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Great Lakes total phosphorus revisited: 1. Loading analysis and update (1994–2008)

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ABSTRACT

Phosphorus load estimates have been updated for all of the Great Lakes with an emphasis on lakes Superior, Michighan, Huron and Ontario for 1994–2008. Lake Erie phosphorus loads have been kept current with previous work and for completeness are reported here. A combination of modeling and data analysis is employed to evaluate whether target loads established by the Great Lakes Water Quality Agreement (GLWQA, 1978, Annex 3) have been and are currently being met. Data from federal, state, and provincial agencies were assembled and processed to yield annual estimates for all lakes and sources. A mass-balance model was used to check the consistency of loads and to estimate interlake transport. The analysis suggests that the GLWQA target loads have been consistently met for the main bodies of lakes Superior, Michigan and Huron. However, exceedances still persist for Saginaw Bay. For lakes Erie and Ontario, loadings are currently estimated to be at or just under the target (with some notable exceptions). Because interannual variability is high, the target loads have not been met consistently for the lower Great Lakes. The analysis also indicates that, because of decreasing TP concentrations in the lakes, interlake transport of TP has declined significantly since the mid-1970s. Thus, it is important that these changes be included in future assessments of compliance with TP load targets. Finally, detailed tables of the yearly (1994–2008) estimates are provided, as well as annual summaries by lake tributary basin (in Supplementary Information).

Introduction

During the 1970s, a huge effort was initiated to reverse the cultural eutrophication of the Great Lakes. Based on the best available scientific evidence, it was determined that this reversal could best be achieved by reducing total phosphorus (TP) loadings. As part of the Great Lakes Water Quality Agreement (GLWQA, 1978), TP loading targets were established for each major part of the Great Lakes (Table 1) and a variety of control measures were subsequently implemented to decrease the loadings down to these targets.

In order to track the progress of these efforts, systematic annual measurements of TP loadings to each of the Great Lakes were implemented primarily by the jurisdictions (the eight Great Lakes States and the Province of Ontario) represented on the Great Lakes Water Quality Board of the International Joint Commission (IJC). However, in 1991, formal reporting of annual Great Lakes total phosphorus loading ceased. Monitoring still continued, but estimated lake loads were no longer compared to their targets. Ten years later, the U.S. EPA's Great Lakes National Program Office (GLNPO) provided funding to renew total phosphorus reporting for Lake Erie and bring the annual load record up to date (Dolan and McGunagle, 2005). This effort has been continued through the EcoFore project funded by NOAA for Lake Erie.

Although significant TP loading reductions had occurred by the early 1990s, there are reasons why annual loading measurements to all parts of the system are necessary. First, as described subsequently, loadings to several parts of the Great Lakes still exceed the targets. Second, although the load reductions have certainly led to many improvements (Chapra and Dolan, 2012; De Pinto et al., 1986), several problems have recurred (or, perhaps, were never really solved in the first place). *Microcystis* blooms in western Lake Erie have become a regular occurrence (Chaffin et al., 2011). *Cladophora* routinely reaches nuisance levels in the nearshore zones of lakes Michigan, Erie, and Ontario (Auer et al., 2010). Hypoxia continues to cause degraded fish habitat in the central (and western) basin of Lake Erie (Pothoven et al., 2009) and lower Green Bay (Qualls et al., 2009; Tracy Valenta, personal communication, 2011). Drinking water restrictions, caused primarily by taste and odor problems due to algal–cyanobacterial growth, have occurred in 33% of Great Lakes Areas of Concern (Watson et al., 2008). Although some of these problems have undoubtedly been exacerbated, if not induced, by non-nutrient factors (most notably the invasion of Dreissenid mussels in about 1990), understanding their dynamics still depends on

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Table 1
Total phosphorus target loads to Great Lakes compared with the baseline load estimates for 1976. Note that the target loads for lakes Huron (Main Lake only), Erie and Ontario include phosphorus inputs from upstream lakes. Loads are in MTA (metric tonnes per annum).

Basin	1976 TP load (MTA)	Target TP load (MTA)
Lake Superior	3600	3400
Lake Michigan	6700	5600
Lake Huron	5050	4360
Main Lake Huron	3000	2800
Georgian Bay	630	600
North Channel	550	520
Saginaw Bay	870	440
Lake Erie	20,000	11,000
Lake Ontario	11,000	7000

knowledge of both the magnitude and location of phosphorus loadings. Finally, because other problem areas are influenced by lake trophic state (e.g., toxic contamination, fisheries), systematic nutrient loading time series are necessary to effectively understand and manage these problems.

These concerns are well understood by environmental scientists and water-quality managers. In 2006, Review Working Group D was charged with reviewing the implementation of Annexes 3 and 13 of the Great Lakes Water Quality Agreement (GLWQA, 1978). With regard to Annex 3 total phosphorus target loads, the group concluded that:

> "It is not possible to determine if P load targets are being met today due to the lack of load estimates in the last 15 years. Even if target loads on a lakewide basis are being met, it seems likely that nearshore areas and embayments may be experiencing excess P loading and the resulting degradation in trophic status. As TMDLs and other local and regional loading targets are developed, the relevant historical record should be examined and updated where necessary."

In response to this conclusion, U.S. EPA's Great Lakes National Program Office (GLNPO) awarded a grant to provide loading estimates for 1994–2008 for TP, chloride, nitrate, and total dissolved phosphorus (TDP) and to update mass balance models in all Great Lakes for TP. The objective of this paper is to describe the effort and summarize the results of the TP loading estimates. A summary of all Great Lakes TP loads for the period 1981–2008 is included in the Supplementary Information (S1 to S14). In order to maintain consistency with previously reported loads and the loading targets established in the GLWQA, the units of loading throughout this publication are given as metric tonnes per annum (year) with the acronym MTA. A second paper describes how this information was used to update the Great Lakes mass balance for TP (Chapra and Dolan, 2012). Among other benefits, this latter effort provides a consistent and systematic means to quantify interlake transfers of phosphorus.

In order to provide a reference for comparison of the updated results reported in this paper, excerpts from the assessments of Review Working Group D (De Pinto et al., 2006) are presented below by lake (except for Lake Superior which is presented in its entirety):

Lake Superior

> "TP loading estimates for Lake Superior exist for 1974–1991. Lake Superior was occasionally above its target load of 3400 metric tonnes per year (MTA) prior to 1981, probably due to lack of state detergent bans up to that point. However, after 1981, there were no reported loads above the target, so it appears that Lake Superior has consistently met its target load since that point."

Lake Michigan

> "Lake Michigan's record has been supplemented by results from the Lake Michigan Mass Balance Study (LMMBS) in 1994 and 1995. After 1980, there were no reported loads above the target of 5600 MTA."

