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Salinization: the ultimate threat to temperate lakes, with particular reference to Southeastern Wisconsin (USA)

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Abstract Many lakes in Southeastern Wisconsin (the metropolitan-Milwaukee area) are gradually becoming increasingly "salty". While these waterbodies would not be considered presently to be saline lakes, there has been a rapid increase in the chloride concentrations in most of these lakes over the last 30 years, with the lakes increasing from a mean chloride concentration of about 19 mg/L to over 100 mg/L in some cases. While ecological impacts can be expected when chloride values exceed 250 mg/L, the rate of increase presents a basis for concern, especially since the underlying geology of the region is based on limestone/dolomite which is deficient in chlorides. Thus, the origin of the chlorides is anthropogenic: human and industrial wastewaters (treatment of which has effected improvements in trophic status but has not affected other water-borne contaminants) and winter de-icing practices based upon large quantities of sodium chloride are major contributors to the increasing concentrations of chloride in the region's waterways. Without taking remedial measures, the rate of salinization is expected to continue to increase, resulting, ultimately, in the alteration of the freshwater systems in the region.

Keyword: salinization; temperate lakes; chloride concentrations; salt management

1 INTRODUCTION

Salinization is the process whereby mineral salts, principally chlorides, enter and concentrate in aquatic systems. Salinization occurs naturally in regions with salt deposits at or near the land surface and as a result of groundwater inflows into surface water courses in such regions. Human activities can exacerbate this process by flushing salts into the surface water courses through irrigation practices and groundwater pumping (Williams, 1998). Well-known examples of the impact of irrigation practices on the salinity of surface waters can be found in the Aral Sea basin of Central Asia (Micklin and Aladin, 2008) and the Salton Sea of the western United States (Carpelan, 1958; Miles et al., 2009; Cohen, 2014), where irrigated agriculture has flushed sufficient salts into the waterbodies that they have become hypersaline. These waterbodies also demonstrate the two key principles associated with salt lakes enumerated by Williams (1998); namely, that saline lakes generally occur as terminal lakes within closed or endorheic basins and in areas where rainfall and evaporation and/or groundwater infiltration are balanced. While such conditions occur across the world, most saline lakes tend to be located in semi-arid and arid parts of the globe.

The waterbodies of southeastern Wisconsin clearly would not fit into the two criteria set forth by Williams (1998). Southeastern Wisconsin is located in a region with moderate rainfall and an abundance of surface waters, many of which are linked by the several major

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rivers of the region (SEWRPC, 1995a). In addition, the underlying geology of the region is comprised of limestone and dolomite, in which chlorides are almost completely absent. Notwithstanding, the concentrations of chlorides within these waters are and have been constantly increasing since the 1970s.

In this paper, we review the rates of increase in chloride concentrations in some of the region's major lakes and explore some of the likely causative factors affecting these increasing chloride concentrations. We further speculate about some of the potential consequences of this increase in chloride concentration, and present some possible remedial measures that will slow this rapid salinization of the region's waters.

2 GEOLOGY OF SOUTHEASTERN WISCONSIN

While the glaciation and subsequent retreat of the glaciers from Southeastern Wisconsin played a major role in shaping the surface water features of the region, the underlying geology of the area has played a major role in determining the water quality of these resources. The landscape of the Southeastern Wisconsin region is comprised of ridges and valleys sculpted by the deposition of glacial debris. Underlying these glacial deposits is limestone and dolomite bedrock, overlying sandstone, from which the limestone and dolomite are separated by a layer of shale. This shale layer limits exchange between the groundwater aquifers contained in the two primary bedrock layers. The result of this geology is that the surface (and ground) waters of Southeastern Wisconsin are rich in carbonates but poor in chlorides. In short, there are few sources of natural chlorides which would contribute to the salinization of the surface waters of the region.

3 THE GEOGRAPHY OF WISCONSIN LAKES

Most lakes in the State of Wisconsin can be dated to the end of the Wisconsonin Ice Age. Many lakes, especially those in Southeastern Wisconsin, were formed as the glaciers retreated from the area that is now the north central United States. The State of Wisconsin claims 15 000 inland lakes, which include both internally drained waterbodies (generally created by ice calving from the glacier and forming single lake basins within a landscape of glacial tills, moraines, and wetlands), and more traditional river-run lakes. The former or so-called "kettle" lakes are scattered throughout the landscape along the various terminal moraines formed by the retreating glaciers. The latter, river-run lakes, either flow in an easterly direction and lie along river courses that typically drain to either the Laurentian Great Lakes (specifically Lake Michigan) and, or in a westerly direction to the Mississippi River system. The distribution of the drainage systems forms the mid-continental divide, which runs through the region from southeast to northwest, as shown in Fig.1. Two of the world's largest lakes, Lake Michigan and Lake Superior, border the east and north of the State of Wisconsin. It is this location at the headwaters of both the St Lawrence River and the Mississippi River that gives the waters of Southeastern Wisconsin their great importance: degradation of water quality in these systems has the potential to initiate a cascade of consequences affecting much of North America (and beyond, as the contaminants enter the global circulation of the Atlantic Ocean).

4 A BRIEF HISTORY OF LAKES IN WISCONSIN

In the mid-1800s, when the Wisconsin Territory was admitted to the United States as the State of Wisconsin, waterways and highways were given the same legal status in Chapter IX of the *Wisconsin Constitution* as essential transportation corridors within the State. For more than 100 years the waterways of the new State had been used as transportation corridors, linking the French and English trading centers of Canada with the fur-bearing areas of the Great Lakes region and the Mississippi River basin. In the early days of the State, these waterways retained their premier position as transportation corridors. These waterways also provided the power to drive the sawmills which produced the lumber necessary to build the growing country.

By the early 1900s, the waterways of Wisconsin retained their supremacy as power sources, but now powering grist mills and turbines to process grains and provide the electrical power for the emerging metropolitan centers. Many inland lakes were augmented with low-head dams to increase their generating capacities, while significant large hydro-electric dams were built on the Wisconsin River, a tributary of the Mississippi River.

