Photo Courtesy: MMSD, Ken Wardius

Trophic State and Chlorophyll in the Milwaukee, Wisconsin Harbor and Surrounding Nearshore Waters

Water Quality Research Department
Milwaukee Metropolitan Sewerage District

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The Clean Water People

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Trophic State and Chlorophyll in the Milwaukee, Wisconsin Harbor and Surrounding Nearshore Waters

Photo Courtesy: MMSD, Ken Wardius

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Executive Summary

Introduction:

An effective surface water quality monitoring program will provide strategic information regarding water quality and ecological status. Monitoring the biological, chemical, and physical characteristics of a lake and its watershed can help stakeholders assess progress in meeting water quality and resource goals. But what does water quality mean? To most people water quality means clean water for drinking, swimming, and fishing but it is really an evaluation of whether a body of water is clean and healthy enough to support its "designated beneficial uses". Water quality, loosely defined, is a report card. Why do we care about water quality in the Great Lakes? "The magnitude of the Great Lakes water system is difficult to appreciate. The lakes contain about 23,000 km^3 (5,500 cu. mi.) of water, covering a total area of 244,000 km^2 (94,000 sq. mi.) The Great Lakes are the largest system of fresh, surface water on earth, containing roughly 18 percent of the world supply. Only the polar ice caps contain more fresh water. In spite of their large size, the Great Lakes are sensitive to the effects of a wide range of pollutants. The sources of pollution include the runoff of soils and farm chemicals from agricultural lands, the waste from cities, discharges from industrial areas and leachate from disposal sites. The large surface area of the lakes also makes them vulnerable to direct atmospheric pollutants that fall with rain or snow and as dust on the lake surface" (USEPA, Great Lakes Atlas 1995). Lake Michigan has an average residence time of 99 years (time it takes for water entering the system to leave the system). Therefore, what we do now will still affect this system a lifetime from now and we are still addressing perturbations exerted a lifetime ago.

The Great Lakes: Photo Courtesy, Visible Earth, NASA

The data collected from a well designed monitoring program can be utilized to determine if water quality conditions (for example, phosphorus concentrations, water clarity and biological productivity (chlorophyll concentration)) are changing or improving over time. The MMSD's surface water quality program is an excellent vehicle for documenting changes over time (the database is long term and consistent) and for determining trends. This "trend analysis" is important when public concerns center around questions like "is Lake Michigan getting worse". Trophic state is one way that this question can be answered and one of the "subjects" that should be presented on the water quality "report card".

Trophic state is an assessment of the "relative health" (pollution tolerance level, nutrient impact, etc.) of a system and is actually a measurement of living biological material (Carlson 1996). Three major categories: eutrophy, mesotrophy, and oligotrophy broadly define trophic state. Generally, an oligotrophic system receives little "artificial / man made" nutrient input (for example, phosphorus, nitrogen) and is considered "unpolluted" (grade "A" on the report card), while an eutrophic system is highly productive, receives higher nutrient inputs and is often termed "polluted" (grade "D" on the report card). Two trophic state indices were utilized for this report: The Carlson Trophic State Index (TSI) and the Lake Trophic State Index (LTSI). Both of these indices use chlorophyll (chl), total phosphorus (TP), and water clarity (secchi disk (SD)) data to calculate trophic state. High trophic state numbers indicate a higher trophic state (higher productivity, higher nutrient content) and therefore, typically poorer water quality. Lower trophic state numbers indicate a lower trophic state (low productivity, low nutrient content) and therefore, typically better water quality. In addition to trophic state indices, chlorophyll trends were also evaluated.

Cole (1979) listed the following features to contrast oligotrophic and eutrophic lakes:

OLIGOTROPHIC	EUTROPHIC
Blue or green water; marked transparency (i.e. secchi disk)	Green to yellow to brown water, limited transparency
Water poor in plant nutrients (i.e. nitrogen & phosphorus)	Plant nutrients abundant
Phytoplankton (microscopic algae) quantitatively poor	Abundant phytoplankton, mass great
Oxygen abundant all the time	Oxygen depletion – summer
Sediments low in organic matter	Sediments abundant with organic matter

Results:

Trophic state is improving (see Figure 1 for site locations)

- Carlson trophic state indices (TSI) improved at all sites except Nearshore 10 (this site is located approximately 11 miles northeast of the Milwaukee Harbor (**Figure 1**) and is not in the zone of influence of the Milwaukee area rivers).
- Lake Trophic State Index (LTSI) improved at all sites except Nearshore 10.
- Chlorophyll concentration decreased (improved) at all sites except Nearshore 10.
- Trophic state and chlorophyll concentration both improved with distance from shore, most likely due to the significant influence of the Milwaukee area rivers.
- The improvements in trophic state and therefore, water quality could be partly due the MMSD Water Pollution Abatement Program (WPAP). The MMSD Water Quality Index shows an overall improvement to the Milwaukee, Menomonee, and Kinnickinnic Rivers (pre vs. post Deep Tunnel data) for sites at or close to the river mouths (for more detail, see the full text of this report).
- The average LTSI data show distinct improvement (pre vs. post Deep Tunnel) at all sites except Nearshore 10.
- The average chlorophyll concentration data show distinct improvement (pre vs. post Deep Tunnel) at all sites except Nearshore 10.