Lake Huron

> "Lake Huron load was occasionally above its target of 4360 MTA through 1985. However, after 1985, there were no reported loads above the target. Some recent Michigan Department of Environment Quality load estimates for Saginaw Bay, an embayment of Lake Huron with an extremely large contributing drainage basin, indicate that this system is not meeting its target load of 440 MTA."

Lake Erie

> "Lake Erie has a continuous P load record from 1967 through 2002. After an exponential drop in TP load, due largely to sewage treatment plants coming into compliance with a 1 mg/L effluent standard, the target load of 11,000 MTA was first achieved in 1981. During the period 1982–2002, the target has been achieved roughly half the time. A breakdown of the load categories indicates that variability in the load occurs as a result of hydrology during a given year, with loads exceeding the target occurring in years with relatively high precipitation and runoff."

Lake Ontario

> "Lake Ontario first achieved its target load of 7000 MTA in 1983, dropping from values above 20,000 MTA prior to the mid-1970s. Since 1983, the Lake Ontario TP load has exceeded its target value five times. Furthermore, it seems that the years when the Lake Ontario target is exceeded align with those years that have a high load to Lake Erie (over its target load)."

Methods

Background

Great Lakes TP loadings have been estimated since 1967. The same basic sources of data as described below have been used for the entire reporting period (1967–2008). Further, the same estimation procedures were used throughout this period. The main differences between early (1967–1979) and later (1980–2008) load estimates were due to improved data availability and refined methods for loads from unmonitored areas as prescribed by PLUARG (1978).

Many of the load estimates that were made prior to the current study period (pre-1994) have been reported previously. Estimates for all five lakes were reported in the 1970s by the International Joint Commission (GLWQB, 1974, 1975, 1976, 1977, 1978, 1979). Fraser (1987) compiled loadings for Lake Erie for 1967 to 1982. Lesht et al. (1991)

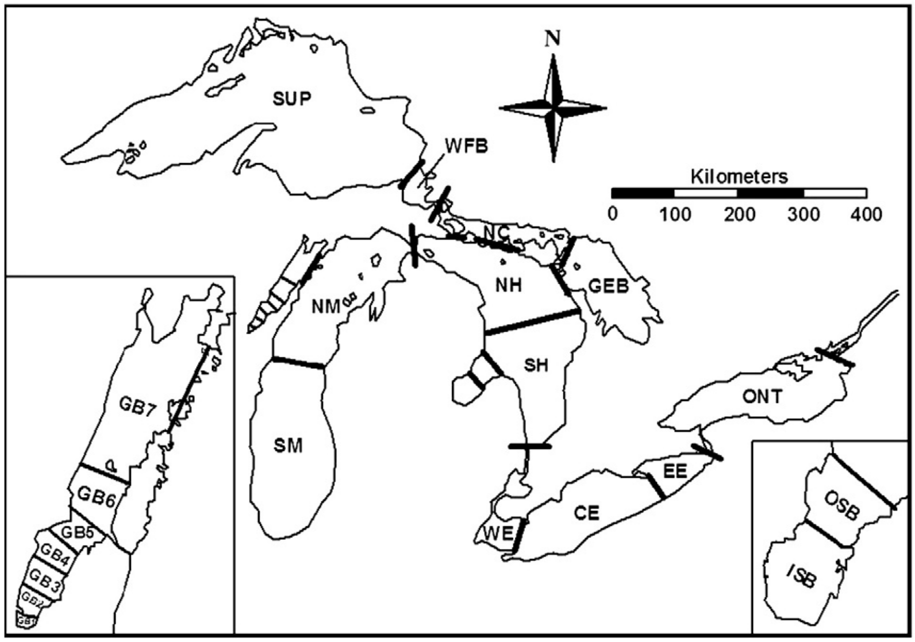

Fig. 1. Segmentation scheme for chloride and total phosphorus models for the Great Lakes. The five Great Lakes and segments therein are abbreviated as follows: SUP = Lake Superior; NM and SM = Northern and Southern Lake Michigan, respectively; WFB = White Fish Bay; NC = North Channel; GEB = Georgian Bay; NH and SH = northern and Southern Lake Huron, respectively; WE, CE and EE = Western, Central and Eastern Lake Erie, respectively; ONT = Lake Ontario. The left inset shows the more refined segmentation used for Green Bay (GB) which is located on the west side of NM and the right inset for Saginaw Bay (SB) which is located on the west side of SH.

compiled loads for the entire system from 1974 to 1986 including breakdowns by sub-basin. Dolan (1993) and Dolan and McGunagle (2005) presented Lake Erie load estimates for the period 1981 to 2002. Load estimates for 1991 were reported by Environment Canada and U.S. EPA at SOLEC (1994). Estimates for 1992 and 1993 were prepared using the same methods as described below, but were never reported. These loads were made available by the IJC (John Gannon, personal communication, 2008) at the beginning of the current project and have been included in the Supplementary Information (S1–S14).

Data sources

All of the data used to estimate Great Lakes TP loads come from government databases except as noted below. Data for U.S. point source dischargers in the Great Lakes basin (monthly average effluent flow and total phosphorus concentration) are retrieved annually from the Permit Compliance System (PCS) which is a database maintained by the U.S. EPA and updated by the States (Indiana, Illinois, Michigan, Minnesota, New York, Ohio, Pennsylvania, and Wisconsin). Beginning in 2006, some of the States (e.g., Indiana) began to transfer their point source data from PCS to a new system called the Integrated Compliance Information System (ICIS). The same type of data was available in ICIS.

Data for Canadian point source dischargers in the Great Lakes basin are stored in the Municipal and Industrial Strategy for Abatement (MISA) database maintained by the Ontario Ministry of the Environment. The same type of data available for U.S. dischargers was retrieved from MISA.

The U.S. daily average tributary flows for gauged Great Lakes tributaries were retrieved from the National Water Information System

Table 2
Great Lakes total phosphorus municipal point sources 1994–2008 (MTA).

Lake	Superior		Michigan		Huron		Erie		Ontario	
Year	Direct	Indirect	Direct	Indirect	Direct	Indirect	Direct	Indirect	Direct	Indirect
1994	88	8	284	442	64	213	1631	441	1002	190
1995	89	7	305	390	204	27	1414	383	986	161
1996	100	8	392	365	62	191	1266	631	1039	173
1997	90	8	691	85	231	18	1741	535	1059	154
1998	74	2	685	103	71	156	1489	507	1056	151
1999	84	1	349	378	212	14	1370	505	1139	38
2000	81	2	347	368	210	14	1522	452	1140	22
2001	83	2	374	368	60	137	1282	437	987	118
2002	88	2	378	352	82	161	1399	512	1031	115
2003	88	8	314	321	54	108	1223	401	1020	120
2004	89	2	350	334	56	142	1375	457	1080	148
2005	70	8	329	357	58	133	1414	441	1070	144
2006	68	2	306	391	60	188	1443	460	1093	117
2007	68	2	324	309	73	137	1481	453	1011	100
2008	59	8	312	348	86	111	1469	443	1051	94
Average	*81*	*5*	*383*	*328*	*105*	*117*	*1435*	*471*	*1051*	*123*
Minimum	*59*	*1*	*284*	*85*	*54*	*14*	*1223*	*383*	*986*	*22*
Maximum	*100*	*8*	*691*	*442*	*231*	*213*	*1741*	*631*	*1140*	*190*
Total municipal	*86*		*711*		*222*		*1906*		*1174*	

Table 3
Great Lakes total phosphorus industrial point sources 1994–2008 (MTA).

