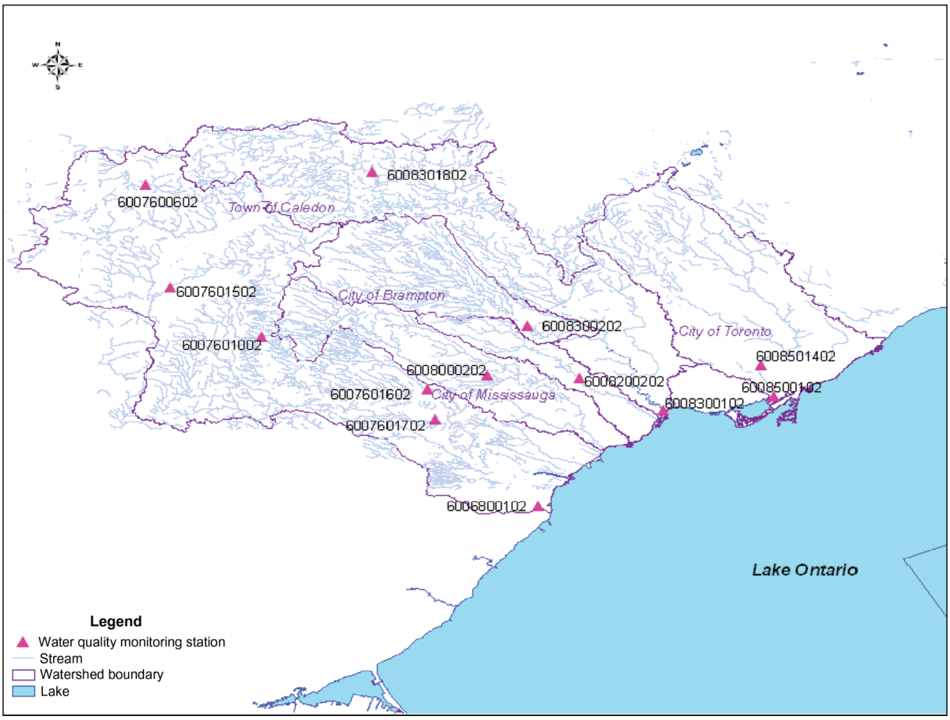

Figure 2. Water quality monitoring stations in the GTA.

unsupervised classification method was chosen, as it usually provides a rapid means of producing land-cover data on a continuing basis. Moreover, this classification successfully meets map accuracy standards in this study as well.

In the PC-based environment of PCI Geomatica V10.0.3, all four multitemporal Landsat-5 TM images were classified using an unsupervised approach known as ISODATA (Iterative Self-Organizing Data Analysis Technique) clustering to generate impervious surface estimates. The ISODATA classifier utilizes the minimum distance method to identify similar spectral clusters according to the number of clusters specified (Jensen 2005). To achieve more accurate results, the parameter setting was changed to 25 classes, 25 maximum iterations, and 0.95 convergence threshold. Following the creation of 25 spectral clusters, each class was labelled into general categories of urban, agriculture, forest, water, wetland, and barren and then aggregated into two major classes labelled as ‘green’ and ‘impervious surface’ for long-term impervious surface change analysis.

The classification accuracy is evaluated through visual comparison of corresponding classified maps with reference data (61 cm digital orthophotos) using the ‘stratified random’ function of PCI Geomatica. The percentage of imperviousness for each map is then calculated based on statistics provided in the classification report generated by the classification process. The mean and median total chloride concentrations of samples collected from May to October (dry season) as well as November to April (wet season) at the monitoring stations in the Peel and Toronto Region watersheds are compiled for the years 1990, 1995, 2000, and 2005. These data were utilized in constructing chloride concentration distribution maps using ArcGIS V9.2. The chloride concentration maps are georeferenced to the World Geodetic System 1984 (WGS84) for correlation and change detection with

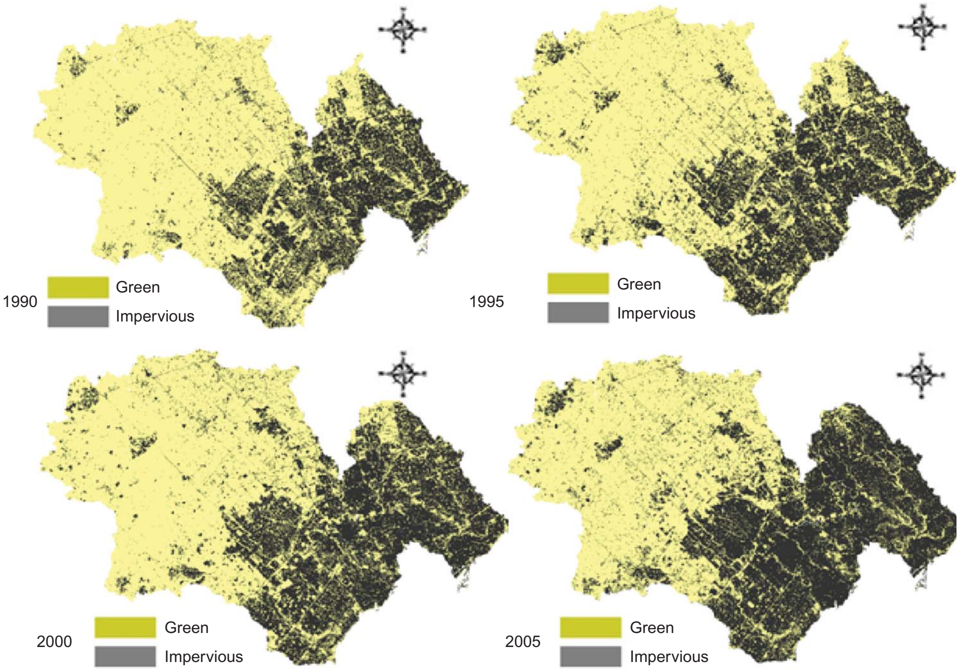

Figure 3. Impervious surface map of the entire study area watersheds.

impervious surface maps. Different colour schemes are applied to years 1990 (pink), 1995 (yellow), 2000 (green), and 2005 (red) to differentiate between separate dates.