The following table summarizes results of the TSI, LTSI (trophic state indices) and Chlorophyll analyses (note: colors correspond to LTSI trend, pale yellow = eutrophic range, pale blue/green = mesotrophic range, blue = oligotrophic range).

General Summary of Results 1980 – 1997

Site	*TSI*	*LTSI*	*Chl a*
NS27	**Improving to mesotrophic**	**Improving to meso – oligotrophic***	**Decreasing**
NS11	**Improving to mesotrophic**	**Improving to oligotrophic**	**Decreasing**
NS28	**Improving, still eutrophic**	**Improving from high eutrophic to eutrophic**	**Decreasing**
NS12	**Slight improvement still eutrophic**	**Improving, to mid eutrophic**	**Decreasing**
NS13	**Improving still eutrophic**	**Improving, from mid eutrophic to low eutrophic**	**Decreasing**
NS14	**Improving eutrophic to mesotrophic**	**Improving from meso-eutrophic* to meso-oligotrophic***	**Decreasing**
NS1	**Improving trend mesotrophic / meso eutrophic* to low mesotrophic / mesotrophic**	**Improving from oligo-mesotrophic* to oligotrophic**	**Decreasing**
NS3	**Improving to steady trend, mesotrophic**	**Improving from oligo-mesotrophic* to oligotrophic**	**Overall decease if 1980's vs. 1990's**
NS10	**TSI(TP) increasing trend to mesotrophic, other TSI's approximately no change to slight improvement**	**Increasing trend from mid oligotrophic to high oligotrophic**	**Decreased then returned to pre 1989 levels**

*indicates a condition between two trophic states.

Site Descriptions (Figure 1)

For this study Nearshore (NS) 27 and NS11 were examined separately due to geographic location. These sites are located east of the South Shore Wastewater Treatment Facility. They are relatively shallow water sites with depths of approximately 7 and 9 meters, respectively. “NS28, 12, and 13 represent a progression of sampling sites in the Milwaukee Harbor starting just downstream of the confluence of the Milwaukee, Menomonee, and Kinnickinnic Rivers and extending east to the main gap of the Milwaukee Harbor. These sites are all within the breakwall and average approximately 10 meters in depth. They have traditionally exhibited high phytoplankton abundances and nutrient levels due to significant influence of the Milwaukee, Menomonee, and Kinnickinnic Rivers. These rivers serve as major sources of nutrient loading to the lake” (MMSD 1997). NS14 is directly east of this site progression, approximately 1 mile from the main gap. It is approximately 16 meters in depth and data from this location are similar to other MMSD Nearshore deep water sites. NS10 is an offshore site and the deep water station. It has been designated as the reference (“clean water”) site. Its’ water chemistry and biological parameters are not influenced by the Milwaukee area rivers. NS10 is approximately 85 meters deep and located about 7 miles directly offshore. It is approximately 11 miles Northeast of the Milwaukee Harbor (MMSD 1997). NS1 and NS3 are offshore sites with depths of 25 meters and 23 meters, respectively. They are located approximately 12 and 20 miles (respectively) southeast of the Milwaukee harbor mouth. Phytoplankton abundance and nutrient levels are generally lower and more indicative of Lake Michigan than at sites within the harbor or located closer to shore. Inshore versus offshore differences in Lake Michigan and the other Great Lakes are often apparent, influencing algal seasonality, species succession, and biomass (Munawar & Munawar, 1996).