Lake	Superior		Michigan		Huron		Erie		Ontario	
Year	Direct	Indirect	Direct	Indirect	Direct	Indirect	Direct	Indirect	Direct	Indirect
1994	64	49	38	196	42	53	50	32	53	67
1995	71	53	46	230	79	27	89	21	65	63
1996	89	104	163	98	34	49	68	32	68	62
1997	105	159	208	83	56	28	59	27	65	69
1998	100	153	175	85	36	51	54	25	68	68
1999	98	134	122	90	57	26	49	24	80	45
2000	89	127	101	104	51	24	47	26	72	38
2001	77	134	105	99	29	31	53	17	55	49
2002	82	103	80	109	30	33	57	24	66	34
2003	80	84	67	101	28	37	34	31	62	32
2004	82	86	99	95	26	36	35	27	60	23
2005	76	85	143	201	29	37	31	25	54	18
2006	64	69	39	175	36	36	32	32	53	22
2007	98	72	40	89	52	15	37	34	48	24
2008	57	61	43	83	57	13	27	33	40	19
Average	*82*	*98*	*98*	*123*	*43*	*33*	*48*	*27*	*61*	*42*
Minimum	*57*	*49*	*38*	*83*	*26*	*13*	*28*	*17*	*40*	*18*
Maximum	*105*	*159*	*208*	*230*	*79*	*53*	*89*	*34*	*80*	*69*
Total industrial	*180*		*221*		*76*		*75*		*103*	

(NWIS) database maintained by the Water Resources Division of the U.S. Geological Survey.

The Canadian daily average tributary flows for gauged Great Lakes tributaries were retrieved from the Hydrometric Data (HYDAT) database maintained by Environment Canada, Water Survey Canada.

Available U.S. tributary TP concentrations for monitored Great Lakes tributaries were retrieved from STORET, the U.S. EPA database for water quality data. Sampling results from State water quality monitoring networks (Michigan DEQ, Minnesota PCA, New York DEC, Ohio EPA, and Wisconsin DNR) are stored in this database. It should be noted that STORET is now accessible on the Internet. Data prior to 1999 are available in the STORET Legacy Data Center and data from 1999 to the present are intended for Modernized STORET. USGS data that was formerly in STORET Legacy has been moved to the USGS water data website where it can be retrieved along with the daily flows referred to above. Data from the Lake Erie Tributary Monitoring Program which is maintained by the Heidelberg College Water Quality Laboratory (Baker and Richards, 2002) have not been stored in either version of STORET for the study period and were available directly from R. Peter Richards (personal communication). Data from the Green Bay Metropolitan Sewerage District (GBMSD) were used to augment Wisconsin DNR sampling of the Fox River. Data for the study period were available directly from Tracy Valenta (personal communication).

The Canadian tributary TP concentrations for monitored Great Lakes tributaries were available from the Provincial Water Quality Monitoring Network (PWQMN) database at the Ontario Ministry of the Environment.

Rainfall amounts and TP concentrations in rainfall for the Great Lakes were available in spreadsheet format from Environment Canada.

All of the data collected for Lake Michigan during the LMMBS were available directly from David Griesmer (personal communication) at the U.S. EPA, Large Lakes Research Station.

Load estimation

The methods used to estimate TP loads varied by source type, but the basic calculation involved forming the product of concentration and flow rate (volume per unit time) to produce the loading rate (mass per unit time). This quantity was then averaged over the required time period. For example, to estimate loads from point

Table 4
Great Lakes total phosphorus tributary loads 1994–2008 (MTA).

Lake	Superior		Michigan		Huron		Erie		Ontario	
Year	Monit.	Unmonit.	Monit.	Unmonit.	Monit.	Unmonit.	Monit.	Unmonit.	Monit.	Unmonit.
1994	817	583	2199	286	1646	787	3593	981	1090	286
1995	961	710	1667	409	1493	923	3188	1621	1039	285
1996	1178	1830	1739	751	2085	1487	6276	2378	2610	1328
1997	1061	1576	2553	975	1843	1276	9108	4345	1379	417
1998	513	394	2296	585	1081	960	6724	2669	2275	683
1999	967	1113	2002	460	686	573	2536	1088	728	220
2000	705	794	1846	479	1320	1330	3393	1626	1077	328
2001	995	1485	2974	579	1395	1015	2990	1391	1246	266
2002	678	810	2243	470	1377	858	4868	1635	1542	878
2003	674	729	1513	297	716	577	4402	1132	1581	698
2004	703	720	2968	778	1520	902	4911	1736	1783	501
2005	732	1226	1774	373	824	432	5628	1451	1341	369
2006	1691	3661	1917	439	1021	398	4968	1396	1580	607
2007	470	670	1890	443	1103	504	7553	2080	2265	589
2008	1446	2711	2756	760	1288	683	6672	1693	1427	457
Average	*906*	*1268*	*2156*	*539*	*1293*	*847*	*5121*	*1815*	*1531*	*528*
Minimum	*470*	*394*	*1513*	*286*	*686*	*398*	*2536*	*981*	*728*	*220*
Maximum	*1691*	*3661*	*2974*	*975*	*2085*	*1487*	*9108*	*4345*	*2610*	*1328*

Table 5
Great Lakes total phosphorus atmospheric and interlake load estimates 1994–2008 (MTA). Upstream contributions are identified as follows: LS (Lake Superior via the St. Mary's River), LM (Lake Michigan via the Straits of Mackinac), LH (Lake Huron via the St. Clair River), and LE (Lake Erie via the Niagara River).