According to reference data and visual interpretation of spectral properties of true-colour images, 25 classified spectral clusters for each image are assigned to appropriate land-cover classes, such as agricultural lands, golf courses, residential areas, industrial zones, road networks, wetlands, and alike. These classes are then grouped into two composite classes referred to as impervious surfaces and pervious areas for long-term urban change analysis. In Figure 3, the grey area represents impervious surfaces while yellow represents pervious areas including vegetation, soil, agricultural lands, open space, etc.

3. Results and discussion

3.1. Impervious surface classification maps and analysis

Figure 3 displays the classified impervious surface maps of the study area between 1990 and 2005 with a 5 year time interval. The classified impervious surface maps reflect the overall urban-related land uses within the study area, which has markedly changed during the 15 year period. For each watershed, the percentage imperviousness in 1990 is estimated and compared to what was measured in the area 15 years later (5 year interval). The percentage of imperviousness growth in each watershed over time is listed in Table 2, while Figure 4 illustrates this growth graphically. Through unsupervised classification, the substantial growth of impervious surfaces within the study area is even further distinguishable.

The results in Figure 4 show steady growth rates throughout the different periods from 1990 to 2005. In the West Humber watershed, the highest rate of urban growth occurred

Table 2. Overall growth of percentage of imperviousness in each watershed between 1990 and 2005.

Watersheds	1990 (%)	1995 (%)	2000 (%)	2005 (%)	15 year growth (%)
West Humber	12.06	17.86	19.47	23.95	11.89
Credit River	17.18	21.94	23.96	27.61	10.43
Main Humber	26.22	27.76	33.21	36.59	10.37
Etobicoke Creek	40.32	48.52	52.67	56.95	16.36
Mimico Creek	66.44	70.77	76.36	80.95	14.51
Don River	69.56	73.46	77.76	83.57	14.01

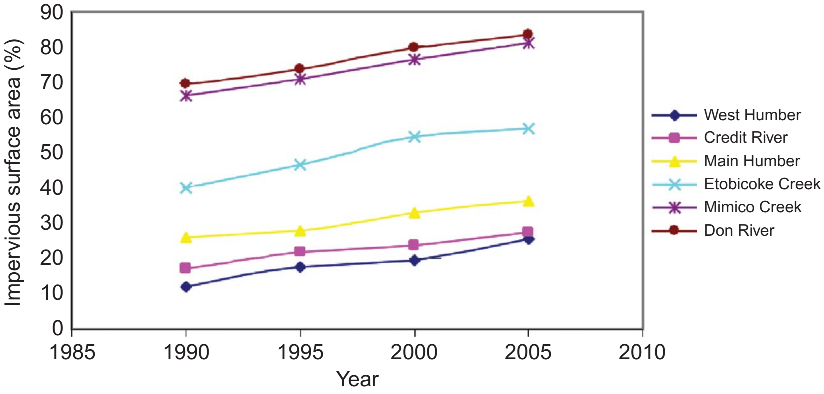

Figure 4. Overall impervious surface changes between 1990 and 2005.

between 1990 and 1995, with a nearly 6% increase in impervious surfaces. Most development took place in the lower half in the watershed. During this period, similar growth rates were seen in the Credit River, Mimico, and Don River watersheds. The Etobicoke Creek watershed, however, faced the highest amount of impervious surface growth of over 8% during this initial 5 year period, while the lowest increase, 1.50%, occurred in the Main Humber watershed. During the second 5 year period, between 1995 and 2000, the Main Humber and Mimico Creek watersheds had the highest rate (around 6%) of impervious surfaces, while the speed of new urban development slowed down in all the other watersheds. Compared to the first 5 year period, different results were seen during the last 5 year period. Between 2000 and 2005, the highest impervious surface growth occurred in the Don River watershed followed by a 4.50% increase in the Mimico Creek watershed.

Overall, the results demonstrated an average of 12.92% increase in impervious surface coverage during a 15 year period in the entire study area. The highest overall growth occurred in the Etobicoke Creek Watershed. This increase, although small in size, is statistically a significant amount of developed land in an already densely populated area. The fastest urbanization areas are northwards from the City of Brampton, west of the City of Mississauga as well as in the Lower Zone of the Credit River watershed. A visual inspection of the region revealed that the entire lower half of the study area watersheds consisted of impervious surfaces by 2005.

3.2. Accuracy assessment of classification

For the 15 year land-cover change analysis, the accuracy of the classified results was evaluated according to the reference data (61 cm resolution digital orthophotos). The classification accuracy of each watershed was evaluated using a stratified random sampling procedure, where 50 samples were randomly selected and tested in each watershed for accuracy assessment. The results are reported by the producer's accuracy and user's accuracy, as well as the kappa statistics for each watershed (Table 3). An overall classification accuracy of over 91% and a kappa statistic of over 0.88 were achieved.

3.3. Mapping of chloride concentrations

The total average and median chloride concentrations of samples collected in 1990, 1995, 2000, and 2005 for both dry and wet seasons are illustrated in Figures 5 and 6, respectively. For data integration, 'median-dry' chloride concentrations are chosen to be overlaid on top of impervious surface maps. This is mainly for two reasons: 'dry' season values are relatively consistent with the Landsat-5 TM data acquisition dates; and 'median' values give a conservative estimate of the adverse effects of chloride concentrations in the study area watersheds.

Table 3. Accuracy assessment report.