By the 1960s, however, many Wisconsin lakes had been reduced to being receptacles of stormwater and wastewater. But, at this time, people increasingly

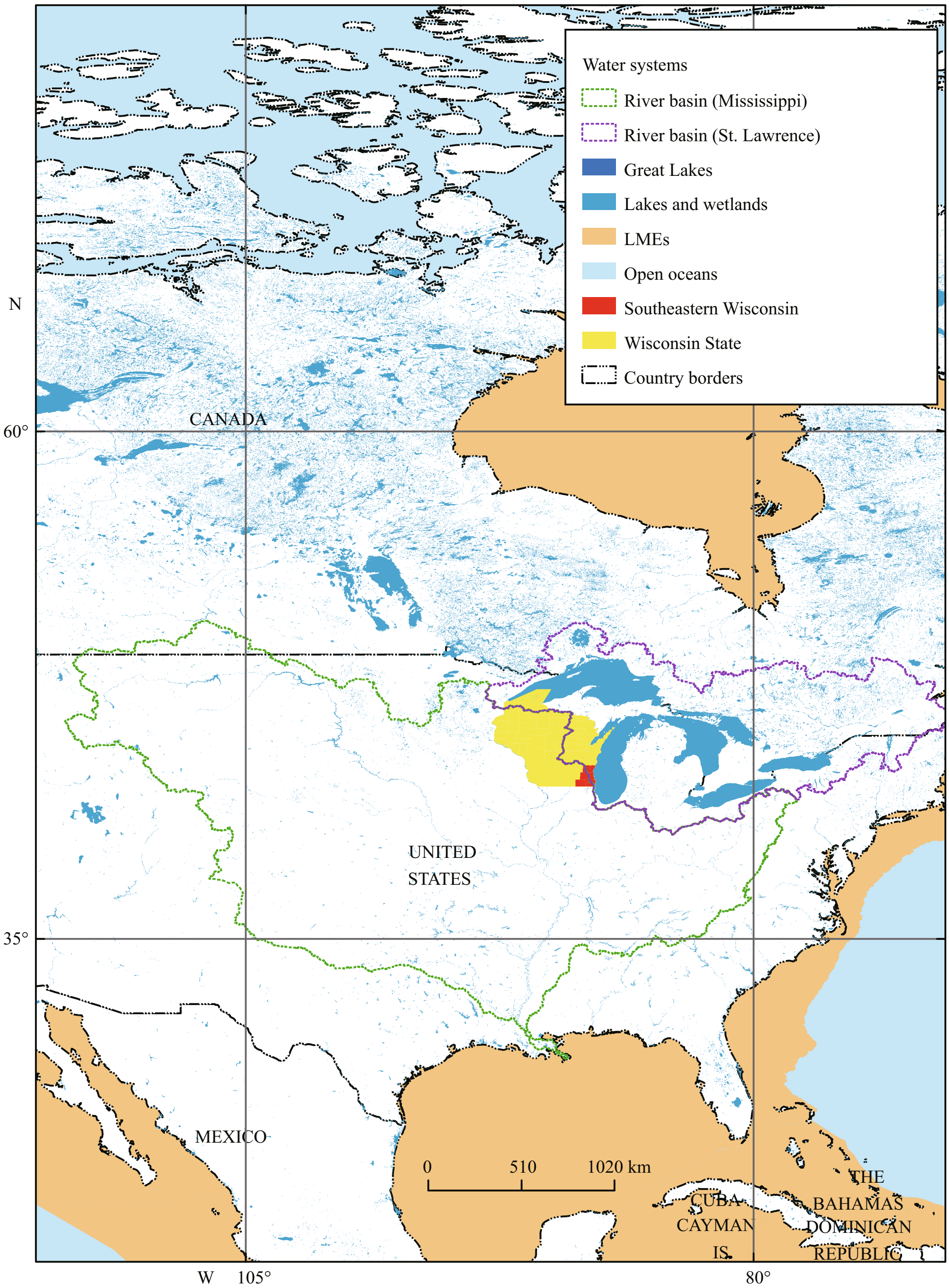

Fig.1 Major lake and river systems of North America and the location of Southeastern Wisconsin in the headwaters of the St. Lawrence and Mississippi River systems

were being drawn to these waterbodies in search of opportunities for the pursuit of leisure activities. Demand for lakefront property rose and Wisconsin became a desirable destination for tourism and recreation. Consequently, in the early-1970s, public outrage at the degradation of their waterbodies had reached a peak and the federal Clean Water Act was adopted. Using both federal and state funds, the municipalities of Wisconsin introduced or improved sewerage systems and undertook the rehabilitation of the heretofore degraded waters of the State. Lakes such as Delavan Lake in Southeastern Wisconsin became watch words for successful lake management interventions (Robertson et al., 2000; SEWPRC, 2002). Currently, the waterbodies in Southeastern Wisconsin are mesotrophic, and have either an improved trophic status or unchanged trophic status as a result of these interventions (SEWRPC, 1995a).

5 METHODS

The data presented herein were compiled in the course of preparing management plans for a number of the major lakes in Southeastern Wisconsin while the senior author was employed as a Principal Planner by the Southeastern Wisconsin Regional Planning Commission (SEWRPC). These plans typically highlighted management interventions focused on nutrients of anthropogenic origin, addressing concerns regarding nutrient enrichment or eutrophication, and the resultant growth of aquatic plants, and addressing recreational water uses by riparian communities and other recreational water users. Review of water quality data formed a major part of the planning programs. In reviewing these data, staff from the SEWRPC attempted to assemble existing data on all aspects of the waterbodies that formed the focus of the planning programs. These data included geographic information documenting not only the physical attributes of the waterbodies and their watersheds, but also quantifying land uses, population distributions, and biological conditions as elements influencing water quality. All of the lake management plans can be accessed through the Commission's website, www.sewrpc.org, under the "Data and Publications" tab.

