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Review

A one hundred year review of the socioeconomic and ecological systems of Lake St. Clair, North America

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ABSTRACT

There is a growing concern about continued impairment of aquatic ecosystems resulting from increasing population size, land use, climate change, and the feedbacks that may harm human well-being. We describe a 100 year multi-disciplinary overview of changes in Lake St. Clair, North America to identify knowledge gaps and needs to build the foundation for creating coupled human and natural system models. Our historical analysis indicates that the socioeconomic dynamics are inextricably linked to the urban dynamics of the Detroit metropolitan area. Environmental degradation and human health issues led to the adoption of relevant policies, including construction of wastewater treatment facilities by the 1960s. Climate trends during the 100-year period indicate a wetter region, which is influencing lake levels. Since the mid-1980s and 90s invasive zebra and quagga mussels (*Dreissena polymorpha* and *Dreissena rostriformis bugenis*) have significantly altered the ecological structure and function of the lake. Waterborne illnesses due to contaminated drinking water were once an issue but current human health risks have shifted to contaminated recreational waters and coastal pollution. Key research needs for building coupled models include geo-referencing socioeconomic and ecological data to accurately represent the processes occurring within the political and watershed boundaries; assessing ecosystem services for human well-being; and developing research hypotheses and management options regarding interactions among land use, people and the lake. Lake St. Clair has gone through extensive changes, both socioeconomically and ecologically over the last 100 years and we suggest that it serves as a useful case study for the larger Great Lakes region.

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Introduction

The Laurentian Great Lakes region has a legacy of over 100 years of water quality science and policy. The history of impairment and management in the Great Lakes can be instructive as we consider the future challenges of climate change and sustainability in freshwater ecosystems. The Great Lakes region serves as an excellent case study for interdisciplinary research on water quality by bringing together a diverse group of scientists and stakeholders. Many scientists, stakeholders and government agencies are already involved in research and management of the Great Lakes, and one benefit of the multitude of programs is the rich and ever-growing data sets on a variety of physical, chemical, biological and socioeconomic indicators. However, the basin suffers from organizational fragmentation and lack of coordination among programs which can be a significant obstacle to synthesis and integration in support of environmental protection and restoration (US Government Accountability Office, 2003). The Laurentian Great Lakes and their connecting channels provide essential ecosystem services to citizens in the basin, such as providing a source of drinking water (U.S. Army Corps of Engineers, 2004b), a sport fishery (Gewurtz et al., 2007; Leach, 1991), recreational uses of beaches (Song et al., 2010), and shipping and transportation (Great Lakes Commission, 2006). The basin is also threatened by stressors common across the globe, such as land use change, pollution from human activities and their interactions with climate change (Allan et al., 2012). In light of these challenges, there is a need to synthesize and integrate available data in ways that advance scientific understanding and provide useful information for managers, decision-makers, and the public.

One approach to synthesizing data is to use the coupled human and natural systems (CHANS) framework that requires scientists to move beyond the methodological barriers of their discipline and develop integrative frameworks and models for analysis of environmental issues (An and López-Carr, 2012; Kotchen and Young, 2007; Liu et al., 2007). At an operational level, the CHANS approach links sub-models of human and natural systems and identifies the key parameters, interactions and feedbacks to develop better policies for tackling environmental issues with respect to sustainability (Carpenter et al., 2009). Defining sustainability remains a controversial issue among and within the various academic disciplines (Neumayer, 2010), and we support the notion that attaining sustainability requires the maintenance of functions and processes of natural systems that provide society with goods and services (e.g. natural resources, human health) (Bithas, 2008; Bithas and Nikjamp, 2006; Ekins et al., 2003).

A challenge to CHANS models is that natural and social sciences, having mainly worked in isolation in the past, use different scales of analysis to approach many environmental issues (Cumming et al., 2006; Ostrom, 2009; Pickett et al., 2005). The CHANS framework, with linkages between socioeconomic and ecological systems, has been used extensively in the last decade to better understand specific case studies (Haynie and Pfeiffer, 2012; Hopkins et al., 2012; Hufnagl-Eichiner et al., 2011; Liu et al., 2007). Liu et al. (2007) presented five case studies within the CHANS framework and highlighted the ability of integrated studies to capture systems dimensions that were previously not well understood. For example, in Wisconsin, ecological condition of lakes attracts tourism but economic development and touristic activities impact the ecological condition and in turn the attractiveness of the area. A study about the social–ecological coupling between agriculture in the Mississippi River Basin and hypoxia in the northern Gulf of Mexico found a mismatch between where the highest nutrient runoff occurs and the investment of socioeconomic resources that would help reduce hypoxia (Hufnagl-Eichiner et al., 2011). The usefulness of thinking in terms of systems' couplings has also inspired the development of a systems approach to define sustainable patterns of socioeconomic development for eighteen coastal systems in the European region (Hopkins et al., 2012).

Long-term data sets and historical analyses are needed to identify key components and couplings among humans and ecological systems to plan for sustainability (Carpenter et al., 2009; Swetnam et al., 1999). We explored data on climate, human population dynamics, land use, lake ecology and human health over Lake St. Clair's past 100 years (1900–2010). We mainly focused on the USA side because of the higher human population density and the available data, but we recognize that Canada's activities and policies are also important for this ecosystem. Our goal was to use the CHANS approach to identify data, research needs and to set the stage for further assessment (e.g. feedbacks, time lags, surprises, sensu Liu et al., 2007) on how the socioeconomic system and the aquatic ecosystem have interacted and changed through time.

Methods

The study system

Lake St. Clair (LSC), a shallow transboundary system in the Laurentian Great Lakes (Leach, 1991) (Fig. 1), connects Lakes Huron and Erie via the St. Clair River to the north and the Detroit River to the south. It is part of the Huron-Erie corridor. Lake St. Clair may seem small compared to the other Great Lakes, but it is the 11th largest lake in surface area in the continental USA (Herdendorf, 1982; Hunter and Simons, 2004). It also has about 1000 km of shoreline perimeter (Fig. 1). The LSC connecting channel contains three Areas of Concern as listed by the Great Lakes Water Quality Agreement, which are located in the St. Clair River, the Detroit River, and the Clinton River with a portion of the western lake shoreline (United States Environmental Protection Agency, access date 2 April 2012, http://www.epa.gov/glnpo/aoc/).

The aggregate area of the local watersheds that drain to LSC (excluding the watershed of Lake Huron and other upper Great Lakes) is 15,305 km^2, with 59% of this area (8988 km^2) on the Canadian side, and the remainder (6317 km^2) on the USA side (Fig. 1). The USA and Canadian portions of the LSC watershed differ greatly in terms of land use according to recent satellite-derived land cover data. On the USA