Classified map	Producer's accuracy (%)		User's accuracy (%)		Kappa coefficient
Credit River	Green	Impervious	Green	Impervious	
1990	96	87	88	93	0.89
1995	100	86	90	98	0.87
2000	91	90	92	89	0.92
2005	96	86	90	89	0.89
Etobicoke Creek					
1990	92	88	89	92	0.90
1995	98	86	90	98	0.90
2000	90	91	92	89	0.91
2005	96	86	90	89	0.89
Main Humber					
1990	100	82	87	100	0.83
1995	98	88	90	98	0.90
2000	89	91	92	89	0.89
2005	96	86	90	89	0.90
Mimico Creek					
1990	91	89	89	92	0.89
1995	95	82	87	98	0.87
2000	90	91	92	89	0.92
2005	96	86	90	89	0.89
West Humber					
1990	95	89	92	97	0.91
1995	97	82	86	98	0.88
2000	90	91	92	90	0.92
2005	96	86	87	90	0.89
Don River					
1990	88	89	88	87	0.89
1995	97	82	87	98	0.87
2000	90	91	89	89	0.88
2005	83	82	81	83	0.88

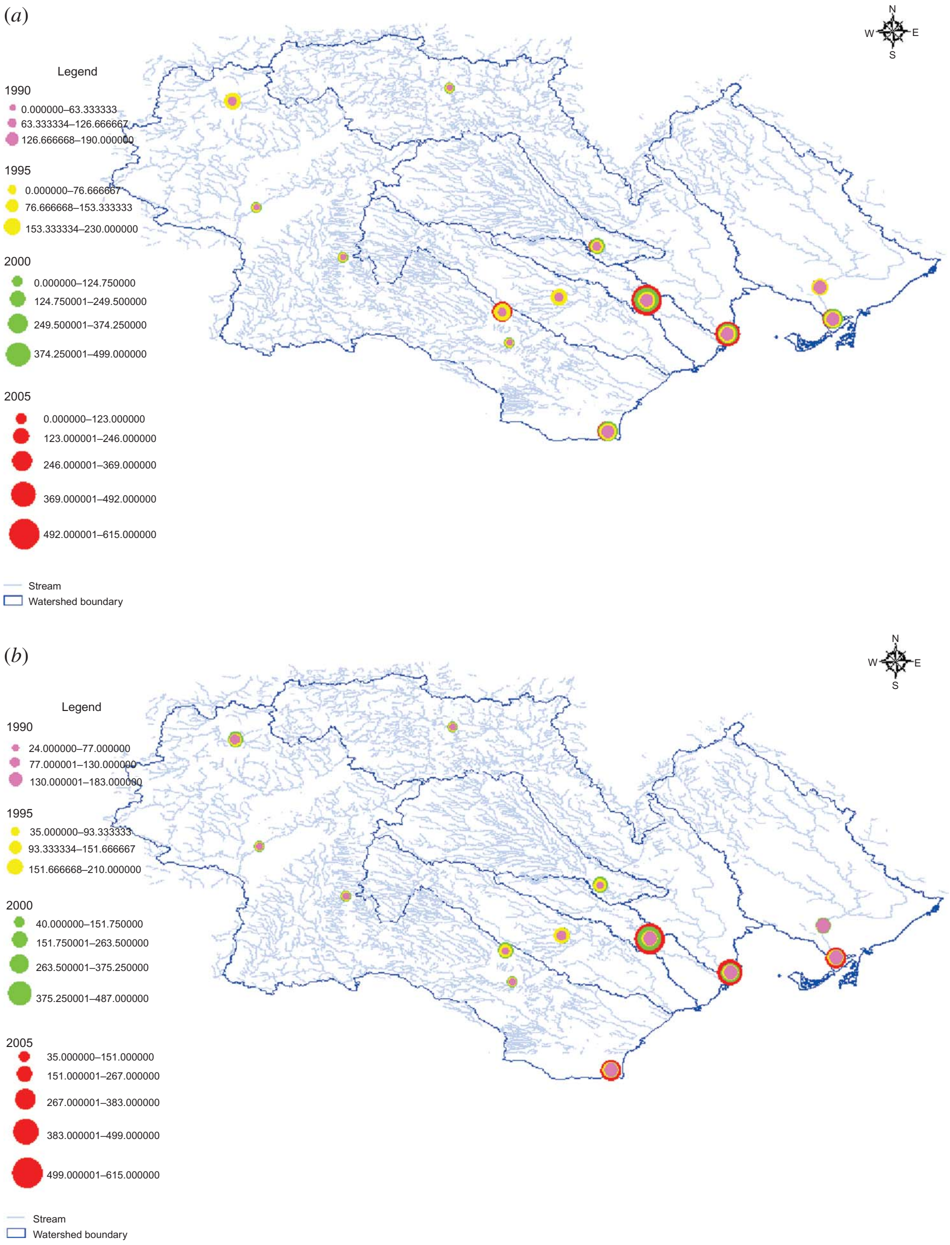

Figure 5. Average (*a*) and median (*b*) chloride concentrations of samples collected from May to October (dry season) in 1990, 1995, 2000, and 2005.

Most water quality monitoring stations showed a gradual increase in chloride concentrations over the years. The most obvious increase, between 1990 and 2005, was a threefold increase in chloride concentrations, which was observed in dry season samples. A synthesis of scientific studies suggests a value of approximately 250 mg l^{-1} as a reasonable target for the protection of aquatic life. The value 250 mg l^{-1} is also a federal threshold chosen by the Government of Canada (Mayer, Snodgrass, and Morin 1999). The results of