The majority of the water quality data used in this paper was abstracted from the annual Water Data reports, published by the United States Geological Survey (USGS) in the series Water-Quality and Lake-Stage Data for Wisconsin Lakes (see U.S. Geological Survey, 2012). These data were contrasted with the data compiled by the Wisconsin Department of Natural Resources (WDNR) based upon a statewide survey conducted during the late-1960s and 1970s (Lillie et al., 1983). All of these data were analyzed by the Wisconsin State Laboratory of Hygiene using standard methods of analysis and federally-accepted quality control and quality assurance practices. Many of the recent data collection programs were supported in part by grants from the Wisconsin Lake Management Planning Grant Program and Wisconsin Lake Protection and Classification Grant Program, codified in Chapters NR 190 and NR 191, respectively, of the *Wisconsin Administrative Code*, and administered by the WDNR. These programs are funded from the State's gasoline taxes, specifically those taxes collected from the sale of boat engine fuels (while there is no easy way to distinguish fuels purchased for use in motor cars versus those utilized in motor boats, the Wisconsin Legislature has established a formula by which the gasoline tax revenues are split between roadways and waterways).

Forty lakes were included in the analysis. The morphology and locations of the lakes are given in Table 1 and shown on Fig.2. The waterbodies ranged from large deep lakes, such as Geneva Lake, to large shallow lakes, such as Lac La Belle. The lakes included both headwater systems, such as Little Muskego Lake, and lakes located within chains of lakes. Both river-run and internally-drained waters also are included.

Several lake chains were sampled. For example, in the western portions of the Southeastern Wisconsin region, the Oconomowoc and Bark Rivers form part of the Rock River system which is a tributary to the Mississippi River. Along the Oconomowoc River are Okauchee, Oconomowoc, and Fowler Lakes, all of which are located upstream of Lac La Belle. Paralleling this river is the Bark River, which, from upstream to downstream, includes Nagawicka Lake, Upper Nemahbin Lake, Lower Nashotah Lake, and Lower Nemahbin Lake. Further south within the region and draining to the Illinois-Fox River tributary of the Mississippi River system, Little Muskego and Wind Lakes form another chain of lakes.

In addition to the lakes and rivers draining to the Mississippi River system, lakes and rivers within the eastern portions of the region drain to the Laurentian Great Lakes system. Within this drainage system, Little Cedar Lake on Cedar Creek forms a tributary drainage system to the Milwaukee River.

Endorheic or internally-drained waterbodies also were included in the lake management plan formulation process. While these lakes are not directly connected to the surface drainage system, they do interact with the regional groundwater aquifers. Data from both the surficial aquifer (the limestone/dolomite aquifer) and the deep sandstone aquifer were abstracted from U. S. Geological Survey data reports and were used to evaluate the potential impacts of onsite sewage treatment systems as a source of chloride entering the surface drainage system.

All of the waterbodies included in this paper were the subjects of lake management plans prepared by SEWRPC. It was through the development of these plans, beginning in the mid-1990s, that the increasing salinization of the region's lakes was first observed and communicated to the scientific community

Table 1 Morphological attributes of the study lakes in Southeastern Wisconsin

	Waterbody name	Watershed (latitude and longitude)	Surface Area (km^2)	Volume (10^6 m^3)	Max. depth (m)	Mean depth (m)	Reference
1	Little Cedar Lake	Milwaukee43.37°N 88.22°W	0.98	3.9	17.1	3.9	SEWRPC, 2004a
2	Pike Lake	Rock43.31°N 88.33°W	2.1	8.6	13.7	4.1	SEWRPC, 2005a
3	Friess Lake	Rock43.26°N 88.28°W	0.48	3.8	14.6	7.9	SEWRPC, 1997b, 2008b
4	Lake Keesus	Rock43.16°N 88.31°W	0.95	4.9	12.8	5.1	SEWRPC, 1998a
5	Ashippun Lake	Rock43.15°N 88.49°W	0.33	1.7	12.2	6.7	SEWRPC, 1982a, 2007c
6	North Lake (Waukesha)	Rock43.14°N 88.37°W	1.7	21.6	21.4	12.2	SEWRPC, 1982b
7	Lac La Belle	Rock43.13°N 88.52°W	4.5	15.9	11.6	3.5	SEWRPC, 2007b
8	Moose Lake	Rock43.13°N 88.40°W	0.32	2.9	18.6	8.8	
9	Okauchee Lake	Rock43.12°N 88.42°W	4.7	40.3	27.5	8.4	SEWRPC, 1981, 2003c
10	Pine Lake	Rock43.12°N 88.38°W	2.8	33.3	25.925	11.712	SEWRPC, 1998b, 2008a
11	Fowler Lake	Rock43.11°N 88.49°W	0.31	1.2	15.2	3.9	SEWRPC, 1994, 2000a, 2012
12	Beaver Lake	Rock43.11°N 88.36°W	1.3	6.2	14.0	4.9	SEWRPC, 2008a
13	Oconomowoc Lake	Rock43.09°N 88.45°W	3.1	30.5	18.3	9.8	SEWRPC, 2009c
14	Forest Lake	Rock43.09°N 88.41°W	0.09	-	5.2	-	
15	Lower Nashotah Lake	Rock43.08°N 88.43°W	0.36	2.2	13.1	6.1	
16	Upper Nemahbin Lake	Rock43.07°N 88.43°W	1.1	10.3	18.3	9.0	SEWRPC, 1995b, 2009d
17	Nagawicka Lake	Rock43.07°N 88.38°W	3.8	56.7	27.5	14.6	SEWRPC, 1999, 2001c, 2006a
18	Pewaukee Lake	Fox43.07°N 88.30°W	9.9	30.8	13.7	3.1	SEWRPC, 2003d
19	Lower Nemahbin Lake	Rock43.06°N 88.42°W	1.1	3.4	10.9	3.1	
20	Middle Genesee Lake	Rock43.04°N 88.47°W	0.41	1.8	11.6	4.4	SEWRPC, 2003b
21	School Section Lake	Rock42.97°N 88.52°W	0.50	0.38	2.4	0.7	
22	Pretty Lake	Rock42.96°N 88.51°W	0.26	0.73	9.5	2.8	SEWRPC, 1998c, 2006b
23	Little Muskego Lake	Fox42.91°N 88.14°W	2.0	8.8	19.8	4.6	SEWRPC, 1996, 2004b, 2009b
24	Upper Phantom Lake	Fox42.85°N 88.35°W	0.43	1.4	8.8	3.3	SEWRPC, 2006d
25	Potter Lake	Fox42.82°N 88.35°W	0.65	1.6	7.9	2.4	
26	Wind Lake	Fox42.82°N 88.13°W	3.7	11.1	14.3	2.9	SEWRPC, 2008d
27	Waubeesee Lake	Fox42.81°N 88.16°W	0.52	3.0	22.2	5.8	SEWRPC, 1990
28	Booth Lake	Fox42.79°N 88.42°W	0.45	1.7	7.3	3.7	SEWRPC, 2003a
29	Green Lake	Fox42.79°N 88.56°W	1.2	-	16.8	-	SEWRPC, 2001b, 2010b
30	Middle Lake	Fox42.78°N 88.56°W	1.0	-	12.8	-	SEWRPC, 2001b, 2010b
31	Mill Lake	Fox42.78°N 88.56°W	1.1	-	13.4	-	SEWRPC, 2001b, 2010b
32	Eagle Spring Lake	Fox42.85°N 88.44°W	1.2	1.4	2.4	1.1	SEWRPC, 1997a, 2010a
33	Browns Lake	Fox42.69°N 88.23°W	1.6	3.9	13.4	2.5	
34	Geneva Lake	Fox42.57°N 88.46°W	21.0	395.9	41.2	18.6	SEWRPC, 2008c
35	Hooker Lake	Fox42.56°N 88.11°W	0.35	1.2	7.3	3.4	
36	Powers Lake	Fox42.55°N 88.28°W	1.8	9.2	10.1	4.9	SEWRPC, 2011
37	Silver Lake (Waukesha)	Rock43.08°N 88.49°W	0.89	8.6	13.4	9.6	SEWRPC, 1993
38	Benedict Lake	Fox42.53°N 88.29°W	0.31	2.3	11.3	4.7	SEWRPC, 2001a
39	George Lake	Fox42.52°N 88.06°W	0.24	0.48	4.9	1.9	SEWRPC, 2007a
40	Elizabeth Lake	Fox42.50°N 88.26°W	3.5	8.5	9.8	3.4	SEWRPC, 2009a