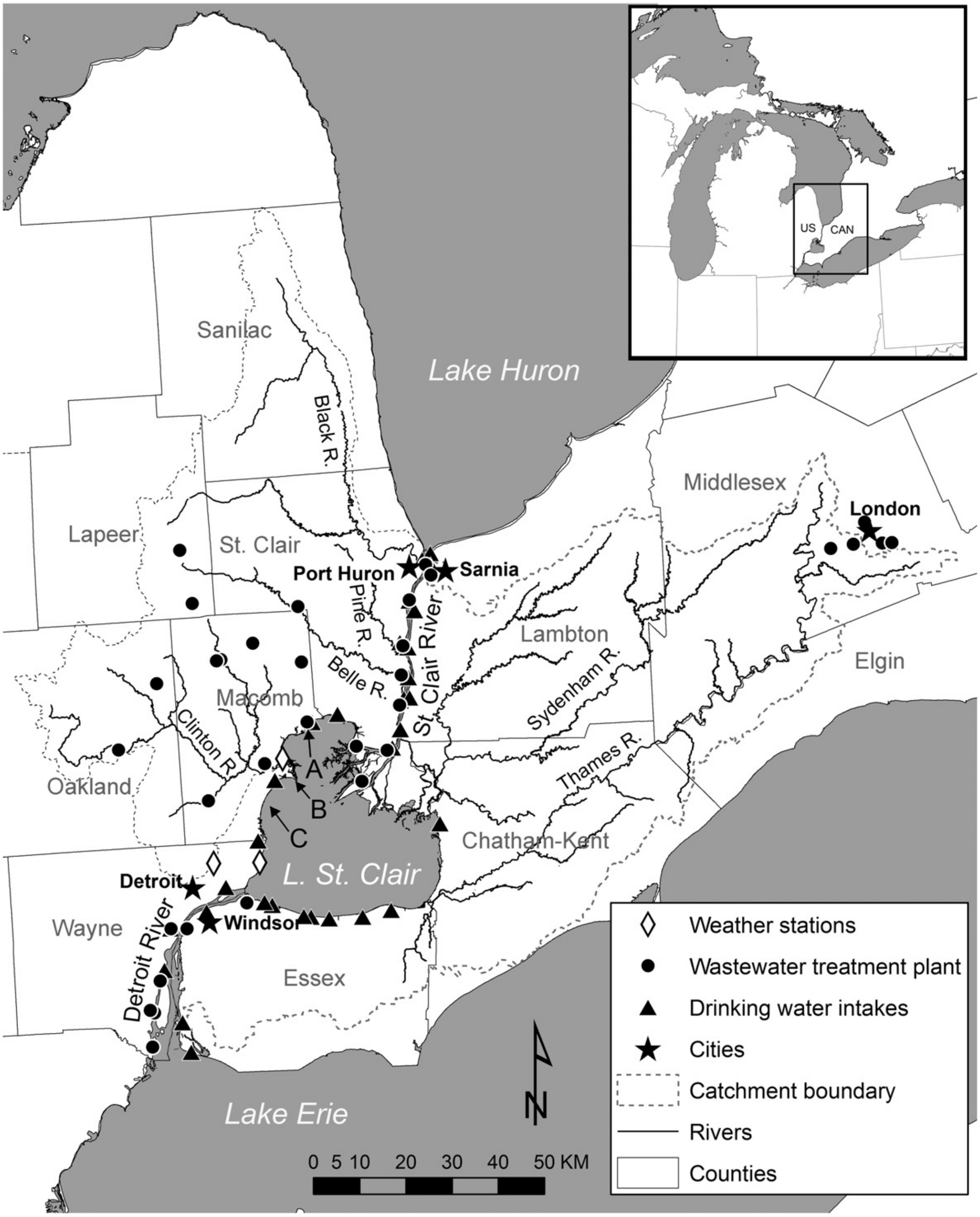

Fig. 1. Watershed of Lake St. Clair (dashed line), including the cities, counties, rivers, and key water infrastructure (drinking water intakes and treatment plants, and wastewater treatment plants) in the USA and Canada. Beaches along the western shore of Lake St. Clair are labeled as (A) New Baltimore Park Beach (B) Metropark Beach (Huron Clinton Metro Authority), and (C) St. Clair Shores Memorial Park Beach.

side in the year 2006, agricultural land use comprised 41% of the watershed and 32% percent was developed (Fry et al., 2011). In Canada as of 2000, land use in the watershed was dominated by agriculture (77%) with 5% cover each in forest and developed land (Agriculture and Agri-Food Canada, access date 8 April 2012, ftp://ftp.agr.gc.ca/pub/outgoing/aesb-eos-gg/LCV_CA_AAFC_30M_2000_V12). It is not likely that land cover change in the short interval between 2000 and 2006 changed these percentages appreciably. The majority of the watershed is located within five counties on each side of the border (Fig. 1). Besides the St. Clair River, the other rivers that drain into the lake include the Black, Belle and Clinton Rivers in Michigan and the Thames and Sydenham Rivers in Ontario. The largest portion of water entering the lake (98%) comes from the St. Clair River, which supports the largest freshwater delta in the Great Lakes system (Herdendorf, 1993), the St. Clair Flats which contains about 170 km^2 of wetlands (Edsall et al., 1988).

Constructing the Lake St. Clair Chronology: 1900–2010

We used primary literature, state and federal governmental reports and websites as well as state and federal governmental data sources to compile our overview and to conduct new analyses about the characteristics of the lake and its watershed. Additional details on the methodology can be found in the Online supplementary materials (S1).

Climate data were gathered from multiple sources (Assel, 2003; Hunter and Croley, 1993; International Great Lakes Datum, 1985; Quinn and Norton, 1982) as well as from weather stations from the NOAA National Climatic Data Center (see Fig. 1 and S1) and Hunter and Croley (1993), which has been continuously updated online since the original publication date (http://www.glerl.noaa.gov/data/arc/hydro/mnth-hydro.html). Relationships between variables were analyzed with Pearson's correlation and linear regression, all with alpha = 0.05 level.

Land use, population, employment, income and households were used as indicators to represent direct and indirect drivers of change induced by human activities and to better understand the economic status of the human population. While we are aware of the differences between the political and watershed boundaries, our analysis of the socioeconomic system is based on the data obtained at the county level. We also obtained historical data from the Detroit metropolitan area on the USA side because it is a significant driver of change and provides a comparison to the other counties within the LSC watershed.

Estimates of the area of the watershed and the land use characteristics were obtained from land use classifications produced by Agriculture and Agri-Food Canada (date of access 8 April 2012, ftp://ftp.agr.gc.ca/pub/outgoing/aesb-eos-gg/LCV_CA_AAFC_30M_2000_V12) and the US Multi-Resolution Land Characteristics Consortium (Fry et al., 2011). Because there were little land use data readily available in 1900, we used a USGS image (United States Geological Survey, access date 31 January 2013, http://www.epa.gov/med/grosseile_site/indicators/landuse.html) of the Detroit metropolitan area to display snapshots of developed land use from 1905, 1938, 1968, and 2001.

Socioeconomic data (human population, households, water and waste water infrastructure, employment and income data) were gathered from USA sources: US Census Bureau (census data accessed 2 May 2012, http://www.census.gov/prod/www/abs/decennial/index.html), Southeast Michigan Council of Governments (SEMCOG, 2002), Camp Dresser and McKee (2003), CH2M HILL (2003), City of Detroit (1959), Detroit Water Service (1966), Morrill (1939), SEMCOG (1971, 2001), St. Clair Regional Planning Commission (1960, 1969), State of Michigan (1966), Tetra Tech MPS (2003), Michigan Department of Environmental Quality (access data 11 April 2012, http://www.deq.state.mi.us/owis/Page/main/Home.aspx), and Drinking Water Protection Network (access date 11 April 2012, www.rwqims.com) and from Canadian sources: Ontario Department of Economics and Development (1967), Statistics Canada (date of access, 10 July 2012, http://www12.statcan.gc.ca/census-recensement/2011/dp-pd/prof/index.cfm?Lang=E&TABID=1#tab1 and http://www.statcan.gc.ca/start-debut-eng.html), Ontario Ministry of the Environment (date of access 11 April 2012 http://www.ene.gov.on.ca/environment/en/resources/collection/data_downloads/index.htm), and Environment Canada (access date 10 July 2012, http://www.ec.gc.ca/inrp-npri/default.asp?lang=en&n=F8D54254-1).

There is a gap in scientific knowledge from about 1900 to 1972 regarding the ecological condition of Lake St. Clair as noted in earlier studies of Leach (1972) and Monheimer (1975). Nutrient concentration data (from 1998 to 2008) were collected near the mouth of St. Clair River (station 740016, 42.6494°N, −82.5133°W) by the Michigan Department of Environmental Quality. Ecological data were gathered from peer-reviewed literature and from state and federal agency reports with some sources providing electronic data (Bell, 1980; Cavaletto et al., 2003; David et al., 2009; Hiltunen, 1971; Leach, 1972; Michigan Department of Natural Resources, 1981; Michigan Water Resources Commission, 1975; Monheimer, 1975; Nalepa and Gauvin, 1988; Nalepa et al., 1996; Reighard, 1894; Upper Great Lakes Connecting Channel Management Committee, 1988). These data were chosen because the sites were located near the middle of the lake (see S1) and provide estimates of the changes in the native mussel species richness, total phosphorus concentrations, chlorophyll *a* concentrations, and transparency depth (via Secchi disk depth) which are useful indicators of the water quality condition of the lake over time. Commercial fish harvest data (thousands of pounds converted to kilograms) were found online from Baldwin et al. (2009) (access date 18 December 2012, http://www.glfc.org/databases/commercial/commerc.php) and the available grand totals (USA + Canada) were used.