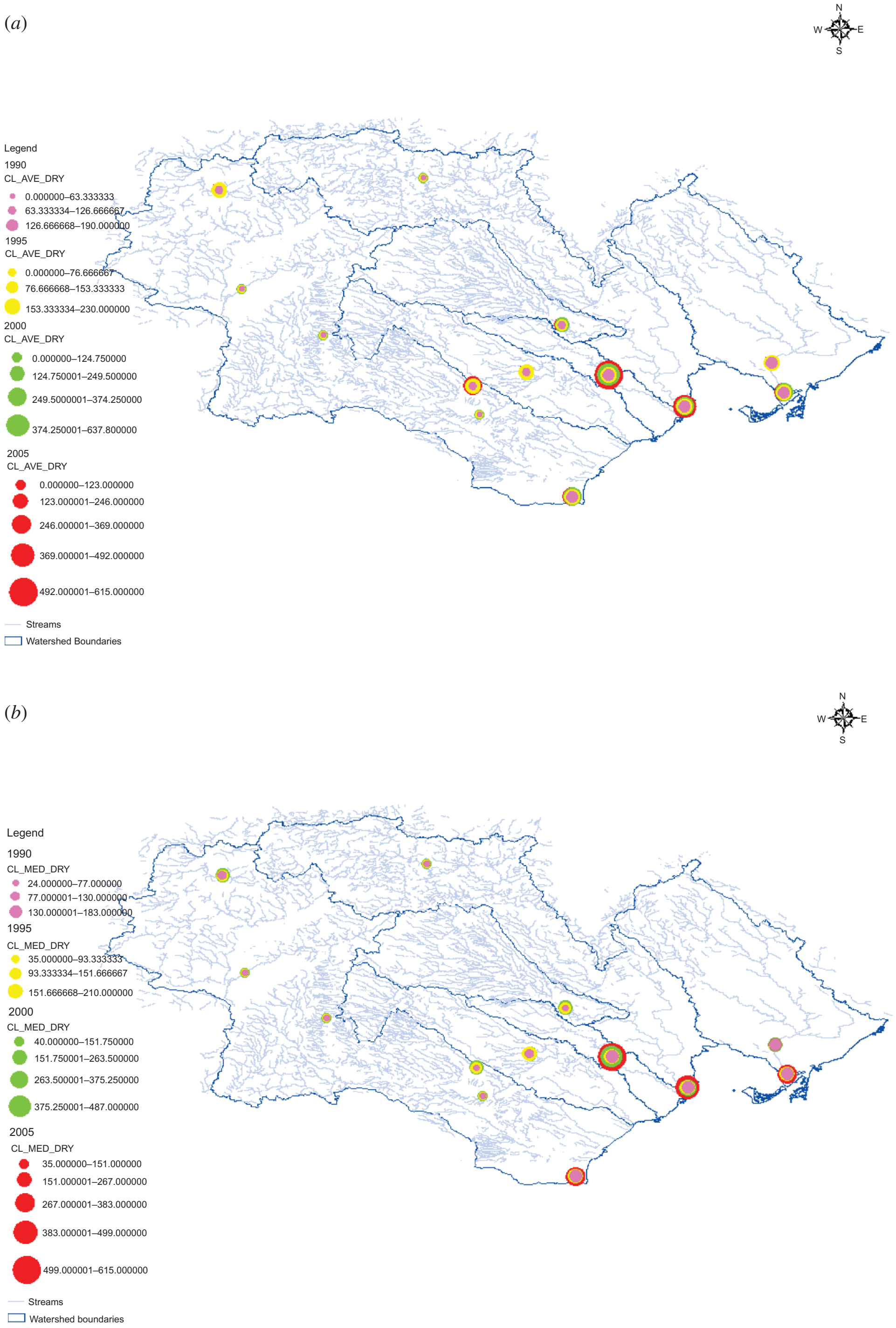

Figure 6. Average (*a*) and median (*b*) chloride concentrations of samples collected from November to April (wet season) in 1990, 1995, 2000, and 2005.

dry season chloride values demonstrated how this federal target was reached in 2000 and frequently exceeded in 2005. The wet season values, however, show how this threshold was reached as early as in 1990.

In Sheridan Creek, a highly developed urban creek located in the Lower Zone of the Credit River watershed and bordering Lake Ontario, the average wet-chloride concentrations increased from 470 mg l^{-1} in 1990 to over 870 mg l^{-1} by 2005. In the Don River in Toronto, concentrations of chloride increased to more than 860 mg l^{-1} in winter, corresponding to winter thaws. The dry season baseline chloride values in the Don River were 360 mg l^{-1} in 2005, while the same baseline values back in 1990 were only 140 mg l^{-1}. Similar baseline concentrations of chloride (120 mg l^{-1}) were seen in Etobicoke Creek, another highly urbanized watershed in the Peel Region. Chloride concentrations 3 times higher than baseline values were measured during the winter months in this creek.

In the Mimico Creek watershed, with over 80% impervious surface cover, average chloride concentrations exceeding 1102 mg l^{-1} were observed during the winter months of January and February with median concentrations of approximately 998 mg l^{-1}, lagging behind average values by only a few units. In general, a similar trend was found between average and median values in both wet and dry seasons, with median concentrations often being slightly lower than average concentrations.

Examination of the spatial distribution of chloride concentrations in surface waters within the study area watersheds also reflects the distribution of transportation-related surfaces. Howard and Maier (2006) observed serious water quality degradation in the Don and Humber Rivers as they passed through the City of Toronto on their journey from headwaters in the Oak Ridges Moraine to Lake Ontario. This study has observed similar results.

Concentrations of chlorides in stations located in predominantly rural lands, i.e. stations 6008301802 and 6007601502, ranged from 25 to 50 mg l^{-1}, whereas the more urbanized watersheds, such as Mimico Creek and Don River, experienced higher chloride concentrations mainly due to the denser and more heavily used highways and road networks. Polluted runoff from major highways such as the Hwy 427 and Gardiner expressways has the potential to influence the spatial pattern of chloride concentrations in the study area.

This further supports the importance of land-use characteristics in the watersheds. Land-use properties in each watershed are important in investigating the correlation between water quality impacts and impervious surfaces.

With regard to temporal variations, research has shown that nonpoint source pollutant concentrations during the wet season are generally higher than during the dry season. Concentrations are often highest in the wet winter months since that is the time when de-icing salts are applied to roads and highways. During summer and fall months, the concentrations are reduced as most of the winter road salts are washed off the surfaces by precipitation (Snodgrass and D’Andrea 1993; TRCA 1998).

The temporal variations in chloride concentrations reflect differences in the source of flow during dry and wet seasons. During dry summer months, the flows are generally small in volume and originate primarily from groundwater, which has already been filtered by riparian vegetation and soil. Summer base-flows are typically less contaminated than surface runoffs. By contrast, the majority of wet season flows are larger in size and more polluted since they originate from impervious surfaces (Snodgrass and D’Andrea 1993; Meyer 2005).