Lake	Superior	Michigan	Huron			Erie		Ontario	
Year	Atmos.	Atmos.	Atmos.	From LS	From LM	Atmos.	From LH	Atmos.	From LE
1994	740	289	473	179	171	403	501	300	1400
1995	752	299	468	150	154	377	482	281	1114
1996	609	313	466	228	127	516	506	204	1353
1997	647	277	495	310	113	520	560	230	2493
1998	815	311	410	183	115	694	528	171	2218
1999	1000	291	752	181	111	485	435	311	1288
2000	1140	331	433	202	102	788	406	392	994
2001	817	339	402	195	100	537	398	244	950
2002	1419	291	464	218	111	694	406	213	1004
2003	603	282	342	183	104	813	366	174	1123
2004	640	352	320	155	102	511	364	233	1272
2005	674	256	523	165	110	363	354	206	1312
2006	1028	336	1175	144	118	632	335	214	1279
2007	786	290	431	130	129	432	325	184	1407
2008	437	387	359	229	152	493	321	294	1573
Average	*807*	*310*	*501*	*190*	*121*	*551*	*419*	*243*	*1385*
Minimum	*437*	*256*	*320*	*130*	*100*	*363*	*321*	*171*	*950*
Maximum	*1419*	*387*	*1175*	*310*	*171*	*813*	*560*	*392*	*2493*

sources, the following calculations (Dolan, 1993) were used to determine annual average point-source phosphorus loads:

$$\text{Loading} = \frac{\sum_{i=1}^{n} Q_i c_i}{n} \tag{1}$$

where Loading = average annual TP loading (metric tonnes per annum or MTA), Q_i = the mean effluent flow for the ith month (km^3/year), c_i = the average TP effluent concentration for the ith month (μg P/L), and n = the number of months of monitoring for a particular year. These calculations were performed on a "per pipe" basis and the estimates summed (for multi-pipe facilities) to provide loads on a "per facility" basis.

For monitored tributaries, the Stratified Beale's Ratio Estimator (Beale, 1962; Tin, 1965; Dolan et al., 1981) was used. For each year and tributary, loads were calculated for each day that a water quality sample was available. These data were then sorted by flow and divided into one or more strata depending on the nature of the flow and concentration

Table 6
Great Lakes total phosphorus load estimates 1994–2008 (MTA). The standard errors (SE) for the loads are included. Upstream contributions are identified as follows: LS (Lake Superior via the St. Mary's River), LM (Lake Michigan via the Straits of Mackinac), LH (Lake Huron via the St. Clair River), and LE (Lake Erie via the Niagara River). Total loadings that exceed the IJC targets (Table 1) have been highlighted.

Lake	Superior		Michigan		Huron					Erie				Ontario			
Year	Basin load	SE	Basin load	SE	Basin load	SE	From LS	From LM	Total load†	Basin load	SE	From LH	Total load†	Basin load	SE	From LE	Total load†
1994	2292	130	3095	230	3011	207	179	171	3361	6658	277	501	7159	2731	222	1400	4131
1995	2584	147	2724	232	3167	188	150	154	3471	6689	278	482	7171	2 655	121	1114	3769
1996	3807	290	3358	248	4134	228	228	127	4489	10505	478	506	11011	5249	385	1353	6602
1997	3479	214	4705	282	3900	217	310	113	4323	15774	906	560	16334	3150	148	2493	5643
1998	1897	142	4053	278	2558	149	183	115	2856	11631	559	528	12159	4253	882	2218	6471
1999	3262	220	3224	261	2280	325	181	111	2572	5526	139	435	5961	2477	103	1288	3765
2000	2809	325	3104	309	3344	178	202	102	3648	7378	290	406	7784	3009	123	994	4003
2001	3456	256	4372	372	2901	162	195	100	3196	6252	371	398	6650	2798	96	950	3748
2002	3076	451	3461	279	2812	207	218	111	3141	8653	390	406	9059	3731	273	1004	4735
2003	2174	146	2472	235	1716	118	183	104	2003	7604	177	366	7970	3536	166	1123	4659
2004	2233	123	4548	309	2825	152	155	102	3082	8568	149	364	8932	3657	209	1272	4929
2005	2778	357	2875	220	1866	189	165	110	2141	8887	190	354	9241	3038	148	1312	4350
2006	6512	1247	3037	269	2689	389	144	118	2951	8472	194	335	8807	3547	132	1279	4826
2007	2091	228	2987	248	2163	168	130	129	2422	11584	285	325	11909	4098	359	1407	5505
2008	4711	413	4258	340	2474	136	229	152	2855	10354	193	321	10675	3268	159	1573	4841

†Total loads for lakes Huron, Erie, and Ontario include the interlake loadings from the updated mass balance model.

Notes:

a. Basin load includes point source, tributary load, and atmospheric load.
b. Total load is the net load plus interlake load.
c. For Superior and Michigan Basin load and Total load coincide.
d. Lake Erie loads for 1994–2002 have been previously reported (Dolan and McGunagle, 2005). These "old" Lake Erie loads include an assumed constant 1080 MTA from Lake Huron. To derive the old Lake Erie Load, reader should add 1080 to the Basin load for 1994–2002.

Table 7
Segmented TP loading (MTA) summary for Lake Superior and probability of exceedance of target load. See Fig. 1 for segment delimitations. Lake Superior Target Load is 3400 MTA (see Table 1). Total loadings that exceed the IJC target have been highlighted.

Year	Segment SUP	Segment WFB	Total Superior	Probability target load exceeded
1994	2231.5	60.5	2292	<0.0001
1995	2534.7	49.3	2584	0.0001
1996	3583.9	223.1	3807	0.9071
1997	3303.3	175.7	3479	0.6417
1998	1828.7	68.3	1897	<0.0001
1999	3104.0	158.0	3262	0.2715
2000	2688.5	120.5	2809	0.0468
2001	3296.3	159.7	3456	0.5849
2002	2943.3	132.7	3076	0.2436
2003	2127.4	46.6	2174	<0.0001
2004	2184.9	48.1	2233	<0.0001
2005	2732.9	45.1	2778	0.0533
2006	6466.5	45.5	6512	0.9859
2007	1972.0	119.0	2091	<0.0001
2008	4429.4	281.6	4711	0.9960

relationship within each stratum. In general, tributaries with greater than monthly sampling frequency were stratified into at least two strata. The ratio estimator method requires uncensored concentration values for all samples to avoid bias (El-Shaarawi and Esterby, 1992). Some tributary TP concentrations were reported as censored (e.g., by Ohio EPA at 0.05 mg/L and by USGS at 0.01 mg/L). Replacement values were calculated using maximum likelihood estimation (MLE) (El-Shaarawi and Dolan, 1989).

Procedures for estimating loads from unmonitored tributaries and the atmosphere were in accordance with Rathke and McCrae (1989). For unmonitored tributaries, a unit area load (UAL) was estimated from nearby monitored tributaries and applied to the unmonitored basin area. For atmospheric loadings (with the exception of Lake Michigan), the flux of TP in units of mass per area was estimated from precipitation collectors and applied to the lake area that the collector represents. For each of the years 1994–2008, the average flux of two or three Canadian sites per lake (e.g., Rock Point, St. Clair, and Pelee, for Lake Erie) was used so that each site represented a fraction of the lake surface. All of these sites are located on the Canadian shore as described by Chan et al. (2003).

For Lake Michigan, due to a lack of monitoring for phosphorus in precipitation during the study period, atmospheric loads were based on 1995 fluxes measured by Miller et al. (2000) during the 1994–1995 LMMBS. In that study, a 5 km × 5 km grid was used for the entire lake, and atmospheric fluxes were provided on this basis. Each grid cell was assigned to the corresponding segment and the grid fluxes were summed. Adjustments based on over-lake precipitation rates were used to estimate the remaining years (GLERL, 2010).