Historic typhoid fever statistics were found online through the state's website on vital statistics (Michigan Department of Community Health, access date 2 April 2012 http://www.michigan.gov/mdch/0,4612,7-132-2944_4669—,00.html). Historically, key beaches and other water bodies along the western lakeshore were monitored for bacterial indicators (which are found in the intestines of all warm blooded animals) in swimmable waters by Macomb County Health Department to protect human health. These historic beach data were digitized and analyzed based on records from the Macomb County Health Department (1948–1998) and more recent data were downloaded from the Michigan Beach Guard online database (http://www.deq.state.mi.us/beach/). Beach violation standards have changed overtime from single sample standards of 5000 CFU/100 mL for total coliform (prior to 1981), to geometric mean 400 CFU/100 mL for fecal coliform (1981 to 1996) and then to a daily geometric mean of 300 CFU/100 mL and a monthly geometric mean of 130 CFU/100 mL for *Escherichia coli* (1996 to current). Because indicators and sampling methods have changed over time, data were normalized to *E. coli* (CFU/100 mL) from the 1950s to 2010 for three selected beaches on the western shore of LSC: HCMA (Huron Clinton Metro Authority) Metropark Beach, New Baltimore Beach, and Memorial Park Beach in Macomb County, MI (for details see S1). A trend line for the entire period of record was calculated using the negative exponential smoothing algorithm in SPSS SigmaPlot. We calculated violations as the percentage of all samples collected during a single beach season that exceeded the relevant water quality standard for the time period.

Results and discussion

We constructed a time-table based on the collected data and literature sources of the key events in the socioeconomic and ecological systems, and assigned each event to one of the following categories: ecology, policy/governance, water infrastructure, human health, economics, human population, or climate (Table 1). Below we describe the findings for larger subsystems of the LSC area, including the climate, socioeconomic, and ecological systems.

Changes in the Lake St. Clair systems: past 100 years

Changes in climate

Lake St. Clair lies in a moist continental climate zone with cool summers and severe winters according to the Koppen climate classification (Kottek et al., 2006) (Fig. 2). Lake levels vary seasonally, with highest levels in June and lowest in January. In the 30-year period of 1972 to 2002, the lake was partially or completely covered by ice from November to the following April, and on average about 83% of the lake had ice cover during January (Fig. 2).

There was a significant interannual variability in winter precipitation and air temperature, and hence in lake level and ice cover (Fig. 2). The winter of 1998–1999 had the highest air temperature and the lowest ice cover. Because March is the major melting period of lake ice, ice cover in March shows the greatest variation between years, with some years experiencing >80% ice cover and other years experiencing <1% ice cover.

There have been long-term changes in temperature, precipitation, lake levels and ice cover over the past 100 years (Fig. 2). Monthly air temperature has been gradually increasing in the last 60 years ($p < 0.001$). The lake temperature in May has shown significant increase since 1948 ($p < 0.001$). Using Great Lakes monthly hydrological data, the

Table 1

Time line of important events by period, date, and category (E = ecology, P = policy/governance, W = water infrastructure, H = human health, Ec = economic, Po = population, and C = climate) that influenced Lake St. Clair and the surrounding region. References: 1 = Edsall et al. (1988), 2 = Leach (1991), 3 = United States Environmental Protection Agency (access date 2 April 2012, http://www.epa.gov/glnpo/aoc/), 4 = Cutler and Miller (2004), 5 = Wolman and Gorman (1931), 6 = Upper Great Lakes Connecting Channel Management Committee (1988), 7 = Great Lakes Restoration Initiative (2010), 8 = Michigan Department of Public Health (1973), 9 = U.S. Army Corps of Engineers (2004a), 10 = State of Michigan (1966), 11 = Hebert et al. (1989), 12 = US Census Bureau (access date 2 May 2012, http://www.census.gov/prod/www/abs/decennial/index.html), 13 = Hunter and Croley (1993), 14 = Assel (2003), 15 = United States Environmental Protection Agency (access date 31 January 2013, http://cfpub.epa.gov/npdes/stormwater/munic.cfm), and 16 = Ontario Ministry of the Environment (access date 2 April 2012, http://www.ene.gov.on.ca/environment/en/resources/collection/data_downloads/index.htm).

Per	Date	Description	Cat	Ref
1	1908	From 1800s, MI commercial fishery of lake whitefish, lake herring, walleye and yellow perch	E	1,2
	1909	International Boundary Waters Treaty creates the International Joint Commission (IJC)	P	3
	1913	Detroit drinking water becomes chlorinated	W	4
	1923	Detroit drinking water becomes filtered	W	4
	1926	Detroit dysentery outbreak	H	5
2	1940	Detroit sewage becomes treated & chlorinated	W	4
	1940s	Organic pollutants and heavy metal contamination becomes concern	E	6
	1959	St. Lawrence Seaway opens to ocean-going vessels	Ec	7
	1963	30 year record of no reported typhoid cases related to public water supply in the state of MI	H	8
	1965	LSC ship channel enlarged and deepened	Ec	9
	1966	State of MI enacted grant program for pollution control programs	W	10
	1966	16 Wastewater Treatment Plants (WWTP) discharge (secondary treatment) into lake	W	10
	1970	Mercury discovered in LSC fish and fishery closed	P	2
3	1972	US Federal Water Pollution Control Act aka Clean Water Act (CWA)	P	3
	1972	National Pollutant Discharge Elimination System (NPDES)	P	3
	1972	Great Lakes Water Quality Agreement (GLWQA) between USA and Canada	Po	9
	1973	72% decline in wetland area since 1873 (Michigan side)	E	2
	1980	LSC fishery re-opened as quota basis	P	2
	1983	Amendment to the GLWQA -phosphorus abatement program	P	3
	1985	Earliest prediction of zebra mussel invasion in LSC	E	11
	1985	Development of the Areas of Concern (AOC) in the Great Lakes	P	9
	1987	Remedial Action Plans (RAPs) for designated AOCs	P	9
	1991	4 million people on USA side of LSC (half were in Wayne County)	Po	12
	1998	Record year: low ice cover, high water and air temperatures	C	13,14
	1999	Phase II Stormwater program —small communities require permits for discharge	P	15
	2000	Beaches Environmental Assessment and Coastal Health (BEACH) Act	P	15
	2006	Ontario Clean Water Act ratified for protection of drinking water	P	16
	2009	$475 million proposed to Great Lakes Restoration Initiative (GLRI)	P	7
	2010	Action Plan describes execution of GLRI (until 2014)	P	7

following significant trends for LSC have also emerged. Since 1900 the annual precipitation has increased by 0.03 mm yr^{-1} ($p < 0.05$). From 1910 to 2012, lake water levels in LSC have been generally increasing in all seasons ($p < 0.001$) with the higher rate of increase during the winter and spring seasons. The highest lake water level occurred in October 1986 and the lowest water level in February 1926, and the average annual rate of increase in lake level is 4.3 mm yr^{-1} ($p < 0.05$) over the period of record. But in the past two decades (1992–2012), the lake water level has been decreasing by 25.9 mm yr^{-1} ($p < 0.05$). On the annual scale, lake water level was correlated with precipitation with a one-year lag ($R = 0.44$). The lack of a stronger correlation is possibly due to dredging in the St. Clair River and the impacts on the connecting channel flows (Quinn, 1985). Ice cover during winter has been generally declining (Fig. 2). Between 1973 and 2002, the percentage of ice cover has decreased by 0.5% yr^{-1} ($p < 0.05$) in January and by 0.8% yr^{-1} ($p < 0.05$) in February. These changes in climate are likely to impact human well-being and their activities that take place in the watershed and shoreline as well as affecting the ecology of the lake, and thus climate change is a significant factor that directly and indirectly influences both the human and natural systems.