Similar to previous studies (Snodgrass and D’Andrea 1993; Rose and Peters 2001; Brandes, Cavallo, and Nilson 2005; Howard and Maier 2006), results obtained in this study show a strong seasonal variation. Figures 7 and 8 demonstrate this variation in chloride

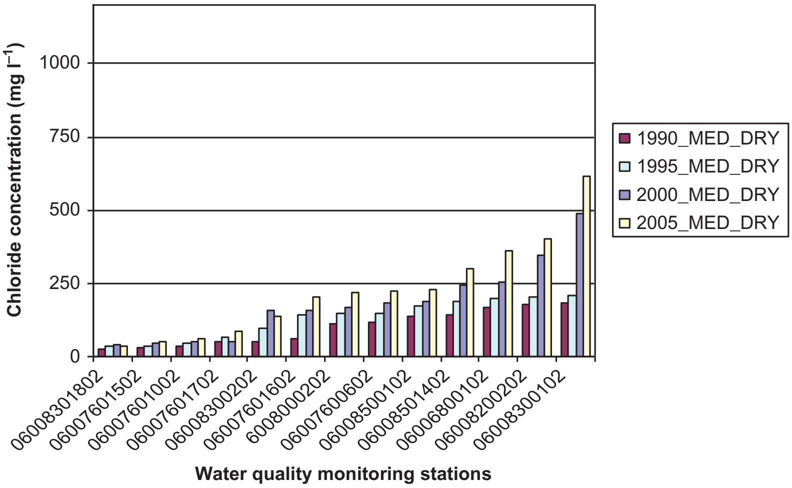

Figure 7. Temporal variations in median chloride concentrations between base-flow and dry season conditions at each monitoring station (where MED_DRY represents the median chloride concentrations in dry season).

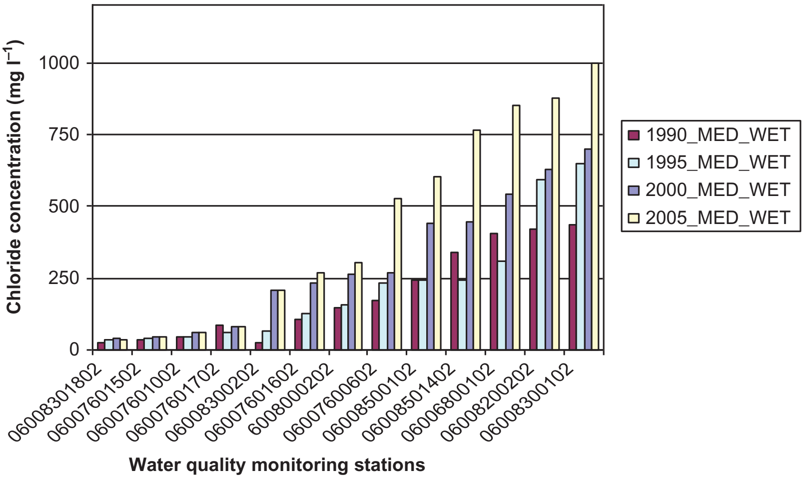

Figure 8. Temporal variations in median chloride concentrations between base-flow and wet season conditions at each monitoring station (where MED_WET represents the median chloride concentrations in wet season).

concentrations between base-flow and dry and wet season conditions. These two figures also show an obvious increase in chloride levels over time for each water quality monitoring station, with wet season concentrations being noticeably higher (i.e. reaching over 1000 mg l^{-1}), indicating peak inputs of road salts in winter.

3.4. *Results of integrating impervious surface estimates with chloride data*

When the two sets of maps are overlaid (Figure 9), a corresponding trend is apparent over the years: the highest chloride concentrations occurred in areas with the highest percentage