In addition to precipitation, dry deposition can also represent a significant atmospheric TP loading. Unfortunately, systematic direct measurements of dry deposition for the Great Lakes are currently unavailable. Consequently, we have adopted the convention used by the IJC that dry deposition is approximately equal to wet deposition. The software used to prepare atmospheric TP estimates has been obtained from the IJC (John Gannon, personal communication) and utilized without modification. Thus, the measured atmospheric precipitation loadings were doubled to account for dry deposition in addition to the wet. It should be noted that this may be a conservative estimate in that studies of other systems (e.g., Anderson and Downing, 2006; Jassby et al., 1994; Tamatamah et al., 2005) indicate that dry deposition may account for up to 75% of the total atmospheric phosphorus flux. This underscores the importance of future efforts to measure dry deposition directly.

The base time period for all estimates is the water year (October of the previous year through September of the current year). All previous annual loading estimates for the Great Lakes (e.g., Dolan, 1993; Rathke and McCrae, 1989) used the water year as the base time period. Although the water year was originally chosen to coincide with the availability of published tributary flow reports from USGS, there is some evidence that this time period better captures the contribution of flow events that occur in the winter months (Dolan and Richards, 2008).

Great Lakes load estimation has always considered the inputs from upstream lakes. For example, Dolan and McGunagle (2005) included a constant TP load estimate from Lake Huron (1080 MTA) in their Lake Erie update. The estimates for inputs from Lake Huron, as well as from lakes Michigan and Superior, were based on measurements made during the Upper Lakes Reference Group (1977a,b). Inputs from Lake Erie to Lake Ontario were based on annual measurements made by Environment Canada at Niagara-on-the-Lake (NOTL) and varied from year to year (e.g., Rathke and McCrae, 1989).

In this study, the results of mass balance modeling (Chapra and Dolan, 2012; Schmitt Marquez, 2010) are used to complete the load estimates with more realistic annual interlake loads from all

Table 8
Segmented TP loading (MTA) summary for Lake Michigan and probability of exceedance of target load. See Fig. 1 for segment delimitations. Lake Michigan Target Load is 5600 MTA (see Table 1).

Year	Segment GB1	Segment GB2	Segment GB3	Segment GB4	Segment GB5	Segment GB6	Segment GB7	Segment SM	Segment NM	Total Michigan	Probability target load exceeded
1994	608.1	8.7	6.5	19.1	19.4	104.1	65.6	1768.3	495.5	3095.4	<0.0001
1995	500.9	11.9	6.7	45.1	26.5	118.9	85.5	1474.8	454.1	2724.4	<0.0001
1996	903.0	27.9	18.8	113.3	73.8	248.5	209.3	1265.9	497.1	3357.6	<0.0001
1997	642.8	18.3	12.0	71.5	25.3	253.9	179.2	2719.0	782.8	4704.9	0.0040
1998	525.4	15.9	10.4	32.6	26.2	181.7	148.0	2575.2	538.0	4053.2	0.0001
1999	426.6	13.2	9.0	15.4	14.9	211.2	143.6	1895.0	495.2	3224.1	<0.0001
2000	413.6	13.1	9.1	51.1	23.1	105.3	204.6	1797.9	486.4	3104.2	<0.0001
2001	596.2	19.8	13.7	27.5	29.6	117.9	157.1	2874.3	535.7	4371.7	0.0031
2002	632.3	20.6	14.3	29.9	32.3	216.9	113.9	1851.2	550.0	3461.3	<0.0001
2003	545.3	17.7	12.3	38.6	31.2	120.0	82.2	1204.9	420.3	2472.5	<0.0001
2004	1174.8	38.0	26.7	97.4	85.3	94.1	76.2	2147.9	807.3	4547.7	0.0026
2005	670.8	20.9	14.4	40.9	20.4	96.6	73.5	1505.8	431.4	2874.9	<0.0001
2006	611.5	18.5	13.0	19.5	18.1	102.5	82.1	1643.2	528.6	3037.0	<0.0001
2007	522.4	16.6	11.5	14.6	21.4	76.2	58.9	1682.5	583.1	2987.1	<0.0001
2008	680.9	20.9	16.0	92.6	21.9	96.5	77.8	2409.1	842.0	4257.6	0.0010

Table 9
Segmented TP loading (MTA) summary for Lake Huron and probability of exceedance of target load. The Total Huron load includes the inflows from lakes Superior and Michigan. See Fig. 1 for segment delimitations. Target loads are 520, 600, 440, 2800, and 4360 MTA, for North Channel, Georgian Bay, Saginaw Bay, Main Lake Huron, and Total Lake Huron, respectively (see Table 1). Total loadings that exceed the IJC targets have been highlighted.

Year	Segment NC	Probability target load exceeded	Segment GEB	Probability target load exceeded	Segment NH	Segment ISB	Segment OSB	Probability target[1] load exceeded	Segment SH	Probability target[2] load exceeded	Total Huron	Probability target load exceeded
1994	387.9	0.0196	353.5	0.0030	474.2	1123.2	66.9	>0.9999	605.7	<0.0001	3361.4	0.0002
1995	477.4	0.2160	383.4	0.0008	445	1019.4	60.1	>0.9999	781.4	<0.0001	3470.6	0.0002
1996	669.4	0.9806	436.4	0.0002	591.7	1034.7	62.2	0.9997	1340	0.0001	4489.4	0.7095
1997	470.4	0.1943	514.9	0.0462	538.6	1354.3	79.9	>0.9999	942	<0.0001	4323.0	0.4338
1998	345	0.0003	514.9	0.0664	388.7	578.2	39	>0.9999	691.8	<0.0001	2855.7	<0.0001
1999	336.7	0.0403	396.7	0.1043	501.7	631.5	47.9	0.9952	365	<0.0001	2571.6	<0.0001
2000	196.5	<0.0001	658.2	0.7743	395.7	723.1	43.2	>0.9999	1327.5	<0.0001	3648.1	0.0009
2001	682.8	0.9144	467.5	0.0041	340.8	725.4	44.2	>0.9999	640.7	<0.0001	3196.3	<0.0001
2002	556	0.7397	376.4	0.0013	412.2	593.1	35.4	0.9856	838.5	<0.0001	3140.6	<0.0001
2003	356.4	0.0086	293.9	<0.0001	411	218.4	16.5	<0.0001	420.1	<0.0001	2003.3	<0.0001
2004	421.7	0.0149	424.9	<0.0001	394.9	743.7	43.5	0.9999	796.1	<0.0001	3081.7	<0.0001
2005	231	0.0001	341.3	0.0052	349.6	448.2	31.6	0.7842	464	<0.0001	2140.7	<0.0001
2006	275.6	0.0236	418.2	0.1736	583.3	804.3	62.9	0.9998	544.7	0.0001	2951.0	0.0017
2007	364.2	0.0023	318.7	0.0005	305.4	598.1	37	0.9815	540	<0.0001	2422.3	<0.0001
2008	535.8	0.6439	400.1	<0.0001	305	570.3	34.7	>0.9999	627.7	<0.0001	2854.6	<0.0001

Notes: [1]Target is Saginaw Bay (ISB + OSB). [2]Target is Main Lake Huron (NH + SH).

upstream lakes. These modeled estimates are based on measured flow between the lakes and observed in-lake concentrations and more accurately capture changes in interlake loading that have occurred over time.