Changes in the socioeconomic system

Three main periods (1900–1940, 1941–1970, 1971–current) were observed in the socioeconomic system based on two main criteria. The first is based on the comparison of the average population and household growth rates between Wayne County and LSC counties that drove the land use changes and economic development. The second criterion concerns the existence of wastewater infrastructure and the level of sewage treatment.

Changes in land use and human dynamics. Prior to European settlement, the LSC watershed was occupied by a combination of beech–sugar maple forest, mixed hardwood swamp, oak savanna, and oak barrens (Comer et al., 1995). It is likely that some of these land cover types were present in 1900, when Detroit was a small settlement situated at the southernmost boundary of the LSC watershed (Fig. 3 top, black area). From 1905 to the peak of Detroit's human population around 1968, developed land in and around the city expanded primarily to the north and west by more than 800% from 190 to 1766 km^2. The area expanded again by three times between 1968 and 2001 to 5500 km^2. Developed land includes areas that have been converted for the purposes of housing, transportation, industry and commerce and tend to have high percentages of impervious surfaces (20–100%), in addition to patches of vegetation such as lawns, golf courses, and city parks.

Dramatic increases in urban and industrial land use were driven by a burgeoning population attracted to Detroit for employment (Fig. 3, bottom). During the first period (1900–1940), Detroit was transitioning to an industrial center and the population growth rate was highest in Wayne County in the early half of the 20th century (Fig. 3), corresponding to the rise of the automobile industry (United States Environmental Protection Agency, access date 20 June 2012, http://www.epa.gov/med/grosseile_site/indicators/landuse.html). The auto industry drew people to the city and also led to a transportation revolution where almost a million motor vehicles were registered to Michigan drivers by 1925 (US Department of Commerce, 1926). At the same time housing was built for those employed in the expanding industry. The Great Depression of 1929 reduced the growth rate of population (from 60% in 1930 to 6% in 1940) and the real median value of houses (Figs. 3, 4).

During the second period (1941–1970), industries and accompanying services (e.g. shops, restaurants) started to decentralize and move from the City of Detroit to the surrounding suburbs that include the counties of Macomb and Oakland. As a result, employment in the City of Detroit declined whereas it increased in the surrounding suburbs.

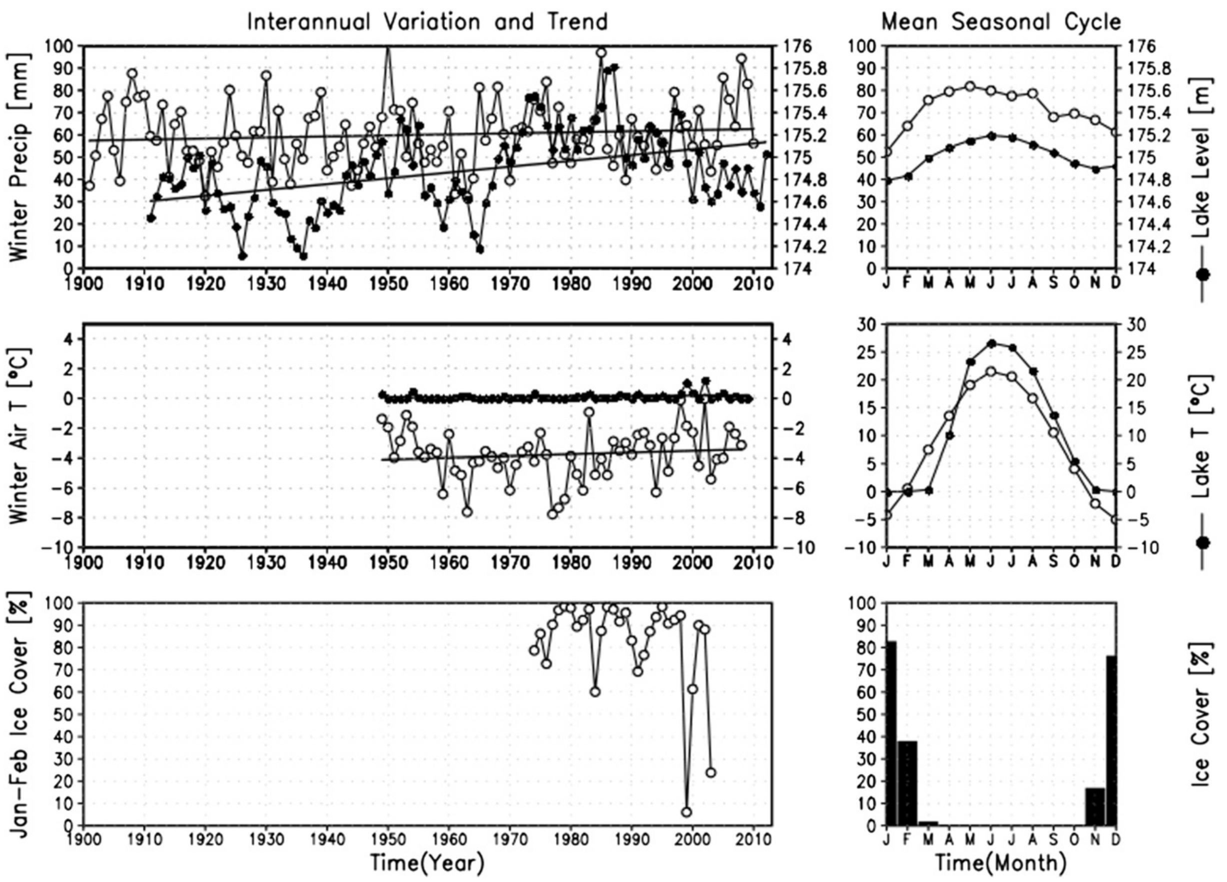

Fig. 2. Interannual variability of mean winter (Dec., Jan., Feb.) precipitation (open circles), mean winter lake level above mean sea level (closed circles, top-left panel), mean winter air (open circle) and mean winter water (closed circles) temperatures (middle-left panel) and mean January and February ice over (bottom-left panel) from 1900 to 2012 for Lake St. Clair, USA and Canada. Mean seasonal cycle (1900 to 2012) of monthly precipitation (open circles, top-right panel), lake level above mean sea level (closed circles, top-right panel), air (open circle) and water (closed circles) temperatures (middle-right panel) and ice cover (bottom-right panel).

This decentralization was facilitated by the construction of federally-subsidized interstate freeways, including Interstate 94 along the shoreline of LSC, which improved access and reduced travel time (Edsall et al., 1988; Surgue, 2005). Construction of housing units continued in each county, with the real median home value higher in Macomb and Oakland Counties compared to the rest of the counties in the region (Fig. 4). However, the population in Wayne County during the period from 1960 to 1970 continued to increase