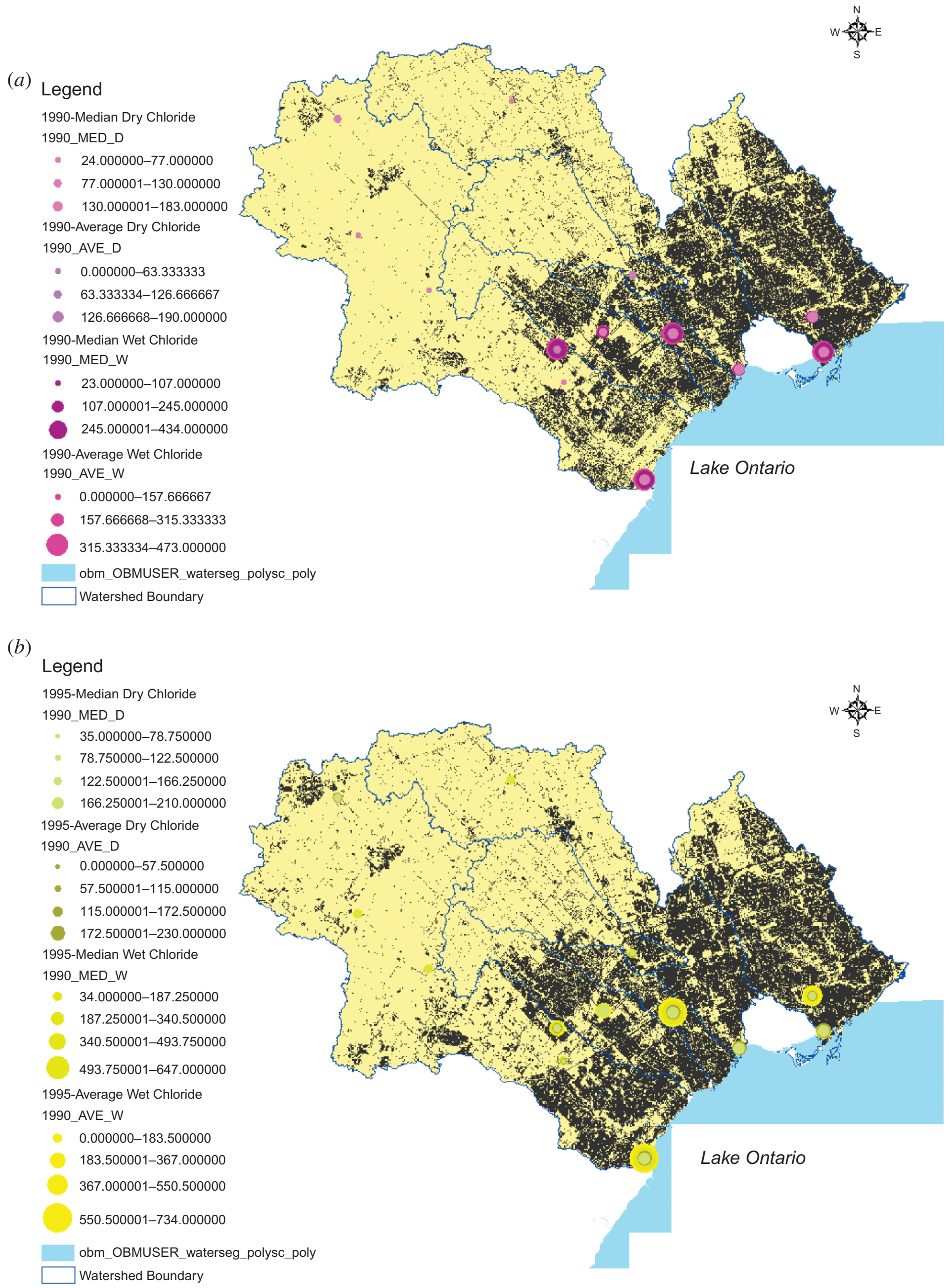

Figure 9. Chloride concentrations overlaid on the impervious surface map of 1990 (*a*), 1995 (*b*), 2000 (*c*), and 2005 (*d*).

of impervious surface area. This indicates that the watersheds with moderate to low levels of development had the lowest chloride concentrations whereas the watersheds that were highly urbanized (i.e. Etobicoke, Mimico Creek, and Don River) exhibited the highest chloride levels. Such results demonstrate the importance in revealing a strong association between water quality as represented by chloride and urbanization.

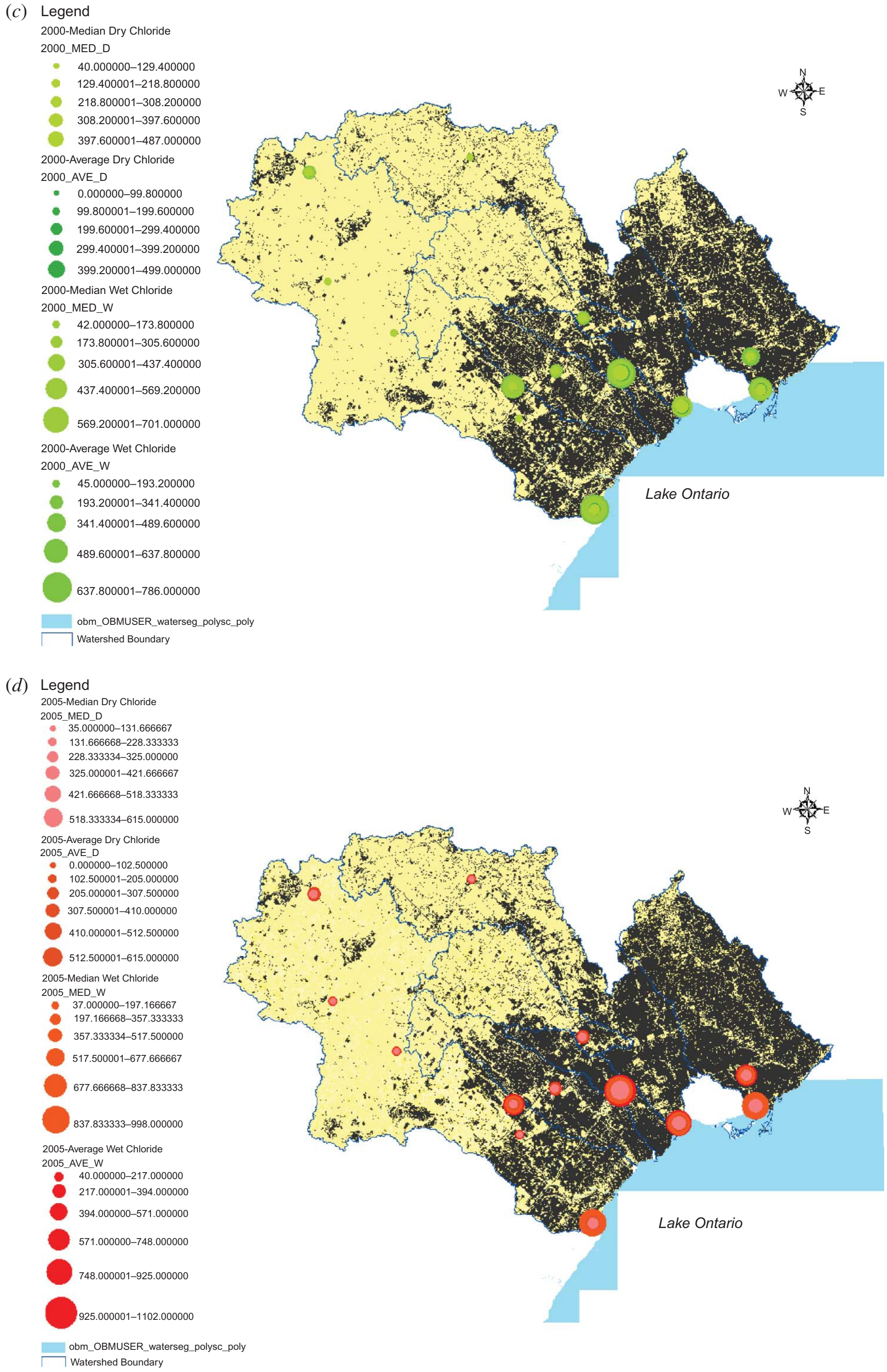

Figure 9. (*Continued*.)