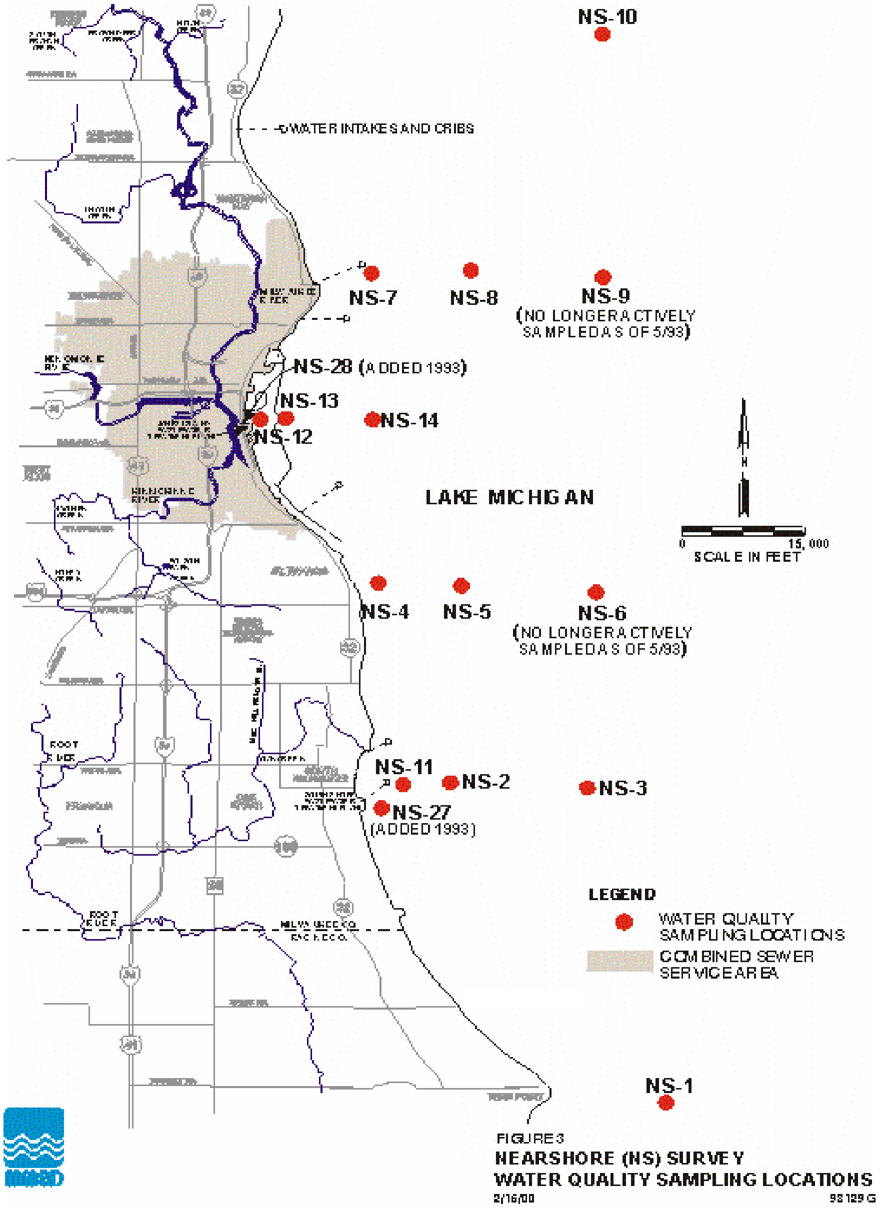
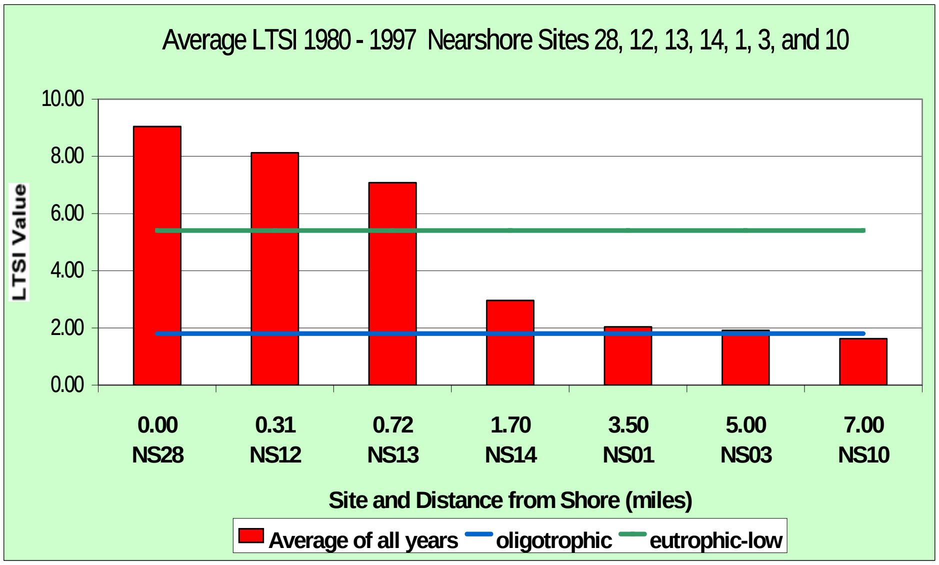


Figure 1

General Discussion and Conclusions:

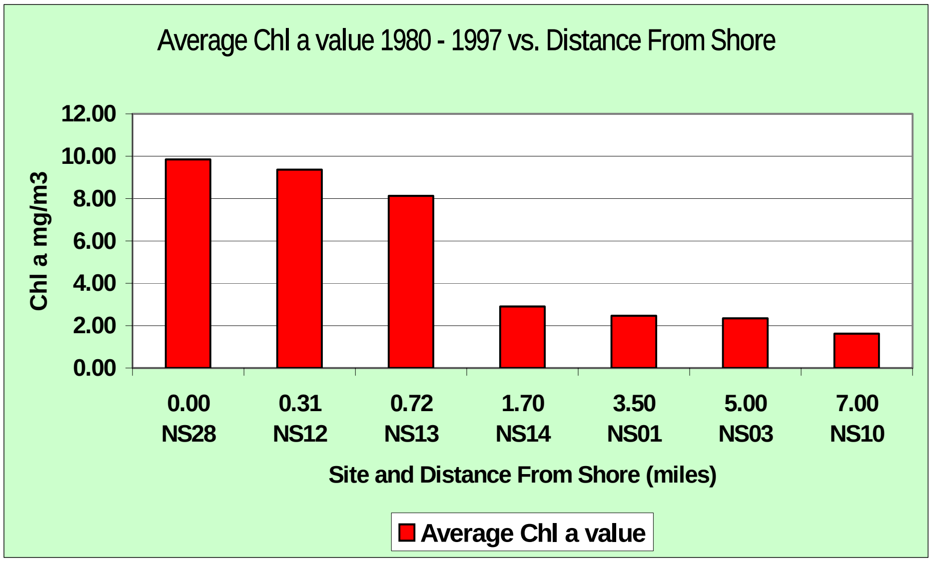
This report represents a first attempt at analyzing the enormous MMSD surface water quality database (using several typical surface water quality variables). It would be more informative and useful to compare species of phytoplankton between sites and major taxonomic groups, but limited time and resources prevents us from achieving this goal at the present time. Hopefully, this biological analysis can be completed in the future, thereby providing us with more answers and a more in depth analysis of “what’s really happening out there”. For discussion on NS27 and NS11, please refer to the full text of this report.