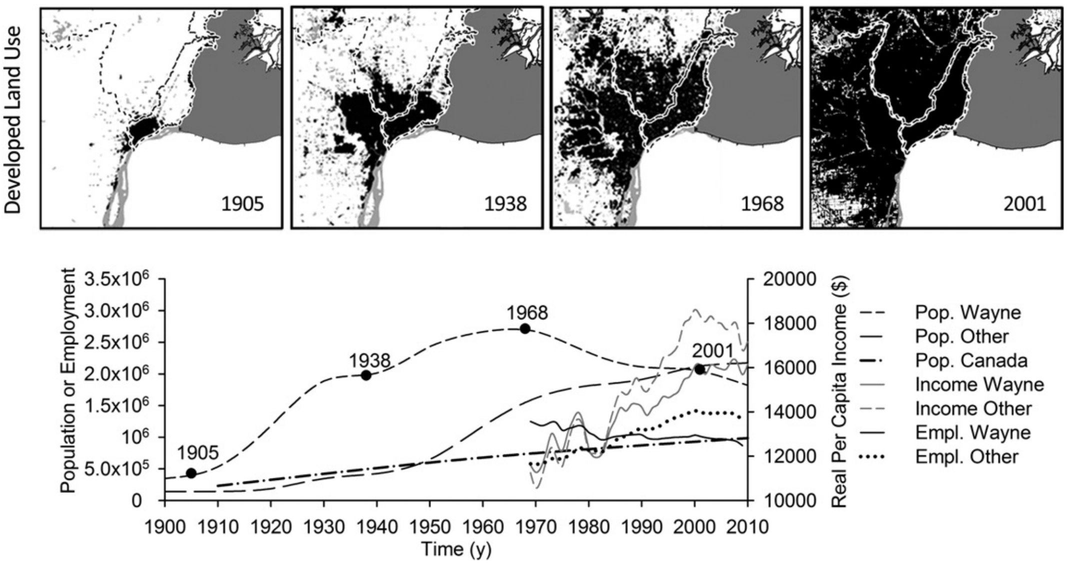

Fig. 3. Developed land use indicated by the black area (top panel), employment, population and real per capita income (bottom panel) in adjusted dollars, consumer price index 1982–1984 = 100, surrounding Lake St. Clair on USA side, including the area around Detroit, Michigan, USA from 1900 to 2010. Wayne refers to Wayne County and other refers to the combined county total of Lapeer, Sanilac, Oakland, Macomb and St. Clair. Canadian population is from the counties of Essex, Lambton, Chatham-Kent and Middlesex (represented by the city of London). Developed land use image was modified from United States Geological Survey (access date 31 January 2013, http://www.epa.gov/med/grosseile_site/indicators/landuse.html).

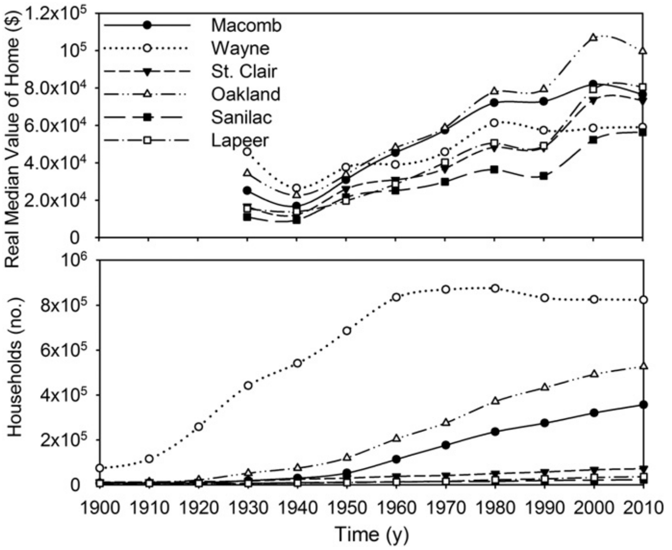

Fig. 4. Real median value of homes in adjusted dollars, consumer price index 1982–1984 = 100 and number of households per county from 1900 to 2010 that are located in the Lake St. Clair USA watershed (Macomb, St. Clair, Oakland, Sanilac and Lapeer) compared to Wayne County where the City of Detroit is located. Data source: USA Census Bureau.

(Fig. 3). Following one theory of urban dynamics, a possible explanation for this population increase is that as housing aged, the rental costs declined and people had a preference to reside in more crowded locations (Forrester, 1969).

After 1970 (third period), the population, number of households and employment in Wayne County continually decreased, whereas these parameters increased in the other five counties (Lapeer, Sanilac, Oakland, Macomb, and St. Clair) although at a slower pace compared to the other two periods. Since 2000 there are some signs of stabilization in human dynamics (e.g. population, income, households) in the five counties probably due to the recent financial crisis (Fig. 3). Although population growth rates for each county slowed since the 1970s, an increasing trend in land development continued as a result of increased residential lot sizes (SEMCOG, 2003) (Figs. 3, 4).

From 1970 to 1980, the average real personal income per capita for the combined five counties in the LSC watershed was slightly lower compared to Wayne County but then diverged starting in 1981 when Wayne County levels became lower than the other counties and stayed lower until now (Fig. 3). This means that the human population with higher income per capita likely shifted from Wayne County (outside of LSC watershed) to the counties within the watershed, and these changes in the land use characteristics were likely to influence the lake. Between 1990 and 2000, the amount of land used for homes increased by 19% while the number of homes grew by only 9% (Rogers, 2003). If these trends continue, urban pressures on LSC from its western catchment can only be expected to intensify. Therefore, human dynamics surrounding the lake provide a critical linkage in the CHANS framework because human activities in the watershed will inevitably influence point and nonpoint source pollutants, recreational activities and the spread of invasive species to LSC (Mavrommati et al., in press).

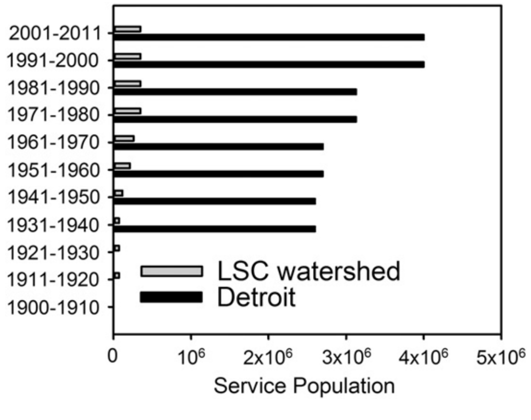

Fig. 5. Service population from the 10 largest wastewater treatment plants in the USA Lake St. Clair watershed compared to the Detroit metropolitan area from 1900 to 2010.

Changes in human health in relation to water quality

Responding to the rapid industrialization and population growth, water and wastewater infrastructure was gradually built primarily to protect human health (e.g., drinking water) and secondarily to improve the ecological condition of the receiving waters (Fig. 5). Numerous wastewater treatment plants (WWTPs) in the watershed were constructed in the 1930s. In 1966 there were an estimated 30 WWTPs with a carrying capacity designed to serve 312,120 people, most with secondary treatment, discharging to LSC via the Clinton River watershed (National Sanitation Foundation, 1964) (Fig. 5). Population growth, especially in Macomb and Oakland County, led to gradual upgrades of WWTPs to serve the additional population and reduce effluent pollutant

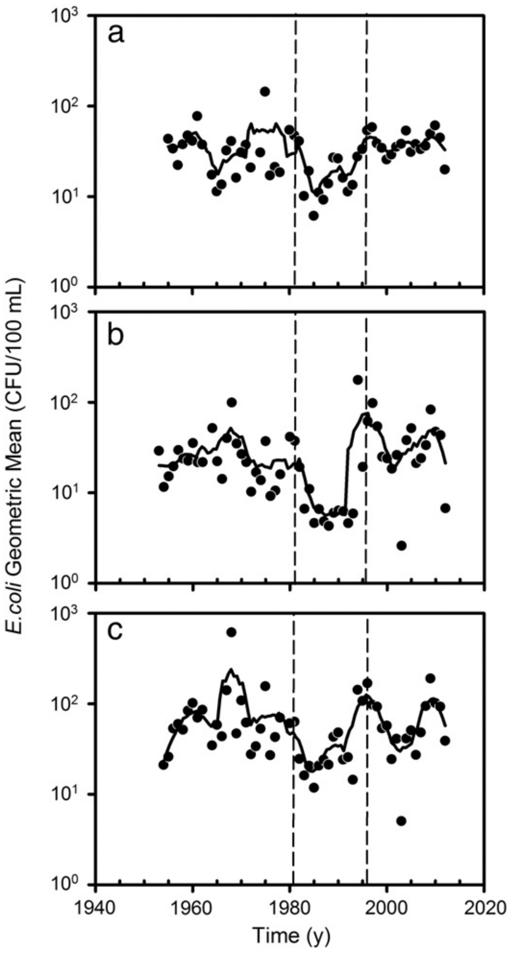

Fig. 6. Monitoring of bacterial indicators from 1953 to 2012 in swimmable waters near beaches at (a) New Baltimore Park Beach, (b) Metropark Beach (Huron Clinton Metro Authority), and (c) Memorial Beach along the western shore of Lake St. Clair. Trend line was developed from a negative exponential smoothing algorithm. Vertical dashed lines (1981, 1996) indicate when the analytical methodology changed, data prior to 1996 were converted to the common unit of *E. coli* (see S1 for details) because prior to 1981 Macomb County Health Department analyzed water samples for total coliforms while from 1981 to 1996 (dashed lines) they analyzed for fecal coliforms.

loads. An important element of this area is that the Detroit Water and Sewerage Department, although outside the LSC watershed, provides management and treatment for some of the drinking and wastewater derived from activities in the LSC watershed.