Approximate two-sided confidence intervals for the true total loading to the Great Lakes can be estimated by applying the procedure described in Rathke and McCrae (1989). Briefly, this involves estimating the total lake standard error as the square root of the sum of all of the variances (or mean-square-errors) associated with each source type. This assumes no covariance among the source types. For unmonitored areas, these variances are weighted by the ratio of the square of the unmonitored area to the square of the monitored area.

Table 10
Segmented TP loading (MTA) summary for the lower Great Lakes and probability of exceedance of target loads. The Total Erie and Ontario loads include the inflows from lakes Huron and Erie, respectively. See Fig. 1 for segment delimitations. Target Loads are 11,000 and 7000 MTA, for Total Lake Erie and Total Lake Ontario, respectively (see Table 1). Total loadings that exceed the IJC targets have been highlighted.

Year	Segment WE	Segment CE	Segment EE	Total Erie	Probability target load exceeded	Basin Ontario	Total Ontario	Probability target load exceeded	St. Lawrence outflow
1994	4140.0	1883.0	635.0	7159	<0.0001	2730.7	4130.7	<0.0001	1953
1995	3819.0	2248.0	622.0	7171	<0.0001	2655.2	3769.2	<0.0001	1538
1996	6671.0	2710.0	1124.0	11011	0.5090	5249.0	6602.0	0.1609	1653
1997	9588.0	3220.0	2966.0	16334	>0.9999	3150.4	5643.4	<0.0001	1862
1998	8037.0	2973.0	621.0	12159	0.9698	4252.8	6470.8	0.2798	1892
1999	3931.0	1198.0	397.0	5961	<0.0001	2477.4	3765.4	<0.0001	1482
2000	4519.0	1951.0	908.0	7784	<0.0001	3008.9	4002.9	<0.0001	1311
2001	4415.0	1069.0	768.0	6650	<0.0001	2798.2	3748.2	<0.0001	1178
2002	5967.0	1871.0	815.0	9059	0.0002	3730.7	4734.7	<0.0001	1234
2003	4103.2	2610.4	890.1	7969.7	<0.0001	3535.6	4658.6	<0.0001	1243
2004	4643.1	2 798.5	1126.5	8932.1	<0.0001	3657.5	4929.5	<0.0001	1369
2005	5287.2	2764.7	834.7	9240.6	<0.0001	3038.3	4350.3	<0.0001	1376
2006	5158.7	2445.7	867.1	8806.5	<0.0001	3547.1	4826.1	<0.0001	1354
2007	6778.0	3723.4	1082.2	11908.6	0.9961	4097.8	5504.8	0.0007	1392
2008	6368.0	2887.7	1097.8	10674.5	0.0589	3268.1	4841.1	<0.0001	1469

Table 11
Results of linear fit of loading data (MTA) versus time for the period from 1980 through 2008 for each of the Great Lakes. The parenthetical percentages in the last column are coefficients of variation computed as the ratio of the standard error of the estimate (SEE) to the mean of the data.

Lake	Intercept 1980	Projection 2010	Decrease	Rate	R^2	Slope *p*-value	SEE (c.v.)
Superior	3062	3043	19	−0.6	2.1×10^{-5}	0.9810	1190 (39%)
Michigan	3972	3310	662	−22.1	0.074	0.1543	678 (18.6%)
Huron	4235	2524	1711	−57.0	0.307	0.0018	742 (22%)
Erie	10,999	8874	2125	−70.8	0.061	0.1979	2418 (24.3%)
Ontario	6879	4497	2382	−79.4	0.255	0.0052	1176 (20.7%)

Segment loading

Various computer programs have been written in SAS, Access, and FORTRAN to prepare the data for the load estimation process, estimate the load from individual and area sources, and summarize the resulting loads by type and geographic segment (Dolan, unpublished). This software permits the breakdown of the load estimates in virtually any configuration (e.g., country, jurisdiction, source, segment, etc.). The tables below have been generated in this manner. Also, the annual loads on a segment basis (Chapra and Dolan, 2012; Maccoux, 2010; Schmitt Marquez, 2010) have been tabulated with these programs. Fig. 1 delimits the segments used in this paper.

Probability of exceedance of loading targets

The target loads in Table 1 were established on a whole lake basis, except for Lake Huron which was broken down into the major embayments and Main Lake Huron. The loading reported in the tables below can therefore be compared to targets on a whole lake or embayment basis. In order to incorporate the uncertainty of the estimates into these comparisons, the probability that the target was exceeded in a given year was calculated. Briefly, this probability is the *p*-value of a one-sided test of the hypothesis that the load exceeded the target vs. the alternative that the load did not exceed the target. The more spatially detailed targets for Lake Huron were compared to the targets by combining the appropriate segments from Fig. 1 (i.e., Saginaw Bay = ISB + OSB; Main Lake Huron = NH + SH).

Linear trend analysis

Linear regression was used to fit the following model to the total lake loadings (including connecting channels) for the loading data for the period from 1980 through 2008,

$$W(t) = b_0 + b_1 * (t-1980) \tag{2}$$

where $W(t)$ = the annual loading for time t (MTA), t = time (year), b_0 is the intercept, and b_1 is the rate of change or slope of best-fit line (MTA/year). This model can be used to assess the goodness of fit and observational variability based on several statistics including R^2, slope *p*-value, and the standard error. In addition, the model provides a useful means to extract the long-term loading trends from the interannual variability.