The integrated maps demonstrated that chloride concentrations tend to increase towards the river–lake boundary. The overall direction of water flow is a southeast direction moving towards Lake Ontario. Monitoring stations closest to Lake Ontario exhibited the highest chloride concentration as the majority of salt applied during the winter months had not infiltrated into the soil, remained on the impervious surfaces, and eventually emptied into the lake via surface runoff.

According to TRCA (2007), approximately three-quarters of the people who live in Ontario rely on water that is drawn from surface sources such as the Great Lakes. Thus, as Lake Ontario becomes polluted, the primary source of drinking water for the region is potentially at risk. Should the primary source of drinking water for the region continue in this trend, over time the resulting changes can significantly stress the area and result in severe adverse socioeconomic impacts.

Broadly speaking, a stressor (i.e. increased imperviousness) is defined as a change that results in a response that disturbs the natural balance of an ecosystem. An indicator (increased chloride levels) is a characteristic of an ecosystem that provides clues as to when something is changing (Schmidt 2004). Long-term study of indicators allows a better understanding of the balance of natural environments and recognition of imbalance by stressors such as urbanization (Jackson and Jobbagy 2005). Land-use change is one of the challenging issues that can potentially alter the ecosystem's health, particularly, the shift from a 'green' to 'impervious' landscape.

In the absence of human activity and anthropogenic sources, salt concentrations in surface waters are mainly related to the chemistry of the bedrock and watershed geology. In 2001, the Priority Substances List Assessment Report for Road Salts indicated that the background salt concentrations of surface waters vary within the range of less than 1 to 5 mg l^{-1} (Environment Canada 2001). However, chloride concentrations in this study were considerably higher than the reported background, reflecting the effects of urban sprawl and road construction. Impacts of high use of road salts were evident from the data, particularly in highly urbanized areas. Chloride concentrations of rural areas were among the lowest in the study area, while a marked increase in chloride concentrations was noticeable in the highly urbanized Mimico Creek and Don River watersheds.

3.5. Statistical results

The best approach to validate the often-assumed adverse effects of impervious surfaces on water quality is by means of statistical examination. To investigate this assumption, linear regression of median dry season chloride concentrations is plotted against the impervious surface estimates for each date to determine the pattern that existed in the watersheds. These plots are presented in Figure 10. Also, the linear regression of chloride as a function of percentage of imperviousness for all four dates combined is presented in Figure 11. The coefficients of regression were calculated between percentage imperviousness and chloride levels. The results are presented in Table 4.

Another consideration is a comparison of chloride concentrations as a measure of water quality with percentage of imperviousness producing only a descriptive measure and not a predictive, causative measure. Accordingly, the relationship discovered does not explain how, or even if, impervious surfaces adversely affect water quality, but rather indicates a quantifiable association between the two variables. According to statistical analyses based on individual dates, a correlation exists between impervious surfaces and chloride concentrations over the years. The findings demonstrate that urbanization and the resultant increase in imperviousness do generate higher chloride concentrations. Correspondingly,

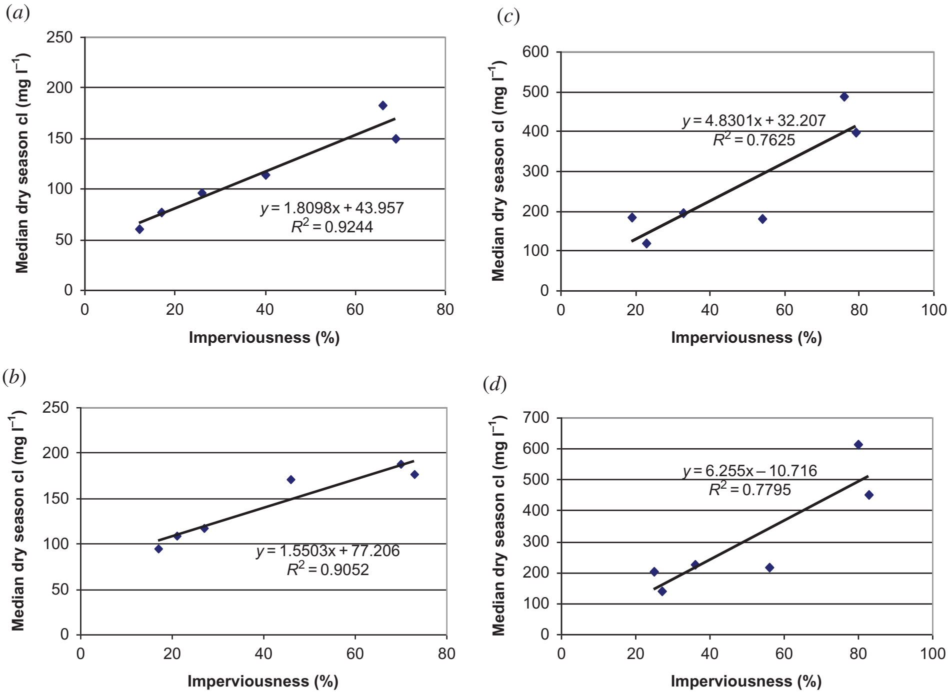

Figure 10. Linear regressions of median chloride concentrations in the dry season against percentage of imperviousness in 1990 (*a*), 1995 (*b*), 2000 (*c*), and 2005 (*d*). R^2, coefficient of determination.

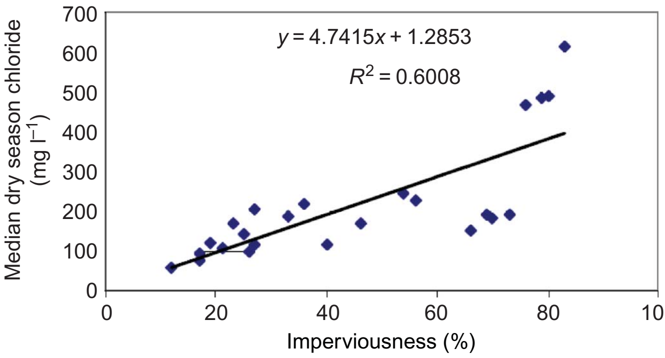

Figure 11. Linear regression plot of chloride as a function of percentage of imperviousness for all four dates (1990, 1995, 2000, and 2005) combined.

the higher levels of chloride can potentially degrade the quality of surface waters in the study area. However, when all dates were combined, the correlation was no longer linear (Figure 11). This can be explained by an uneven increase in chloride concentrations with respect to impervious surface growth.