Not all domestic waste was treated at facilities; some was treated in septic systems, which are another source of non-point source pollution (e.g. nutrients, pathogens) to LSC that could potentially influence algal blooms and beach closures due to *E. coli* contamination of the coastal waters. In both 1960 and 2000, the combined total number of septic systems in Macomb, Oakland, St. Clair and Wayne Counties held steady at approximately 140,000 (Camp Dresser and McKee, 2003; National Sanitation Foundation, 1964). The total number of septic systems in Macomb and Wayne counties decreased between1960 and 2000, and the total number of septic systems in Oakland and St. Clair Counties increased between those years. Oakland County had the highest number of septic systems in both years out of the four counties listed above. For example, Oakland County had approximately 80,000 septic systems in 2000, which is about twice as many as any other county listed.

In the early 1900s, wastewater was a major source of pathogens associated with drinking water outbreaks. Typhoid and general dysentery were the common waterborne infectious diseases. Pollution and disease impacts were influenced by population and infrastructure (water treatment). The establishment of sanitary practices for the disposal of sewage in the late nineteenth century and the increasing use of filtration and chlorination of drinking water throughout the twentieth century resulted in a dramatic decrease in bacterial waterborne diseases in the United States. Death rates due to typhoid fever in Michigan dropped from 35.9 per 100,000 cases in 1900 to 0.1 per 100,000 cases by 1950 (Michigan Department of Community Health, access date 2 April 2012 http://www.michigan.gov/mdch/0,4612,7-132-2944_4669—,00.html). One of the last major waterborne outbreaks was documented in February 1926 when a large outbreak of dysentery occurred in Detroit with approximately 100,000 people ill (Wolman and Gorman, 1931).

Recreation on the sandy beaches located on the western shoreline remains an important ecosystem service provided by LSC. Water quality based on fecal bacterial indicators was fairly stable prior to 1980, showed improvement during the 1980s, then declined in the1990s (Fig. 6). The percentage of beach violations occurring during a recreational season also increased in the 1990s. Generally, beach violations during a swim season were below 15% of all samples collected until 1990 and then violations began increasing to approximately 20%. Wastewater and stormwater infrastructure changes, precipitation and lake levels were likely associated with these trends and further analyses are warranted. Human health in relation to the LSC water quality is possibly one of the most pressing issues that demands better understanding of the linkages in the CHANS framework.

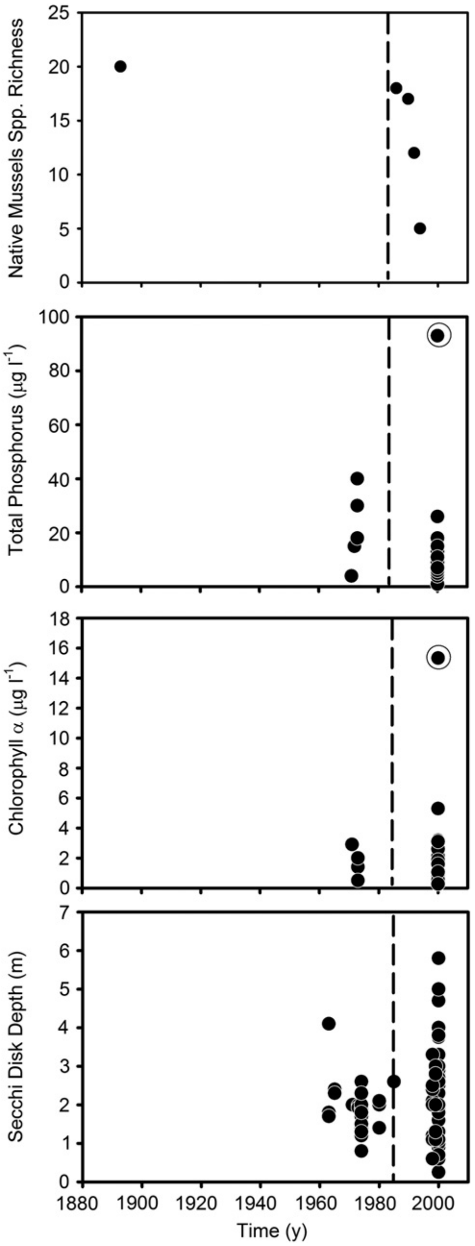

Fig. 7. General ecological conditions of the open water of Lake St. Clair from 1880 to 2010 including before and after the invasive zebra and quagga mussels (dashed line at 1985). Circles indicate outliers and likely do not represent the typical ecological condition. See methods for description of data sources.

Changes in ecological system

Generally, LSC was and still is considered to have high water quality (David et al., 2009; Herdendorf et al., 1993; Leach, 1972, 1991; Vanderploeg et al., 2002) because of the large input (98%) of Lake Huron water via the St. Clair River which has low nutrient concentrations. For example, the mean total phosphorus concentration was 9.10 µg L^{-1} (±0.51 std. err, $n = 85$) and the mean total Kjeldahl nitrogen concentration was 183.5 µg L^{-1} (±8.0 std. err, $n = 85$) from samples collected near the mouth of St. Clair River between 1998 and 2008 (data source: Michigan Department of Environmental Quality). Any future changes to Lake Huron will have a direct impact on LSC (Leach, 1972). Runoff from agricultural activity in the LSC watershed, especially from the eastern and western rivers (e.g. Clinton, Sydenham, and Thames) is the major source of nutrients into the lake and the longer resident time of the southeastern water mass compared to the northwestern promotes higher biological production (Leach, 1972, 1973, 1991). Past studies indicate four rivers, the Thames and Sydenham Rivers in Ontario and the Clinton and Black rivers in Michigan contributed significantly to the non-point source nutrient pollution (Lang et al., 1988; Upper Great Lakes Connecting Channel Management Committee, 1988). A model analysis of average total phosphorus loads to LSC indicated that the average phosphorus load inputs equaled the outputs during their 1975–1980 period and suggested that the lake was not acting as a sink for phosphorus (Lang et al., 1988). An updated analysis is needed for the current contributions of point and nonpoint phosphorus loading into and out of LSC.

PCBs, organochlorine insecticides, DDT, and mercury were released from historic chemical–industrial sources located on the major tributaries, such as St. Clair River that drain to LSC (Fimreite et al., 1971; Gewurtz et al., 2007; Leach, 1991). The LSC fishery closed from 1970 to 1980 when high levels of mercury were discovered in fish tissues and the low economic returns prevented a rebound in the commercial fishery (Leach, 1991). In the early 1980s lead, cadmium, and octachlorostyrene were found in clams that were downstream from the St. Clair River suggesting it was a primary source of these contaminants (Great Lakes

Institute, 1986; Leach, 1991; Pugsley et al., 1985). The Clinton River was also found to be a source of PCBs in clams during this study. There has been a substantial reduction in sediment contaminant concentrations since the 1970s likely from the remediation actions of eliminating sources, upgrading industrial and municipal facilities and dredging sediment (Gewurtz et al., 2007, 2010). But the USEPA 2008 waterbody report for LSC described the designated use of fish consumption as impaired because of high levels of mercury and PCBs in fish tissue and stated that atmospheric deposition was the likely source (United States Environmental Protection Agency, access date 31 July 2013, http://iaspub.epa.gov/tmdl_waters10/attains_waterbody.control?p_au_id=MI040900020001-01&p_state=MI&p_cycle=2008).