Figure 2: Average LTSI vs. Distance from Shore



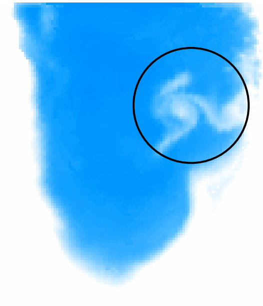
Obviously differences exist between sites with the most notable being inner harbor vs. outside sites (**Figures 2 & 3**) with NS14 exhibiting characteristics of both regions. The inner harbor is a highly productive environment, subsequently the phytoplankton community (and ultimately chlorophyll) will be reflective of the various ecological consequences of heightened productivity and exposure to both point and non-point source pollution. Many factors affect the planktonic community, which has the ability to respond very quickly. This response can be evaluated using chlorophyll data as an indication of algal biomass.

Figure 3: Average Chlorophyll vs. Distance from Shore



Potential factors that impact surface water quality and therefore the phytoplankton are; exotic species effects (for example, zebra mussels, spiny water flea, etc.) and subsequent food web (and nutrient) implications, temperature, thermal gradient, light penetration and availability, nutrient availability, turbulence, water circulation patterns, episodic events (resuspension and recycling of nutrients, erosion etc.), zooplankton predation, and sampling methodology. Other impacts to surface water quality not discussed previously but also important are; organic chemical contamination, metal toxicity, potential silica limitation to diatoms, algal production and related regulation of carbon flow in the aquatic system (Epplett, 2000) and bacterial competition for nutrients.

Southern Lake Michigan



A major storm in Lake Michigan with 30 – 40 mph winds and 20 ft. waves initiated the plume captured in this image. This event is transporting huge quantities of resuspended (sediment) material offshore. PHOTO: EEGLE project

In regard to nutrient availability and recycling of phosphorus from the sediments: it has long been accepted that productivity in the Great Lakes is limited by phosphorus (Brooks 1990) because of the extremely low concentrations present in the water column. It is also known that phosphorus is recycled into the aquatic system through sediment resuspension events, dissolution, re-adsorption at the sediment/water interface, and that zebra mussels may potentially control ecosystem function by providing nutrients at a rapid rate through pseudo-fecal inputs (Heath 1995). DePinto (1999) noted that in Lake Erie beginning in 1988 and especially in 1989-90, there was a decrease in phytoplankton biomass with **no decrease in phosphorus**

load. He further stated that the only logical hypothesis was the additional loss of algal biomass due to zebra mussel activity. Effler (1998) found that zebra mussels contributed to phosphorus dynamics alterations in a system by significantly enhancing the amount of soluble reactive phosphorus in the water column without a change in total phosphorus concentration.

Trophic state was drastically different at Inner Harbor locations versus outside sites. All of the Inner Harbor sites were rated as eutrophic to highly eutrophic while the outside sites were rated as mesotrophic to oligotrophic (**Figure 2**). These trophic state conditions are consistent with the literature; Vollenweider (1974) summarized the offshore regions of Lake Michigan as being oligotrophic while the inshore regions were classified as eutrophic. This is probably a factor of the heightened nutritional input that the Inner Harbor receives from point and non-point source pollution. Nitrogen and phosphorus are well known essential nutrients for algal productivity. They act much like fertilizers on lawns and can promote excessive algal growth. The combination of nutrient additions coming from streams and rivers, and the recirculation of nutrients from the bottom sediments can cause considerably more productivity than the waters of open lakes (Stoermer 1978).

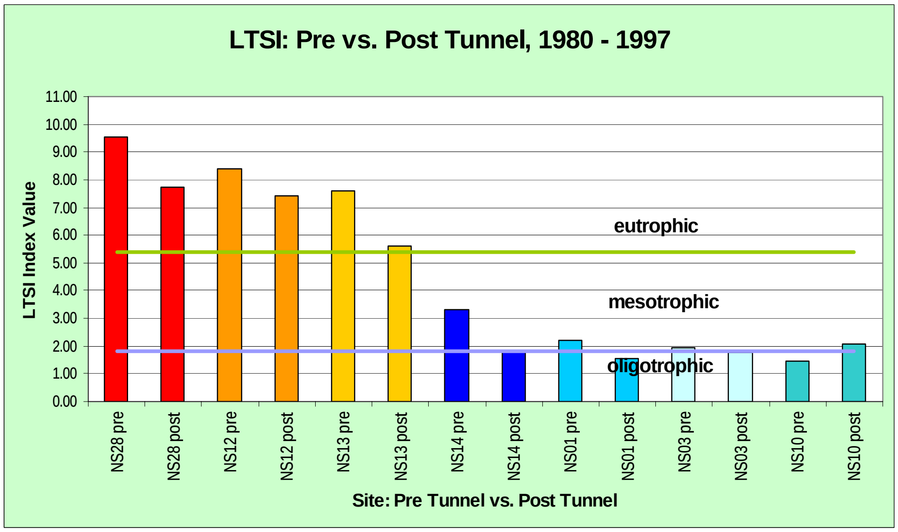
A major difference between inner harbor and outside sites was the magnitude of chlorophyll concentration (**Figure 3**). This variable was much higher at the inner harbor sites. Chlorophyll has been significantly correlated with phytoplankton density (Nicholls 1993) and higher inshore chlorophyll concentrations are a common phenomenon in the Great Lakes (Nicholls 1993). These differences could also be attributed to the increased nutrients available from the area rivers.