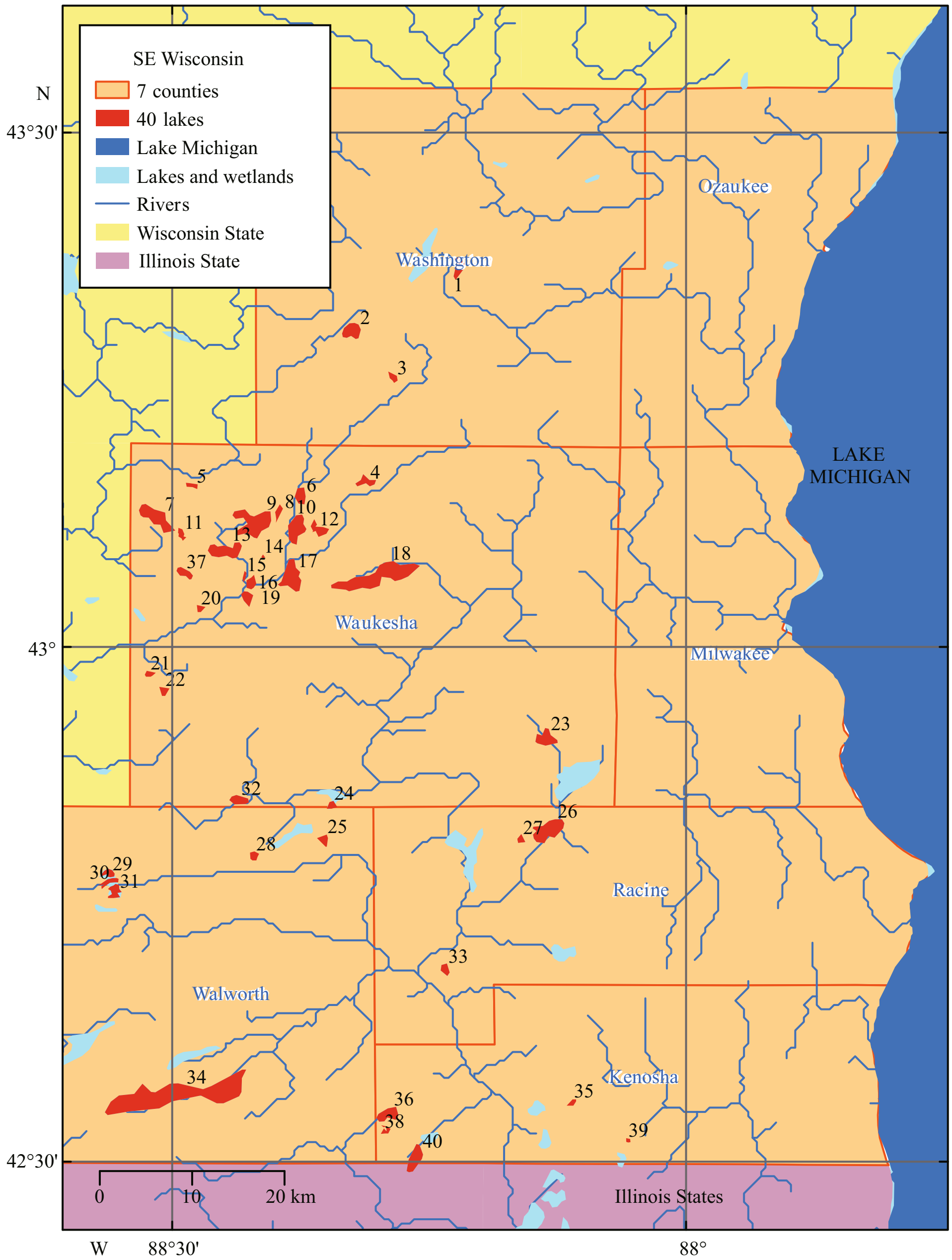

Fig.2 Locations of the studied lakes within the Southeastern Wisconsin Region

through conference presentations, lectures, and plans. The resultant concern has led other researchers to identify similar trends elsewhere (see Löfgren, 2001; Marsalek, 2003; Jackson and Jobbágy, 2005; Smol and Douglas, 2007; Stefan et al., 2008).

Finally, in order to test the hypothesis that at least a portion of the chlorides entering the aquatic ecosystems of the region are derived from wastewater sources, we have compiled groundwater quality data from both the deep aquifer and the shallow, surficial aquifer. Should wastewater be a contributing factor to the salinization of the lakes of Southeastern Wisconsin, there should be a gradual increase in the chloride concentrations observed in the surficial aquifer as many of the residential properties of the region are served by onsite sewage disposal systems.