Figure 12 further illustrates the degree of association between the two variables, representing impervious surface growth of each watershed as it relates to increases in chloride concentrations from 1990 to 2005. Overall, as the percentage of imperviousness increases

Table 4. Coefficients of determination for linear regressions between chloride concentration and percentage imperviousness by year.

Water quality measure	1990 (R^2)	1995 (R^2)	2000 (R^2)	2005 (R^2)	All dates combined (R^2)
Median dry chloride	0.92	0.90	0.76	0.77	0.60

Note: R^2, coefficient of determination.

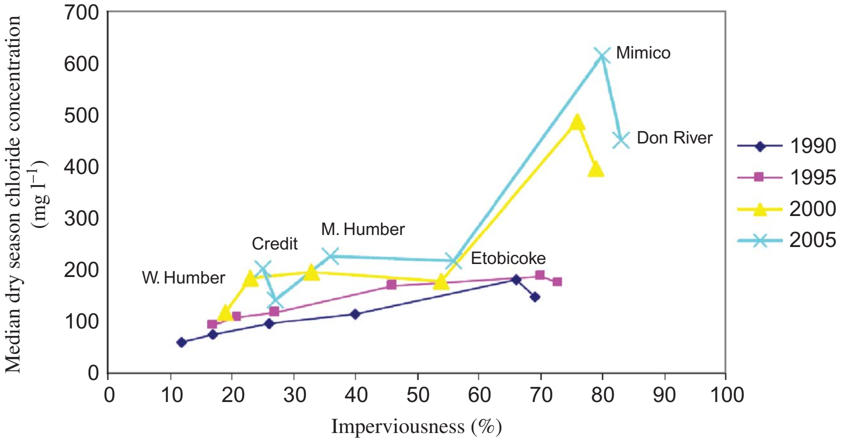

Figure 12. Linear correlations between chloride and percentage of imperviousness in six selected watersheds by year.

in each watershed, chloride concentrations also increase, with the exception of the Don River watershed, where chloride concentrations slightly decrease with increasing impervious surfaces. Also, while impervious surfaces increase at a relatively constant rate over the years, there is a dramatic increase (i.e. threefold increase) in chloride concentrations in the Mimico Creek and Don River watersheds, particularly in 2000 and 2005.

4. Concluding remarks

This article presents an average of 12.9% increase in impervious surfaces and a corresponding threefold increase in chloride levels in the GTA from 1990 to 2005. Two of the most urbanized watersheds in the GTA, the Mimico Creek and Don River watersheds, exhibited the highest chloride concentrations. Overall, through the use of an integrated remote-sensing approach, the empirical evidence collected in this study was successful in demonstrating a strong relationship between increases in impervious surface areas and chloride levels over time as well as identifying areas most vulnerable to surface water quality degradation by road salts. A considerable benefit of remotely sensed impervious surfaces is that this type of data alone can provide clues as to which areas are more prone to water quality degradation. In areas where up-to-date and accurate chloride data are unavailable, continuous spatially explicit remotely sensed impervious data may provide equally beneficial coverage of areas under stress.

This study found a steady increase in the impervious surface coverage over the years and a corresponding increase in chloride levels in surface waters. For this reason, it was expected that there would also be an increase in salt usage by the municipalities. However, not much correlation was observed. This lack of correlation is primarily attributed to the lack of comprehensive public salt usage data. Gathering salt usage data from the municipality officials proved very challenging and it was an insurmountable obstacle because the municipalities were the sole proprietors of public salt usage data. Finally, the major issue that limited the scope of this study is that although the results presented in this article indicate that a correlation does exist between the level of imperviousness and chloride levels, due to lack of funding, continuous historic chloride data were missing for a significant number of monitoring stations, not to mention the uneven distribution of water quality monitoring stations. Therefore, not enough sample sites could be included in the investigation to provide a truly quantitative and statistically robust analysis. The relationships reported here are strictly qualitative, and they warrant further investigation and quantification.

Urban nonpoint source pollution represents one of the most complex environmental challenges facing the Great Lakes Basin. Watershed and urban planners constantly look for ways to reduce nonpoint source pollution. One way to reduce this pollution is to reduce imperviousness. In recent years, impervious surfaces have emerged as a water quality indicator. The studies of the past two decades have consistently shown a strong correlation between the imperviousness of a watershed and the quality of its streams and rivers. Understanding the spatial and temporal relationship between imperviousness and water quality would allow for informed land-use management decisions (Clausen et al. 2003; Moore and Palmer 2005).

The long-term nature of this study suggests an increasing trend in both chloride levels and impervious surfaces in the coming years. The next step would be for the urban planners and decision-makers in the Peel Region and City of Toronto to reverse the adverse effects caused by impervious surfaces and road salts. Minimizing the negative effects of chloride on the environment can be achieved through regulatory approaches, utilization of best management practices (BMPs), public education, and more importantly, considerable reduction in use of inorganic salts through use of alternative products.

Apart from salt management plans, other urban BMPs can be implemented to decrease the urban impacts of road salts. These practices include grassed waterways, porous pavement, green roofs, nutrient and chemical management, detention basins, infiltration facilities, catch basins, wetlands, and buffer strips (Brabec, Schulte, and Richards 2002; Groffman et al. 2004; Vanwoert et al. 2005). It is important to note that these practices have limitations; therefore, the effectiveness of these BMPs in the study area watersheds grants further examination. Proper management and conservation of the Oak Ridges Moraine should be continued to ensure a healthy environment in the region.

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