A few words should be devoted to the importance of algal productivity and composition to trophic state. In a lake system such as Lake Michigan, the greatest contributor to primary production is the phytoplanktonic community. These small plants form the basis of the food chain and play an extremely important role in the overall biological makeup of the lake. This community is complex; varying not only by season but also by many other biological, chemical and physical factors, and can be reflective of the systems “relative health”. Ultimately, the factors that “drive” algal populations, productivity, and competition, also control trophic state.

In analyzing the data presented in this report it appears that both trophic indices utilized indicated that trophic state was improving except for the deep-water station (NS10). This is curious but not surprising since NS10 is outside of the influence of the Milwaukee Harbor and Rivers. If improvements to the inner harbor sites were indeed due to remediations within this area, then these affects would not be noted at NS10, which would still remain reflective of Lake Michigan trophic condition in general. NS10 was still in an oligotrophic state. Chlorophyll decreased at all nearshore sites, however at NS10, chlorophyll eventually increased again, returning to pre 1989 levels.

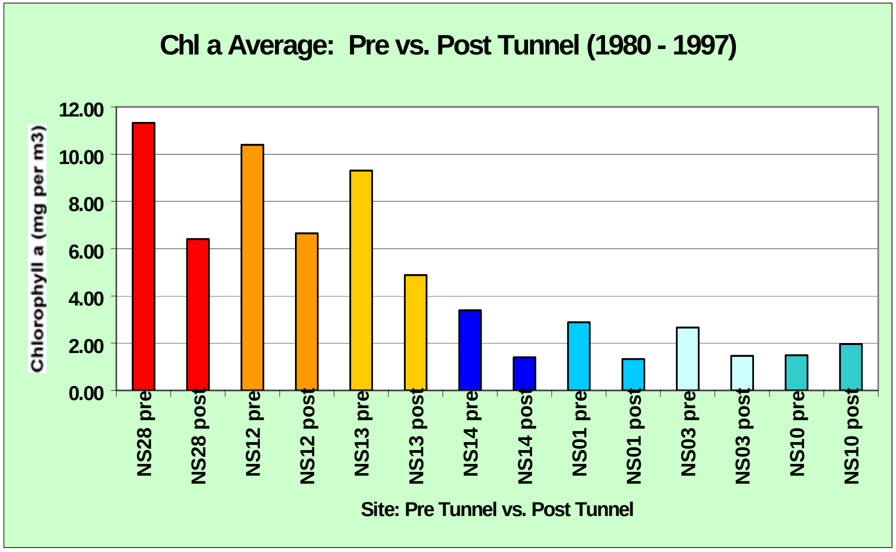
Improvements made during the MMSD Water Pollution Abatement Program (Deep Tunnel Project completed in mid 1993, fully operational 1994) could also be having a positive effect on water quality in these areas. With the Deep Tunnel completion, overflow events have been significantly reduced. This system has prevented more than 40 billion gallons of wastewater from entering Milwaukee area rivers and Lake Michigan since becoming operational in 1994 and has reduced overflow events from approximately 50 per year to an average of two (MMSD 2000). It follows then that nutritional inputs from these sources would also have been significantly reduced. The MMSD found that “phosphorus and fecal coliform bacteria have a major influence on water quality at all sites and that inside the CSO area, dissolved oxygen is a consistent variable determining bad and very bad water quality” (MMSD October 1997). The Deep Tunnel system not only keeps sanitary and combined sewage from entering the river systems and ultimately Lake Michigan, but also captures non-point pollutional material such as fertilizers, pet waste, street runoff etc. In fact, LTSI pre vs. post tunnel data (**Figure 4**) show distinct improvement at all sites except NS10, with NS3 experiencing a slight improvement in trophic state. NS13 actually changed from a highly eutrophic state to a slightly eutrophic LTSI. NS14 improved from a mesotrophic LTSI to a highly oligomesotrophic state. NS1 improved from a mesotrophic state to an oligotrophic state. In contrast, NS10 experienced a slight degradation in trophic state. NS10 is unaffected by Milwaukee area rivers and harbor water quality and could be reflecting a general trend for Lake Michigan. Additionally, due to the physical location of NS3, the impact from Milwaukee area water quality is probably minimal. General current patterns have a tendency to follow the lake shoreline in a southerly direction, therefore NS 1 would more likely be affected by changes in Milwaukee area water quality.