6 RESULTS

Figure 3 shows the trend in chloride concentrations in many of the major lakes within the Southeastern Wisconsin region. In almost every case, there is an upward trend in the data. This trend extends across all of the subwatersheds within the Southeastern Wisconsin region. These subwatersheds included the

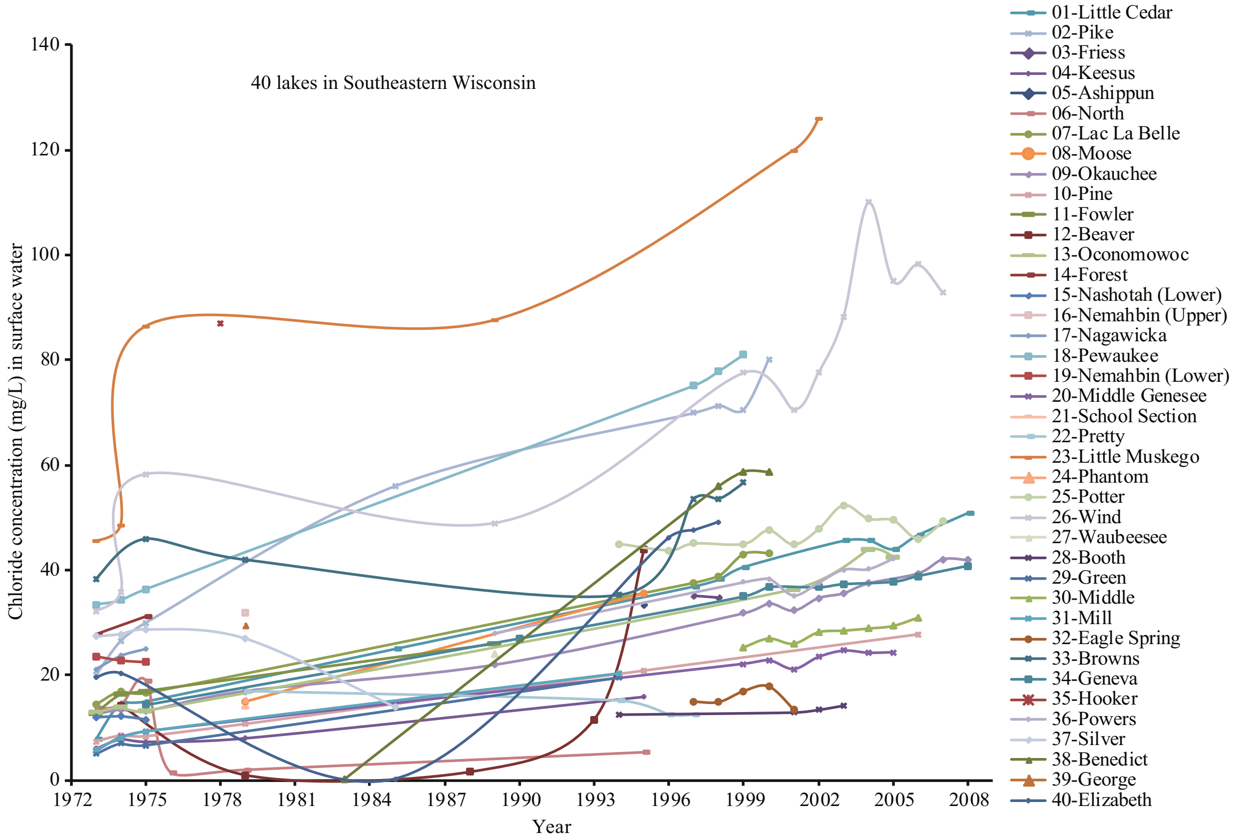

Fig.3 Chloride concentrations in surface waters of Southeastern Wisconsin: 1970–2010

Milwaukee River watershed draining to Lake Michigan, and the greater Rock River basin and Illinois-Fox River basin draining to the Mississippi River. The majority of the waterbodies sampled were river-run lakes, with the majority of these waterbodies having an initial chloride concentration of less than 10 mg/L in the 1960s (Lillie et al., 1983). By 2005, most of the waterbodies sampled had chloride concentrations of greater than 20 mg/L. In some lakes, the levels of chloride approached and even exceeded 100 mg/L.

Several lakes showed an initial decline in chloride concentration during the 1970s. Lakes such as North Lake, Beaver Lake and Okauchee Lake are all waterbodies located along the Oconomowoc River tributary of the Rock River system draining to the Mississippi River. It is likely that this initial decline in chloride concentration is coincident with the start of operations of the Delafield-Hartland Water Pollution Control Commission, which diverted wastewater to a regional wastewater treatment centre during this period. In contrast, other lakes, such as Little Muskego and Wind Lakes, showed an initial increase in chloride concentrations even though wastewater was diverted from their inflows to treatment plants. In these two cases, road and highway improvements occurred at about the same time as the wastewater diversions, which may have offset and overwhelmed the benefits achieved from wastewater diversion (see SEWRPC, 1995a, 2006c).

Figure 4 shows a similar trend line for the chloride concentrations in surficial groundwater. The well depth of 150 m (500 feet) was selected as the depth at which the surficial aquifer gave way to the deeper sandstone aquifer at all points across Southeastern Wisconsin. While this depth varies with location within the region, ranging from a minimum of about 30 m, the break point of 150 m is adequate to encompass all surficial groundwater. In contrast, Fig.5 shows the trend line for chloride concentrations in deep groundwater, within the sandstone aquifer. The same caveat regarding the 150 m depth applies; below 150 m the groundwater can be described as totally within the sandstone aquifer. In spite of the different scale, it is clear that the trend of increasing chloride concentration with time is present in the surficial aquifer but absent in the deeper sandstone aquifer. In the surficial aquifer, chloride concentrations rose from about 40 mg/L in the 1970s to about 80 mg/L in the mid-2000s.