Results

Point source loadings

Direct and indirect municipal point sources of TP to the Great Lakes have been estimated (Table 2). Direct sources are facilities that have effluents discharging directly to the lakes (including Lake St. Clair), the connecting channels (St. Mary's, St. Clair, Detroit, and Niagara Rivers) or to unmonitored areas. Indirect sources are facilities that have effluents discharging to monitored areas of tributaries and are not used in computing the total load. The attribution of point sources to direct or indirect load fluctuates from year to year depending on the degree of

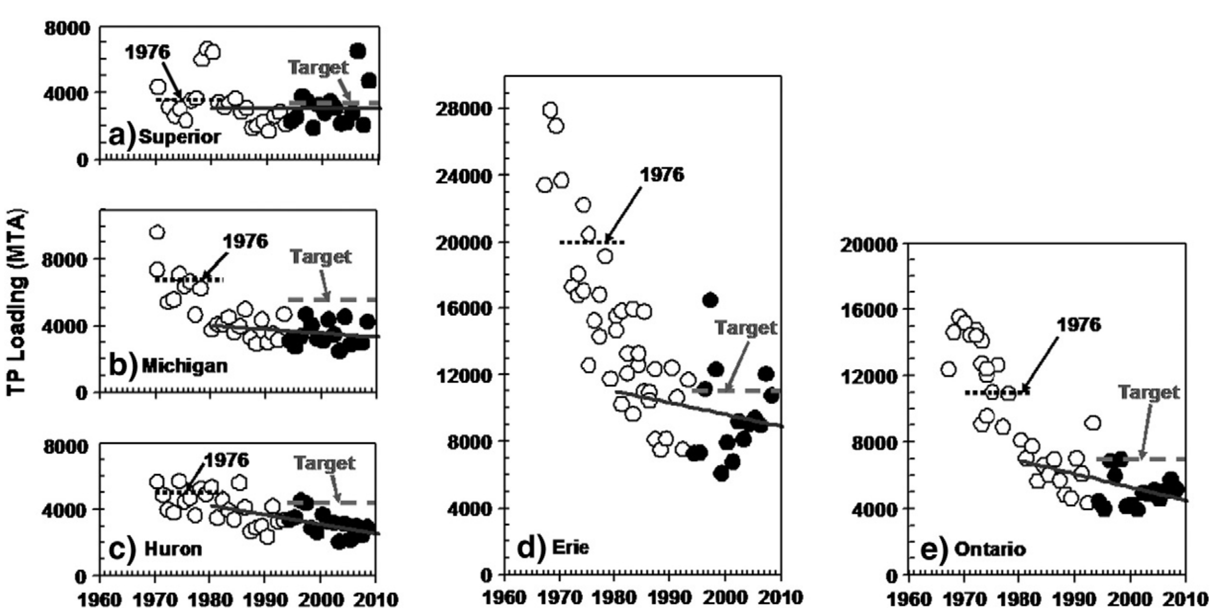

Fig. 2. Time series of TP loading (MTA is metric tonnes per annum) for each of the five Great Lakes (a–e). The filled points are new estimates reported in this paper. The open points are data compiled previously. The dotted lines are the 1976 loadings assumed by IJC and the dashed lines are the IJC target loadings. The solid lines are the trends from Table 11.

tributary monitoring in a particular lake basin. If a tributary is unmonitored in a given year, all of its point sources are treated as direct for that year.

The total municipal point-source load to each lake has been fairly constant during the study period. Lake Superior has the smallest municipal contribution at an average of 86 MTA and Lake Erie has the largest at 1902 MTA (Table 2) with municipal sewage treatment plant sources comprising most (95% or more) of the point-source load. Table 3 contains the industrial point-source load estimates.

Tributary loading

Total phosphorus loadings from tributaries were much more variable than point-source loadings for the period 1994–2008 (Table 4). The combined contribution of monitored and unmonitored tributary loadings varied from a minimum of 907 MTA in 1998 for Lake Superior, the watershed of which is dominated by forests, to a maximum of 13,453 MTA in 1997 for the largely agricultural Lake Erie watershed. The inter-annual variation in tributary loadings seen in Table 4 was due mainly to differences in rainfall and hence tributary flow among years. 1996 and 1997 stand out in the table and were particularly wet years, while 1999 was a notably dry year. Also, the unmonitored contribution to total tributary loadings varied from about 20% in Lake Michigan to 58% in Lake Superior on average. This, in turn, contributes to increased uncertainty in the estimates.

Atmospheric loading

The atmospheric TP loads to the surface of the Great Lakes were more variable than point sources but less variable than tributary loadings (Table 5). Atmospheric loadings ranged from 171 MTA in 1998 for Lake Ontario to 1419 MTA in 2002 for Lake Superior. Atmospheric loadings usually comprised <15% of the total TP budget, except for Lake Superior which was substantially higher (about 28% on average). This is primarily due to Lake Superior's large surface area relative to its small total loading.

Interlake loading

Due primarily to decreasing TP concentration in lake waters, the interlake loadings from the upstream lakes have declined steadily during the study period (Table 5). Therefore this component of the load represents a smaller and smaller contribution to the total lake load. However, as in the past, the load from Lake Erie still represents a significant portion of Lake Ontario's total loading. Based on 5-year moving averages, the Lake Erie contribution to Lake Ontario currently stands at about 27% as compared to about 32% in the mid-1990s.

Standard errors for the total input to the Great Lakes

Standard errors for the total load to each lake have been estimated (Table 6) as the square root of the sum of the mean-square-errors of the individual loading components as described in Rathke and McCrae (1989). The standard errors vary from 1.5 to 19% of the total lake load depending on the lake and the year. Lake Superior typically has larger standard errors (9.1% of the load, on average), while Lake Erie has some of the smallest estimates (3.5% of the load, on average). Approximate confidence limits (one or two-sided) can be estimated for the total Great Lakes TP load. The margin of error or half-width of these confidence intervals will vary depending on the degree of confidence desired, the effective sample size, and the standard error. Although not reported here, the tributary standard error usually dominates the estimated variability of the total load (Rathke and McCrae, 1989), so it is reasonable to use a sample size based on the dominant tributaries in each lake for determining the degrees of freedom in the margin of error estimate.

Segment loading

Breakdowns of Great Lakes TP loading estimates by segment or sub-basin (e.g., western, central, and eastern Erie) are presented in Tables 7–10. Lake Ontario has not been segmented for this work. As depicted in Fig. 1, lakes Superior, Michigan and Huron have been segmented to better account for the influences of major embayments (i.e., Whitefish Bay, Green Bay, North Channel, Saginaw Bay, and Georgian Bay). For Lake Erie, the western-basin loading includes everything upstream to the lake as far as the head of the St. Clair River. The approximate boundary of the western and central basins is Point Pelee and the Lake Erie islands. The approximate boundary of the central and eastern basins is Long Point and Erie, Pennsylvania.

Time-series of the whole-lake TP loadings are presented in Fig. 2. Along with the new loading estimates reported in this paper, we have also included previous estimates in order to provide historical context for assessing the changes that have occurred over the past 40 years. In addition, we have included the trend line developed with linear least-squares regression (Table 11) for the 1980–2008 data. The following provides a summary of how the time-series for each lake compare with the target levels. This is followed by a brief discussion of the linear trend analysis.

Lake Superior

For Lake Superior, the target load of 3400 MTA has been exceeded in about five of the last 15 years (see Tables 6 and 7). In 1996 and 1997, the exceedances were due mainly to high rainfall in the basin. In 2006 and 2008, the unmonitored area load dominated other sources and caused significantly greater load estimates. In 2001, the target was exceeded by only 56 metric tonnes and the marginal nature of this result is reflected by the lower probability in Table 7.