Historically the benthic faunal community was diverse and stable, reflecting the high water quality of the lake (Nalepa et al., 1996). However, since the invasion of zebra mussels (*Dreissena polymorpha*, see dotted line in Fig. 7) during the period between 1985 and 1988 (Griffiths, 1993; Griffiths et al., 1991; Hebert et al., 1989) the structure and function of the benthic community changed (Nalepa et al., 1996). After zebra mussel invasion, the composition of zoobenthos included a higher abundance of amphipods, snails and worms and lower abundances of native mussels compared to the pre-invasion abundances (Griffiths, 1993; Nalepa et al., 1996). The native mussel species richness significantly declined due to invasion of zebra and quagga mussels (*D. rostriformis bugenis*) that now dominate the lake. The invasive zebra and quagga mussels likely increased water transparency, loaded the sediment with bioavailable phosphorus, expanded the range of macrophytes, influenced fish habitat, and provided an essential fall stop over area for diving ducks (Auer et al., 2013; David et al., 2009; Higgins et al., 2008; Luukkonen et al., in press; Nalepa and Gauvin, 1988; Nalepa et al., 1996). Zebra mussels also may have impacted fish communities via habitat alteration (Vanderploeg et al., 2002). Visual predators, such as bass, muskellunge, and pike increased while fish that preferred more turbid waters, such as walleye (*Sander vitreus*) decreased (MacIssac, 1996; Nalepa et al., 1996).

The data we found and synthesized to represent the general ecological condition of LSC (total phosphorus concentrations, chlorophyll *a* concentrations and Secchi disk depth, see Fig. 7) did not show a clear shift after the invasion of zebra mussels. Vanderploeg et al. (2002) also reported variation in chlorophyll *a* concentrations with levels decreasing between 1970s and 1991–1993 but returning to 1970's concentrations between 1994 and 1996. Trends in these data sets (that were combined for long-term analysis) may be difficult to detect because of the spatial and temporal heterogeneity in zebra mussel abundance and biomass at these sites as well as the proximity of these sites to riverine influences.

From 1880 to 2008, the commercial fishery production in USA and Canadian waters of LSC declined (Fig. 8). Walleye, northern pike (*Esox lucius*), yellow perch (*Perca flavescens*), lake herring (*Coregonus artedii*), lake whitefish (*Coregonus clupeaformis*), and lake sturgeon (*Acipenser fulvescens*) were once harvested in large quantities (Baldwin et al., 2009; Edsall et al., 1988; Leach, 1991) but commercial harvest is now heavily restricted and recreational catch of four major sport fishes (walleye, yellow perch, smallmouth bass and muskellunge) is a more common activity (Thomas and Haas, 2004). The fish community of LSC has been diverse and abundant with about 70 species of warm and cool-water species, including yellow perch, walleye, smallmouth bass (*Micropterus dolomieui*) and muskellunge as well as introduced species such as round gobies (Leach, 1991; Thomas and Haas, 2004).

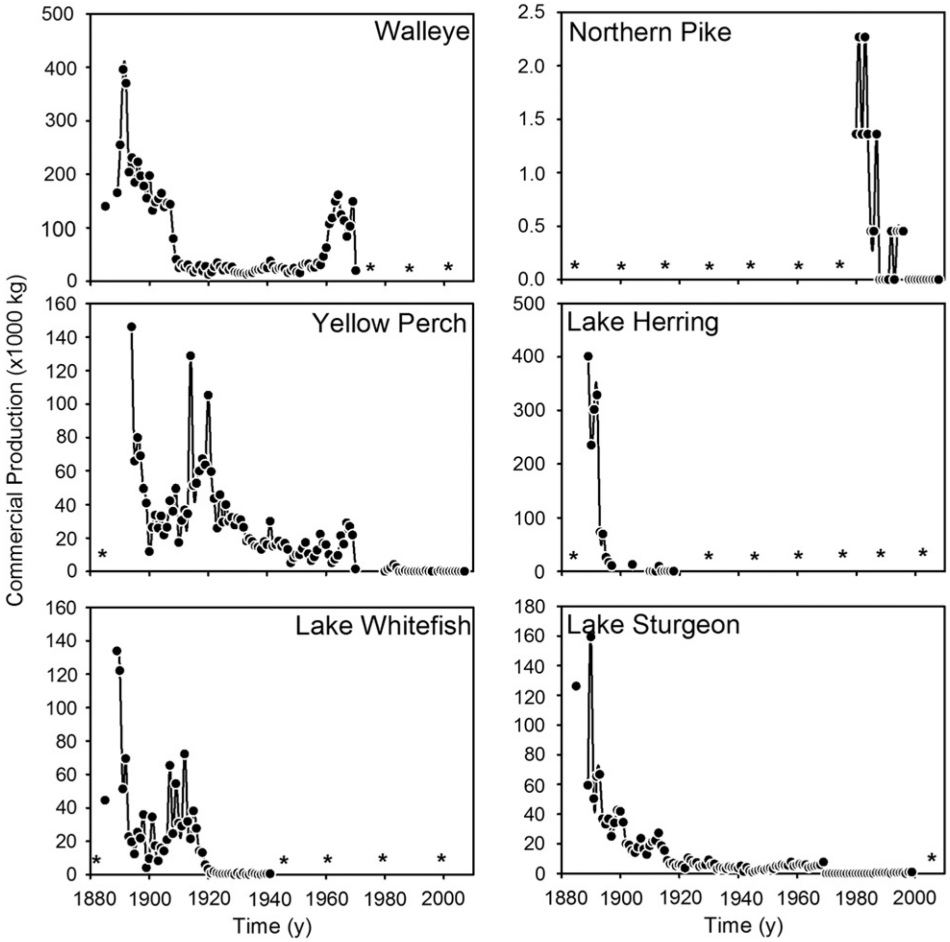

Fig. 8. Commercial fish production (grand total, thousands of kilograms) in Lake St. Clair waters of USA and Canada from 1880 to 2008 (from Baldwin et al., 2009). A blank area (indicated by *) in the data line indicates no reported catch for either USA or Canada side and therefore no grand total was calculated.

The wetland area of LSC was much greater historically than at present (especially along the Michigan side). It is estimated that 72% of the wetland area was lost from 1873 to 1973 mainly due to urbanization (Jaworski and Raphael, 1976; Leach, 1991). Conversion of wetlands to agriculture was also common on the Ontario side. Emergent wetland vegetation, including cattails (*Typha latifolia*, *Typha angustifolia*), bulrush (*Schoenoplectus tabernaemontani*), common reed (*Phragmites australis*) and spike rush (*Eleocharis quadrangulata*) were common in undeveloped areas including the St. Clair Flats and the eastern shoreline (Edsall et al., 1988; Leach, 1991). For migratory birds like mallards, black ducks, Canada geese and tundra swans, the vast wetlands provided essential flyway resting and feeding habitat (Leach, 1991). Most of the native fish species spawned along the St. Clair Flats or along the shoreline areas adjacent to the tributaries (Goodyear et al., 1982; Leach, 1991). The invasive common reed (*P. australis*) expanded across LSC when low lake levels followed the high lake levels in1986. *P. australis* can now be found along the coast line of LSC and poses problems because it forms thick strands, reduces functionality, biodiversity, and property values (USGS Great Lakes Science Center, 2011; Wilcox, 2012). Once *Phragmites* is established it can be difficult and expensive to remove (USGS Great Lakes Science Center, 2011). In summary, the natural system of LSC has been influenced by human activities (i.e. contaminants and spread of invasive species), but the ecological condition also influences humans that depend on it for drinking water, recreational activities, and fishing. Thus identifying these components and linkages between human and natural systems is critical in planning for sustainability.