With respect to the specific changes in chloride

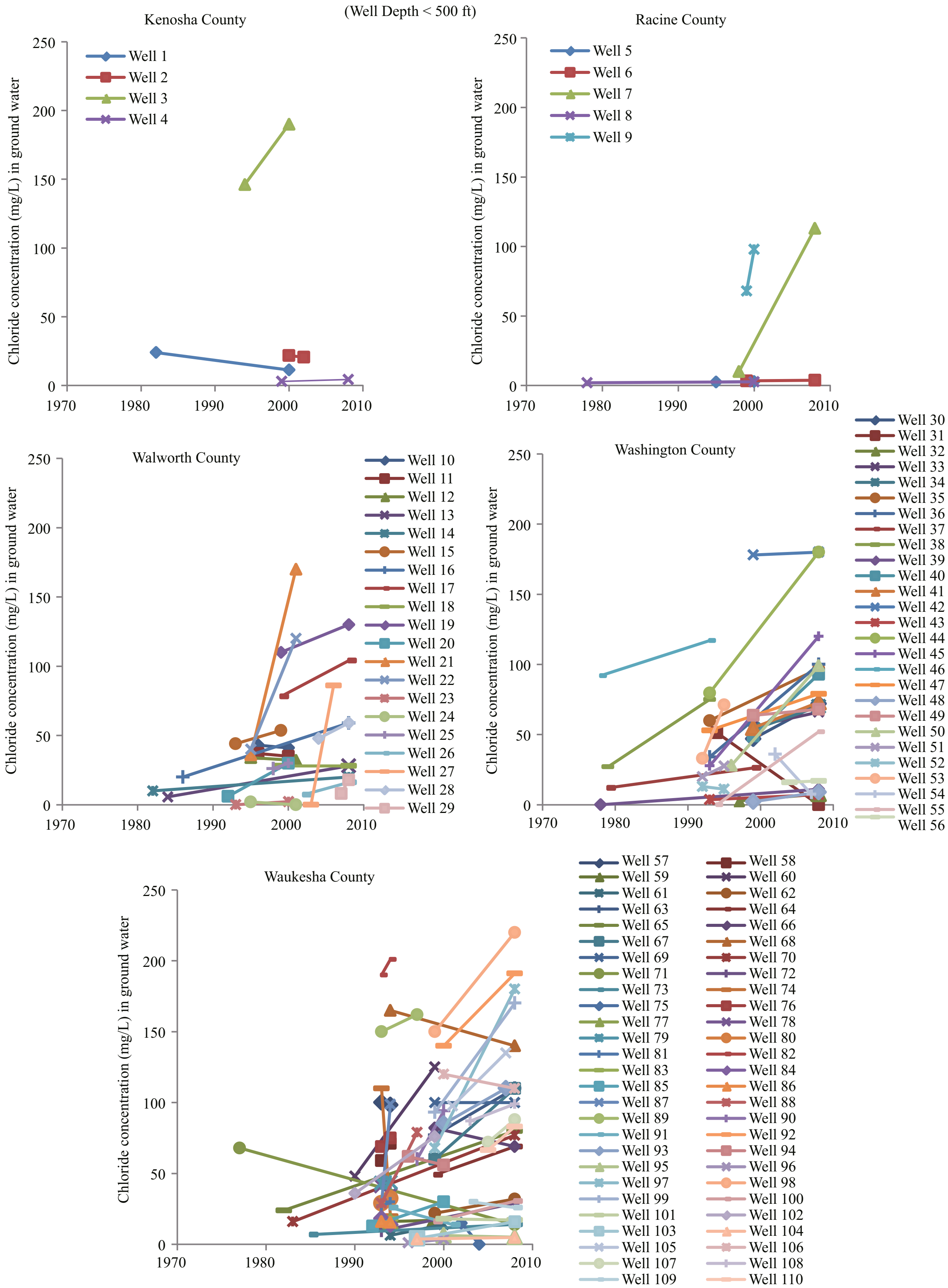

Fig.4 Chloride concentrations in surfacial groundwaters of Southeastern Wisconsin: 1975–2010