Lake Michigan

For Lake Michigan, the target load of 5600 MTA has been met consistently since 1981 (but see Anstead et al., 2005). The target load has been questioned because the atmospheric loading component (based on bulk sampling) used to set it was later replaced by wet-only sampling that resulted in substantially lower loads. The highest total load occurred in 1997, but comparable loads were also estimated in 1998, 2001, 2004, and 2008 (see Tables 6 and 8). None of these loads approach the target as indicated by the extremely low probabilities in Table 8. If the target load had been set lower (e.g., 4000 MTA), these years would have been notable exceedances.

Lake Huron

For Lake Huron, the target load of 4360 MTA has been exceeded only once since 1994 (see Table 6). This exceedance occurred in 1996, again due to high rainfall in the basin. The situation is just the opposite for Saginaw Bay. The target load of 440 MTA has been met only once (2003) during the study period (see Table 9). This is consistent with De Pinto et al. (2006). Main Lake Huron never exceeded its target load during the study period, although the major embayments (besides Saginaw Bay) occasionally exceeded their targets (Table 9).

Lake Erie

For Lake Erie, the target load of 11,000 MTA has been exceeded four times (1996–1998 and 2007) in the last 15 years (see Tables 6 and 10). The late nineties "pulse" was due to the reinforcing interaction between flow and concentration for the period 1996–1998 (Dolan and Richards, 2008). The 2007 exceedance was due partly to high rainfall and partly to agricultural practices in the basin (Pete Richards, personal communication, EcoFore, 2011).

Lake Ontario

For Lake Ontario, the target load of 7000 MTA has not been exceeded in the last 15 years (see Table 6). However, the load estimates in 1996 and 1998 years were not significantly different (see Table 10) than the target of 7000 MTA and were elevated due in part to high inputs from Lake Erie.

Linear trend analysis

Table 11 provides a summary of statistics and projections based on fitting a straight line (Eq. (2)) to the total lake loadings for the loading data for the period from 1980 through 2008. The linear trends are also superimposed on Fig. 2. For reference, the endpoints of the trend line (1980 intercept and 2010 projection) and the resulting decrease have been included in the table. As might be expected, all the lakes with the exception of Lake Superior exhibit some downward tendency. However, as is evident from the plots as well as the standard errors, the interannual variability is considerable amounting to approximately 20–40%. As noted previously, the high uncertainty associated with Lake Superior is related to the contributions from large unmonitored tributaries. Consequently, despite the fact that we have about three decades of systematically-compiled loading data, only lakes Huron and Ontario exhibit statistically-significant linear trends with weaker trends for lakes Michigan and Erie and no trend for Lake Superior. Inspection of Fig. 2 suggests that initial declines were occurring in most of the lakes and that the trend slowed or reversed in later years. This would explain the relatively poor fit of the simple linear model. Dolan and McGunagle (2005) reported a "break" or point of intersection for the Lake Erie trend at 1991. This was the year that the statistically significant linear trend for previous years ended and a non-significant trend for subsequent years was estimated. A similar analysis for the other lakes was attempted, but no single breakpoint was detected.

Discussion

Dolan and McGunagle (2005) have described the history of Great Lakes total phosphorus load reporting and the rational for continued effort on this aspect of the GLWQA. By the time this paper appears in print, these loads will once again be out of date. Hopefully, the next update will appear sooner than this one. Given the effort required to collect the various sources of information, as well as changing funding priorities, it is reasonable to expect an update such as this one every two or three years. Naturally, the full loading picture can only be reported at the pace of the slowest component, but if researchers and managers come to expect this kind of reporting, data should become available on a quicker basis.

The standard errors reported in Table 6 are indicative of the sampling effort allocated to the various lakes. Because point sources and atmospheric fluxes usually have the same sample size (i.e., $n=12$), the main factor influencing these standard errors is the tributary sampling frequency. Lake Superior typically has some of the lowest samples sizes (e.g., $n=4$), while the major tributaries to Lake Erie (Maumee, Sandusky, and Cuyahoga) often have sampling frequencies greater than daily (i.e., $n>365$). This, in turn, is probably driven by the need for more monitoring information in problem areas.

Previous load estimation efforts (e.g., Rathke and McCrae, 1989) did not always provide the level of detail required by users of the estimates. Now, these details can be shared (via the Internet and databases such as Access) with those who wish to incorporate GIS into their analyses or work with subsets of the loads. These estimates can be used by modelers who wish to include more spatial detail in mass balance (Chapra and Dolan, 2012) or ecosystem (e.g., Pauer et al., 2011; Rucinski et al., 2010; Schwab et al., 2009) models. They can also be used to make inferences about the geographical nature of the loading trends. For example, most (~75%) of the Lake Erie loading in any given year comes from the western basin (see Table 10). Mida et al. (2010) used these estimates to partition loadings to Southern Lake Michigan into East and West loadings.

As noted above, readers are encouraged to use these results and those available in the Supplementary Information (S1 to S14) to conduct their own analyses of Great Lakes total phosphorus issues. A major result of the work reported here is the updating of the mass balance models used in the second part of this paper (Chapra and Dolan, 2012). Numerous other questions will occur to readers as they examine the tables and graphs presented here. Many of these cannot be fully explored in this paper and may warrant detailed investigation. For example, Lake Erie loads are usually below the target, yet the lake routinely experiences harmful algal blooms and continued anoxic conditions. Does this mean that the 11,000 MTA target was set too high? Is there internal loading? Or perhaps, does this imply that, in addition to TP, it might be important to measure loadings of phosphorus species (e.g., dissolved and particulate P)? These are ongoing research questions that the results in this paper can contribute to but cannot provide the complete answer for. Another example can be found by examining Tables 2 and 3. Point source loadings are more or less constant for the study period. Does this mean that Best Available Technology (BAT) has been implemented and that no further significant reductions can be gained from the point source sector? Dolan (1993) addressed this issue for Lake Erie for 1986–1990. An updated analysis may be appropriate for all of the lakes.

Conclusions

The questions regarding the TP loading status of each of the Great Lakes and Saginaw Bay have been addressed. In terms of frequency of meeting target loads, the lakes can be ranked as follows: Michigan, Huron, Ontario, Erie, and Superior. Lake Michigan may have a target load that is too high as Anstead et al. (2005) have noted. Lake Superior has the least monitoring of all the lakes and hence the highest measurement uncertainty. Saginaw Bay has a relatively low target load based on taste and odor in the drinking water supply and its continued water quality problems (Environment Canada and US Environmental Protection Agency, 2007) are consistent with the record of exceedances (14 out of 15 years).

Given the state of water quality monitoring in 2008, lake-wide annual estimates of TP are feasible. High-quality data are still available to allow reasonable estimates of total phosphorus to the Great Lakes. Recent concern about lakewide changes in trophic status as well as the recurrence of local and regional water-quality problems should be ample justification for renewed monitoring efforts.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.jglr.2012.10.001.

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