Figure 4: LTSI, pre vs. post Deep Tunnel



When the average chlorophyll pre v. post tunnel data (**Figure 5**) are compared; the same general trends are exhibited. Distinct improvement at all Nearshore sites, except NS10, which experienced an increase in chlorophyll values. This is consistent with trophic state data. The deep tunnel system could be a significant contributor to this reduction in algal biomass since algal growth and productivity are controlled by nutrient and light availability.

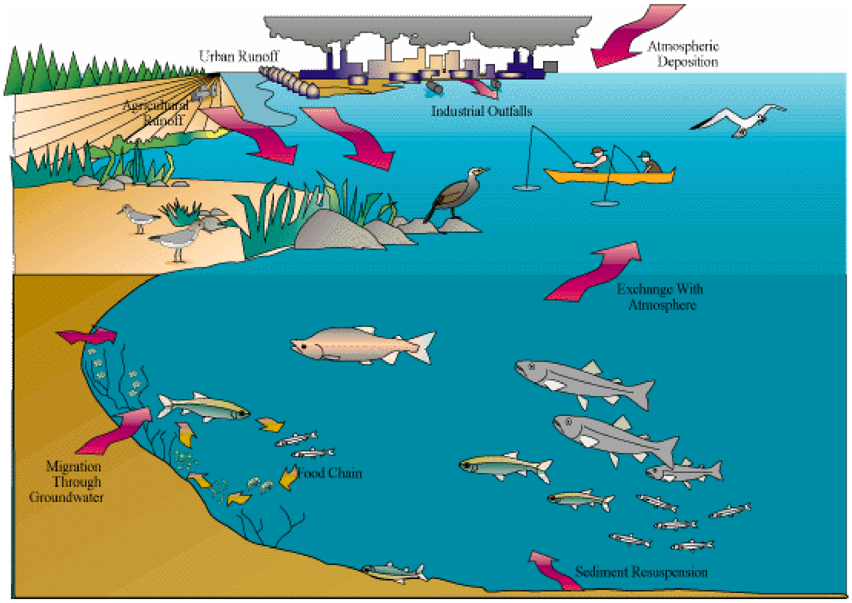
Figure 5: Average Chlorophyll, Pre vs. Post Deep Tunnel



Improvements to both chlorophyll and trophic state could be due to other factors as well. Certainly, zebra mussels with their incredible filtration capabilities could be removing nutrients as well as solid particulates (and algal cells). This in turn would limit algal biomass and improve secchi disk readings (through reduced nutrient availability and removal of the algal cells from the water column and by removing fine and suspended particulates from the water column).

Figures 22 through 27 in the main body of this report graphically illustrate the overall improvement to the Milwaukee, Menomonee, and Kinnickinnic Rivers, pre vs. post tunnel, utilizing the MMSD Water Quality Index (WQI). This index is a rapid assessment tool developed by MMSD staff to aid in the presentation and interpretation of surface water quality data (for further information, see MMSD September 1994 and MMSD October 1997). The WQI is an effective tool for documenting relative changes in water quality over time, providing a “snap shot” of water quality and a means to compare different locations over space and time. The WQI (pie charts, Figures 22 – 27) illustrate a rather dramatic improvement in water quality when comparing pre vs. post Deep Tunnel data. The largest improvement occurred in the “Fair” water quality. The most notable improvement was at RI 17 (Menomonee River at 2nd Street). This site experienced an improvement from 28% “Bad” WQI rankings for pre tunnel years to 3% “Bad” WQI rankings for the post tunnel years (fair ratings increased from 70% to 94%). With these improvements to surface water quality in the rivers, we would expect to see a concurrent improvement to water quality in the Milwaukee Harbor. Indeed, based on trophic state and chlorophyll data, significant improvements have been seen in the Milwaukee Harbor and to the waters outside of the breakwall, which are affected by water quality in the Milwaukee area. An analysis of the biological community (phytoplankton species) would substantiate improvements to water quality in the Milwaukee Harbor and Nearshore water of Lake Michigan.