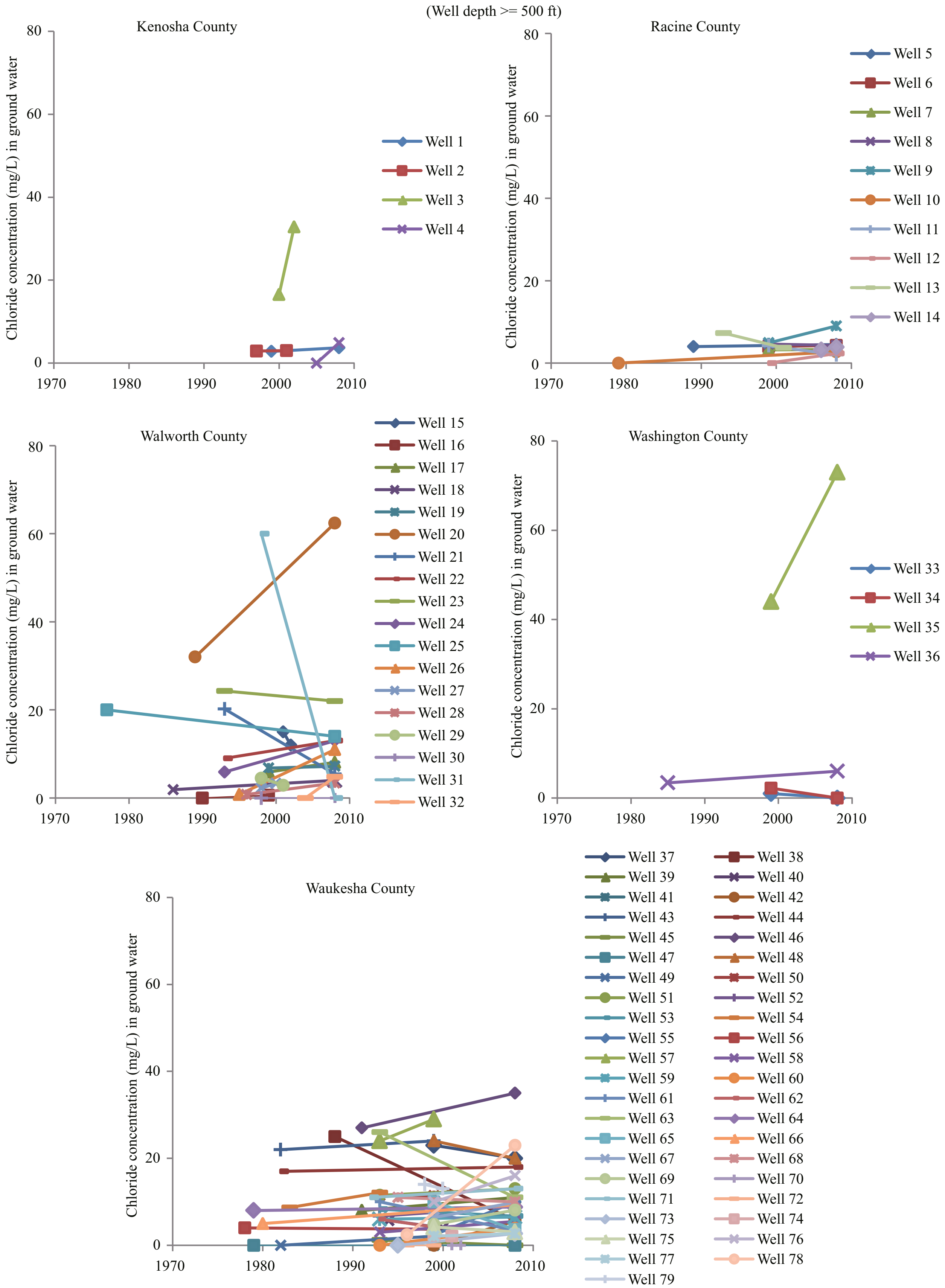

Fig.5 Chloride concentrations in the deep sandstone aquifer of Southeastern Wisconsin: 1975–2010

concentrations in the forty lakes which represent the range of lakes and lake conditions within Southeastern Wisconsin, the majority showed a consistent increase in chloride concentrations (Fig.3). Lake Keesus, Lac La Belle, and Pine, Middle Genesee, Moose, Okauchee, Oconomowoc, Powers, Potter, Pretty and Little Cedar Lakes represent the majority of the lakes, increasing from about 5–15 mg/L chloride in 1972 to between 20 to 40 mg/L by the turn of the millennium. Of these lakes, Lake Keesus, Lac La Belle and Oconomowoc Lake are relatively shallow. Together with Pine Lake and Okauchee Lake, these lakes form part of the Oconomowoc River drainage system. Middle Genesee Lake and Moose Lake are internally-drained waterbodies, and all of these waterbodies lie within an area of Waukesha County that has been experiencing increased urban development (SEWRPC, 2005), primarily comprising single-family housing units which have been built in planned unit developments (PUDs) with good highway access to metropolitan Milwaukee and its transportation hub linking the City to the greater Chicago region (SEWRPC, 2006c).

Lakes with the greatest rate of increase in chloride concentration included Little Muskego, Wind, Pewaukee and Pike Lakes, which had chloride concentrations in excess of 60 mg/L by the turn of the millennium. Little Muskego and Wind Lakes lie along a tributary to the Illinois-Fox River, while Pewaukee Lake drains through the Pewaukee River into the Illinois-Fox River system upstream of the point at which the combined flows from the Muskego Lakes and Wind Lake enter the main stem of the Illinois-Fox River. Pike Lake, in contrast, lies along a tributary to the Rock River. Pewaukee Lake and Little Muskego Lake may be considered as headwater lakes, while Pike Lake and Wind Lake are river-run or through-flow waterbodies.

The forty lakes included large, shallow lakes (such as Wind Lake and Lac La Belle); large, deep lakes (such as Little Muskego and Nagawicka Lakes); and, lakes of intermediate size and depth (such as Benedict, Okauchee, and Pewaukee Lakes). These lakes, also, included lakes within the Rock River subwatershed (such as Lac La Belle, Okauchee and Nagawicka Lakes), the Illinois-Fox River subwatershed (such as Benedict, Little Muskego, Pewaukee, and Wind Lakes), and the Milwaukee River subwatershed (Little Cedar Lake). Both shallow and deeper internally-drained lakes (such as Middle Genesee and Forest Lakes, respectively) also were included. Land uses in the watersheds of these lakes range from urban, as in the case of Fowler Lake, to rural and peri-urban, as in the case of Potter Lake. All of the lakes supported a lakeshore residential community. While the rates of increase in the chloride concentrations of these lakes ranged from about 0.5 mg/L/year in the Oconomowoc River lakes (Okauchee Lake and Lac La Belle) to about 2.5 mg/L/year in the Illinois-Fox River lakes (Wind and Little Muskego Lakes), there was a consistent upward trend in chloride concentrations that occured regardless of lake morphology.

7 DISCUSSION

The WDNR noted that the average chloride concentration of lakes in Southeastern Wisconsin in the 1970s was 19 mg/L (Lillie et al., 1983). For our data set, the regional average for the period through 1970 was minimally higher, with a mean of about 20 mg/L. During the recent period, 2000 through 2008, however, the mean chloride concentration in the region was about 44 mg/L, or approximately double the concentration observed during a similar period approximately 40 years earlier. Prior to this time, Beeton (1965) noted that the chloride concentrations in Southeastern Wisconsin had remained relatively unchanged from the (unpublished) early observations of Birge and Juday between 1900 and 1910.

Although the inputs of nutrients to Southeastern Wisconsin lakes have been moderated, the water environment remains at risk. Sewage treatment practices are designed to remove nutrients, specifically phosphorus and nitrogen, reduce oxygen demand of the effluent, and minimize the discharge of viable pathogenic bacteria to the environment. These practices are ineffective at removing cations and anions from the waste stream, and many of these mineral salts pass through the wastewater treatment works relatively unaffected by the treatment process. In fact, Lillie et al. (1983) noted that where reductions in chloride concentrations have been recorded, as in the Madison Lakes, this has been due to the diversion of wastewater effluents from the receiving waters and their subsequent dilution once the waste stream has been diverted.

This is not to say that the role of wastewater is negligible. Rather, the findings of Lillie et al. (1983) reinforce the suggestion that chloride is entering the surface waters of Southeastern Wisconsin through the waste stream. This is supported by the fact that the surficial groundwater system also is being subjected to increasingly higher chloride concentrations. The seepage of chloride from wastewater treated using onsite sewage disposal systems can be inferred from the data presented in Fig.4 and Fig.5, which show that there has been a consistent increase in chloride concentrations in the surficial aquifer while there has been no similar increase in the deep sandstone aquifer.