Synthesis and conclusions

Integrating data for coupling socioeconomic and ecological systems: findings and limitations

The ecological condition and ecosystem services of LSC depend to a great extent on the human population, land use, climate and technological advances in water and wastewater management. We identified three periods during the last century that indicate fundamental changes to the socioeconomic system that might be appropriate for understanding changes to the ecology of LSC (Table 1).

The first period (1900–1940) was characterized by a high population growth rate, industrialization, and urbanization (Edsall et al., 1988). The main water resource concern during this period was treating drinking water to minimize threats to human health. In the 1920s, dysentery and typhoid impacted the communities as a result of no or low treatment of sewage and drinking water. Walleye, yellow perch and lake whitefish were commercially harvested in larger quantities compared to the other species during this time. Due to the lack of socioeconomic and ecological data during this period we cannot sufficiently identify the impact of socioeconomic systems on the ecological condition of LSC (and vice versa), but the health issues arising from water consumption infers poor water quality that directly affected human health.

During the second period (1941–1970), the population continued to increase but at lower rates, urbanization was significant, and precipitation and lake levels of LSC increased. Point sources of pollution, such as wastewater discharges from residential and industrial water use, began to be regulated through the construction of wastewater treatment plants and the adoption of environmental policies, such as the USA Federal Water Pollution Control Act of 1948. One of the main concerns during this period was controlling chemical pollutants using engineering solutions (Karr, 1991). By 1966, 85% of the total population was served by sewers with secondary treatment (State of Michigan, 1966); however, beach monitoring for *E. coli* suggested that water quality degraded over this time. Walleye was the only fish commercially harvested in large quantities during this period. The opening of the St. Lawrence Seaway in 1959 stimulated the shipping industry, which would later influence the spread of invasive species.

During the third and most recent period (1971–2010) the population and the economic importance (e.g. real median value of homes) of the watershed increased. This is likely due to the population moving from the metro-Detroit area into the suburbs in the LSC watershed. Wayne County for the first time had lower employment and population than the surrounding counties (Macomb, St. Clair, Oakland, Sanilac, Lapeer) in the LSC watershed. After adoption of the Clean Water Act of 1972, new policies, such as the Great Lakes Water Quality Agreement between USA and Canada were implemented to protect the designated uses (e.g. fishable/swimmable) of aquatic resources (Table 1). However, water quality problems associated with waterborne pathogens persisted although the risk was associated with recreational exposure rather than drinking water. Wetland area loss was greater than 70% in the 1970s compared to 1873, due to residential, commercial, industrial and recreational development (Herdendorf et al., 1986; Jaworski and Raphael, 1976). The LSC fishery closed from 1970 to 1980 when high levels of mercury were discovered and the low economic returns prevented a rebound in the commercial fishery (Leach, 1991). Even today recreational fish consumption advisories exist because of high tissue levels of mercury, PCBs and dioxins (Michigan Department of Community Health, 2011; Ontario Ministry of the Environment, 2013). The spread of invasive species, such as zebra mussels in the mid-1980s, has and currently is impacting the ecological structure and function of the lake (Vanderploeg et al., 2002). Recreational uses such as boating, fishing and visiting beaches have great contemporary importance. Our findings suggest that while drinking water risks have decreased over the last 50 to 100 years, coastal pollution resulting in beach advisories and closures are still occurring.

Climate change trends all point to an overall tendency for a warmer and wetter climate (Kling et al., 2003) and when combined with lake paleohydrograph data (Baedke and Thompson, 2000) suggests that the fluctuations of lake levels will continue. Since 1910, LSC average annual levels have increased 4.3 mm yr^{-1}, even with general fluctuations of the lake levels. The impacts from climate change (combined with changes in infrastructure and human population, loss of wetlands and invasive species) are not well understood for this lake but are hypothesized to increase primary production, including harmful algal blooms and nuisance macrophyte densities (Kling et al., 2003). Plant and animal communities will likely shift to more tolerant species, including invasive species such as the wetland plant *P. australis*, that will expand their ranges (Wilcox, 2012). Major fluctuations in lake levels are also a concern for ecological condition and the provision of ecosystem services to human well-being (e.g. boating, aesthetics, property values) (Kling et al., 2003).

Integrating data for coupling socioeconomic and ecological systems: needs and next steps

In our study, the key challenges for preparing to develop transdisciplinary models were finding and managing historic data sets starting from early 1900s in both countries and aligning the data to the same spatial scale, such as the natural (e.g. watershed level) or political boundaries (e.g. county level). Similar to Carpenter et al. (2009) and Hufnagl-Eichiner et al. (2011), we found that the simple lack of the data and infrequent geo-referencing of both socioeconomic and biophysical data were a major challenge when working with the CHANS approach. Considering that long-term data are essential for studying CHANS and designing for sustainability, then collecting and synthesizing the available data are initial critical steps for understanding the past and preparing for the future (Mavrommati et al., in press).

Ecosystem services have been proposed as an appropriate concept to link human and natural systems and the main idea underlying this concept is that changes in natural systems affect human well-being (Millennium Ecosystem Assessment, 2005; Stevenson, 2011). The literature is growing with respect to ecosystem services valuation (Boyd and Banzhaf, 2007; Brauman et al., 2007; Daily and Matson, 2008; Goldstein et al., 2012; Salles, 2011). A historical review of ecosystem services suggests that “since ecosystem services relate to the value society assigns to the goods and services produced by nature, the same delivery of service might be valued quite differently over time” (Lautenbach et al., 2011) implying that comparing ecosystem services over time is not the best way for studying them. For this reason, our analysis does not include a historical review of ecosystem services, but we acknowledge the need to employ novel methods to understand their change through time, similar to Lautenbach et al. (2011). Recreational activities such as boating, fishing, and beach usage are important contemporary cultural ecosystem services in this system and are being promoted by local initiatives (e.g. Macomb County Blue Economy Initiative, Lake St. Clair Tourism Initiative). However, there are little readily-available data for a one hundred year time series on the number of visitors to LSC beaches or boating activity that can be compared. Given that future generations' needs and preferences related to ecosystem services are unknown and unknowable, there is a need to maintain the full range of services provided by the ecosystems. Investigating the critical linkages among ecosystem function, derived ecosystem services and human activities are needed to better formulate environmental policies that will help maintain human well-being in the long run.

From this initial historical review of LSC, we have identified components of long-term data sets for developing dynamic models which include but are not limited to: lake levels, ice cover, human population, households, native mussel diversity, Secchi disk depth, and *E. coli* contamination near beaches. We can further study the linkages of these components, such as investigating if changes in climate (i.e. lake levels and ice cover) account for the variability in *E. coli* concentrations near beaches. Identifying data gaps provides a starting point to employ and develop methods for filling in knowledge gaps and to design future studies based on these needs for integrated approaches. The next step is to continue gathering data and to further analyze the couplings and interactions of the components of human and natural systems to determine the structure, feedbacks, time lags and surprises between the systems and to determine if past couplings have legacy effects on present conditions (Liu et al., 2007). Research tools, such as models, can help answer key research questions about climate change and sustainability in freshwater ecosystems. For example, we need to understand why beach contamination in LSC has varied over time and has not improved in recent decades even with the adoption of environmental policies (e.g. Clean Water Act). Are there time lags of beach contamination related to climate, policy or interactions with zebra mussel invasions? How resilient is the socioeconomic-ecological system of LSC to disturbances (e.g. invasive species, fluctuating lake levels)? Under the uncertainty of future generations' preferences and needs, what ecological attributes do we need to preserve? Finally, which ecosystem services are most preferred or valued by humans in this region and therefore should be heavily managed for sustainability? This review helps to identify critical system components and their trends in order to set the stage for further research and to develop models of coupled human and natural systems, which are of vital importance to help protect and sustain aquatic ecosystems.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.jglr.2013.11.006.

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