Howard et al. (2006) give the average concentration of chloride in human excreta as 50 mg/L. Considering that the majority of the resident populations in the vicinities of the lakes, especially those in the rural areas, live in low-density suburban-density dwellings which are dependent upon onsite sewage disposal systems (SEWRPC, 2006c), it is likely that such systems provide a chronic input of chloride to the surficial groundwater system, and thereby to the lakes. In the urban areas, wastewater conveyance systems collect and transfer wastewater to treatment plants, which, since the 1980s, no longer discharge directly to lakes but rather drain to river reaches (SEWRPC, 1995a). While these treatment facilities do not remove chloride from the waste stream, they are unlikely to form a major contribution to the increasing chloride levels in the region's lakes; concentrations of chloride discharged from treatment works in the region range from about 20 mg/L to about 130 mg/L.

A more likely factor contributing to the higher levels of chloride in the waste stream is the increasing and ongoing use of water softeners utilizing sodium chloride as an ion source. The Delafield-Hartland Water Pollution Control Commission notes that, nationwide in the United States, some 2.6 million tons of sodium chloride is used annually to operate water softener (Dela-Hart, undated). Operating these water softener as recommended typically consumed about 20 kg of sodium chloride per month; approximately one-half of this mass is discharged into the waste stream as spent chloride solution, entering the aquatic environment. SEWRPC (2005) has estimated that the numbers of households in the Southeastern Wisconsin region will have almost doubled between 1960 and 2010, increasing from about 465 913 households in 1960 to about 749 039 households in 2010. Assuming that about one-half of these households are in the metro-Milwaukee area and therefore are served by water-borne sewerage systems, and assuming that a further one-quarter of these households are in other urban centers served by water-borne sewerage systems, it can be estimated that remaining households, using onsite sewage disposal systems, would introduce about 1 875 tons of chloride into the surficial groundwater system annually. An equal mass of chloride is delivered to the surface water drainage system and thereby to the lakes, while about 3 750 tons of chloride are discharged to Lake Michigan in the treated wastewater effluents of the coastal cities.

While wastewater and the household waste stream is one likely avenue for the introduction of chloride into the waters of Southeastern Wisconsin, it is probable that the major pathway for chloride to enter the aquatic ecosystem is through the application of sodium chloride as a de-icing agent during the winter months. The Wisconsin Department of Transportation estimates that the City of Milwaukee applies 55 000 tons of sodium chloride to 11 265 km of road surface each winter, whilst the larger Milwaukee County applies an additional mass of 40 000 tons of sodium chloride to its 3 862 km of roadways (Lins, 2010). In 2007–2008, the State of Wisconsin collectively applied 644 485 tons of sodium chloride to the State's highway transportation network. All of this sodium chloride is ultimately washed off the road surfaces and into the closest streams, drains, and other conveyance systems which are generally connected to the waterways of the State. Assuming that one-half of this mass is comprised of chloride and that, being conservative and not utilized to any great extent by aquatic organisms, this seasonal input of chloride would amount to more than 47 000 tons of chloride annually, or 25 times that of onsite sewage disposal systems.

That said, the management challenge is one of maintaining highway safety during the winter months while minimizing the potential damage of aquatic ecosystems. To this end, the State of Wisconsin has encouraged local governments to use a salt-sand mix to minimize the mass of chloride being applied to the land surface during the winter. The sand can be swept up and potentially re-used, although there are concerns regarding heavy metals and other contaminants that may enter the sand during its time on the road surfaces. Alternatively, re-use of brines which are generated as waste products from the State's industries has been proposed. Cheese brines, containing sodium chloride have been used with some success in the region, for example. Such waste re-use also may have negative consequences such as introducing oxygen-consuming substances into the environment. Finally, managing snow disposal to areas such as stormwater detention areas where flows can be controlled during the spring may have some effect in minimizing the movement of chloride from the land surface to the waters of the State.

The technique with the greatest promise for winter roadway maintenance is the use of calcium chloride as a wetting agent. Due to the fact that these solutions generate heat upon contact with water at air temperatures of -5°C and below they can be applied prior to a storm event, potentially resulting in savings associated with labor costs by allowing road maintenance to be undertaken during normal working hours. This solution also can be combined with sand in a 1:1 ratio for an even greater savings and reduction of chloride loads to the natural environment (SEWRPC, 2009c; Corsi et al., 2015).

Finally, the effect of variations in weather patterns should be considered. SEWRPC (2000b) analyzed the regional rainfall patterns and concluded that there was “no statistical basis to reject an assumption of stationarity” in regional climate over a planning period of up to 50-years in the metropolitan Milwaukee area. That said, review of the time series data shown in Fig.3 does shown that years with high rainfall can result in slight reductions in chloride concentrations. For example, the 2001 data show a consistent dip in chloride concentrations in the majority of the lakes surveyed. This coincided with a period of extreme weather experienced throughout the upper Midwest of the United States (NCDC, 2002). However, the intensity of the response to this and previous events, such as the regional floods in 1993 and 1996 (see U. S. Geological Survey, 2004), was relatively small in comparison with the trend in increasing chloride concentrations in the region.

8 CONCLUSION

While current chloride concentrations in Wisconsin’s waterbodies and ground waters is well below the action level of about 250 mg/L recommended by the U.S. Environmental Protection Agency and the World Health Organization (Baldwin et al., 2012, 2013), the steady increase in concentration at a rate of up to 2 mg/L per year during the last 40 years gives rise to a cause for concern, especially in Southeastern Wisconsin where naturally occurring chloride is virtually absent from the region’s geology. Therefore, the chloride entering the biosphere has to be of anthropogenic origin. Our analysis suggests that winter highway maintenance and the application of sodium chloride to highways as a de-icing agent is most likely to be the major pathway by which anthropogenic chloride is entering the biosphere in this region. Consequently, consideration should be given to alternatives, such as the use of a sand-calcium chloride mixture, which, while maintaining public safety, introduces much less chloride into the environment and consequently slows the rate at which chloride accumulation is occurring.

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