Zebra Mussels: Courtesy: The Detroit News, John Galloway



Sources and Pathways of Pollution: USEPA, Great Lakes Atlas 1995

Why is it critical to evaluate and continue to monitor surface water quality in the Milwaukee Harbor and Nearshore water of Lake Michigan? Clean water is a resource at risk and in many ways is the fuel that powers the nations economic engine (USEPA 1996). Aquatic (and terrestrial) ecosystems are of fundamental environmental and economic importance, and perform many beneficial functions (IJC 2001). Lake Michigan is an aquatic ecosystem and is the second largest of the Great Lakes. It receives water and nutrients from a 45,600 square-mile watershed (USEPA 1994). Many of the changes in species composition in the Great Lakes over the last 200 years have largely been the result of human activities (USEPA, Great Lakes Atlas 1995). “The integrity of the Great Lakes ecosystem has been and continues to be compromised. Contaminated sediments in the lakes produce health problems. Contaminants are reaching the lakes through the air from places within and far beyond the basin. Drinking water must be extensively treated. Swimming must often be prohibited and beaches closed. Fish in the Great Lakes are contaminated with persistent toxic substances; these fish pose a threat to the health of those who eat them and to their unborn children. Increasing urbanization is adversely affecting water quality; as a result of human activities. Alien invasive species are entering the lakes and causing billions of dollars in damages and massive aquatic ecosystem disruption. **Moreover, the public lacks the information to identify sources of contamination, or judge the adequacy of remedial and preventive programs**” **(International Joint Commission 2000).** The District’s surface water quality monitoring program provides the data necessary to dispense water quality information to the public. Moreover, due to the long-term nature of the District’s water quality monitoring program (and data), problems, which are inherent with other programs, are not exhibited. These problems include difficulties with trend analysis and interpretation, difficulties tracing and examining causes and pathways of pollution, and difficulties determining effects of exotic species, nonpoint source pollution, point source pollution, episodic events, watercourse and other improvements, etc. These lapses in monitoring ultimately affect the quality of infrastructure management decisions and our ability to adequately address the concerns and education of the public. Continued long term water quality monitoring improves the effectiveness of protecting our water resources for the public’s many uses and future generations. In the words of the International Joint Commission: “Every delay in achieving this purpose carries a price (in regard to restoring and maintaining the integrity of Great Lakes Basin Ecosystem and to coordinated monitoring and surveillance programs necessary to fulfill commitments under the Great Lakes Water Quality Agreement). With time the price will grow heavier, and the line between delay and outright failure will be stretched thinner. Governments need to show a new sense of urgency and a commitment to action in restoring and protecting the Great Lakes.” (International Joint Commission 2000).

Photo Courtesy: USEPA, Great Lakes National Program Office

Introduction:

The monitoring programs that have been developed by the Water Quality Research (WQR) department support and substantiate MMSD's goals and policies of improved water quality and environmental protection.

The goals of the Milwaukee Metropolitan Sewerage District (MMSD) water quality monitoring program are to:

- Document long term water quality changes due to MMSD's actions and activities,
- Assess the impact of point and non point sources of pollution within the District's service area,
- Document the effectiveness of MMSD's operations,
- Aid in facilities and strategic planning,
- Aid in flood control projects – track and document water quality changes before, during and after flood remediation efforts,
- Provide the Wisconsin Department of Natural Resources (WDNR) with required WPDES (Wisconsin Pollutant Discharge Elimination System) surface water quality data and nearshore survey data have been used to establish background lake concentrations used in the development of WPDES permit limits,
- Provide expertise, data, etc. to other agencies, environmental groups, and educational institutions as requested.

Long term characterization of trophic state and its' implications to surface water quality is an important aspect in assessing "relative water body health". But, what does water quality mean? To most people water quality means clean water for drinking, swimming and fishing but it is really an evaluation of whether a body of water is clean and healthy enough to support its "designated beneficial uses". Water quality, loosely defined, is a report card.

Why do we care about water quality in the Great Lakes? "The magnitude of the Great Lakes water system is difficult to appreciate. The lakes contain about 23,000 km^3 (5,500 cu. mi.) of water, covering a total area of 244,000 km^2 (94,000 sq. mi.) The Great Lakes are the largest system of fresh, surface water on earth, containing roughly 18 percent of the world supply. Only the polar ice caps contain more fresh water. In spite of their large size, the Great Lakes are sensitive to the effects of a wide range of pollutants. The sources of pollution include the runoff of soils and farm chemicals from agricultural lands, the waste from cities, discharges from industrial areas and leachate from disposal sites. The large surface area of the lakes also makes them vulnerable to direct atmospheric pollutants that fall with rain or snow and as dust on the lake surface" (USEPA, Great Lakes Atlas 1995). Lake Michigan has an average residence time of 99 years (time it takes for water entering the system to leave the system). Therefore, what we do now will still affect this system a lifetime from now and we are still addressing perturbations exerted a lifetime ago.

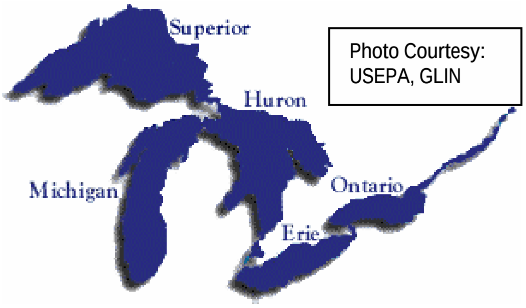


Photo Courtesy: USEPA, GLIN

Determining and tracking trophic state is one of the "subjects" that should be presented on the water quality "report card". Trophic state is an assessment on the "relative health" (pollution tolerance level, nutrient impact etc.) of a system. Three major categories; eutrophy, mesotrophy, and oligotrophy generally define trophic state. Generally, an oligotrophic system receives little “artificial / man made” nutrient input (for example, phosphorus, nitrogen) and is considered “unpolluted” (grade “A” on the report card), while an eutrophic system is highly productive, receives higher nutrient inputs and is often termed “polluted” (grade “D” on the report card). Trophic state is a measure of a systems productivity or metabolism. A succession from low productivity (oligotrophy) to high productivity (eutrophy) is a natural “aging” process. However, lake “productivity can be greatly accelerated by nutrient inputs” (Wetzel, 1983). When this natural process (eutrophication) is accelerated by man it has been termed “cultural eutrophication” (Likens, 1972). People can accelerate the eutrophication process by allowing nutrients from agriculture, lawn fertilizers, streets, septic systems, and urban storm drains to enter lakes (WDNR 1999). Simply stated, eutrophication is the “movement of a lake’s trophic state in the direction of more plant biomass” (Carlson 1996). “When the results of eutrophication are undesirable to man, it is often considered a form of pollution; but these two terms are not synonymous” (Likens, 1972). Lowe (1974) characterizes the various states of trophy into nutrient spectra as follows:

- Eutrophic: Characteristic of water with high nutrient concentrations
- Mesotrophic: Characteristic of water with moderate nutrient concentrations
- Oligotrophic: Characteristic of water with low nutrient concentrations.

Cole (1979) listed the following features to contrast oligotrophic and eutrophic lakes:

Table 1

OLIGOTROPHIC	EUTROPHIC
Blue or green water; marked transparency (i.e. secchi disk)	Green to yellow to brown water, limited transparency
Water poor in plant nutrients (i.e. nitrogen & phosphorus)	Plant nutrients abundant
Phytoplankton quantitatively poor	Abundant phytoplankton, mass great
Oxygen abundant all the time	Oxygen depletion – summer
Sediments low in organic matter	Sediments abundant with organic matter

The most important nutrients that contribute to trophic state are phosphorus and nitrogen. These nutrients are key to potential production by phytoplankton and when abundant can promote excessive algal growth and each nutrient, when sparse, can limit algal growth. They act much like lawn fertilizer in the aquatic system. This is evidenced by the extreme cultural eutrophication of Lake Washington and Lake Erie and their subsequent “recoveries” upon remediation. It should be noted that carbon also plays a key role in algal cell metabolism however, that nutrient was not investigated for this report.

Two trophic state indices were utilized to evaluate the Milwaukee area Nearshore waters using the District’s water quality monitoring data:

1. The Trophic State Index (TSI) developed by Carlson (1977) for use in lakes incorporates Secchi Disk (SD), Total Phosphorus (TP), and Chlorophyll (Chl) data. These three variables are considered to be indicators of productivity. The TSI converts raw data to a numerical scale. The higher the number, the higher the overall productivity and therefore, typically poorer water quality. The basic concept of a TSI is that trophic state (oligotrophy, mesotrophy, eutrophy) is based on nutrient levels (as measured by phosphorus), which in turn affects algal biomass (as measured by chlorophyll), which in turn affects water clarity (as measured by secchi disk). The Carlson TSI is a useful tool for evaluating trophic state (eutrophication / “pollution”) over time and for comparisons within geographic areas (site to site) (Bates 1999). Carlson’s equations for TSI are as follows:

$$\mathbf{TSI(SD) = 10(6 - (\ln SD/\ln 2))}$$
$$\mathbf{TSI(Chl) = 10(6-(2.04-0.68 \ln Chl/\ln 2))}$$
$$\mathbf{TSI(TP) = 10(6-(\ln(48/TP)/\ln 2))}$$

Carlson notes that “**a trophic state index is not the same as a water quality index**. The term “quality” implies a subjective judgement. Excellent, or poor, water quality depends on the use of that water and the local attitudes of the people” (Carlson 1977). MMSD water quality data (1980 – 1997) were analyzed using Carlson’s trophic state indices.

2. The Lake Trophic State Index (LTSI) is based on the principle that the contribution of each parameter (TP, Chl ^{a}, Secchi Disk) can vary by season and by lake but the combination of these 3 parameters into a single index serves to mathematically stabilize the index. Thus it can be used over a broad range of water body types (Yang and Dickman 1993). The LTSI is a mathematical modification of other trophic state indices and uses the following formula:

$$\mathbf{LTSI = 1.37 \ln [1+ (TP * \frac{Chla}{SD})]}$$

For purposes of this report, Trophic State Index (TSI) values are defined as follows:

Oligotrophic: 20
Mesotrophic: 40
Eutrophic: 60

And Lake Trophic State Index (LTSI) values as defined as follows:

Oligotrophic: 0.24 to 1.80
Oligomesotrophic: 1.81 to 3.00
Mesotrophic: 3.01 – 4.20
Mesoeutrophic: 4.20 – 5.40
Eutrophic: 5.41 – 9.50

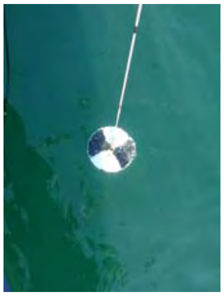
Interactions with chlorophyll were also examined as well as other possible factors that may influence trophic state (zebra mussel effects, MMSD deep tunnel system).

Methods:

Collection and Preservation

Whole water samples were collected from the MMSD Pelagos using a Kemmerer water bottle from the surface (1 meter below the actual surface), mid depth, and bottom (1 meter above the actual bottom) at each site. Samples bottles for total phosphorus were preserved and placed into a sample cooler with ice pending transport to the laboratory. Sample bottles for chlorophyll analysis were unpreserved and placed into a cooler with ice for transport to the laboratory. Analyses for total phosphorus and chlorophyll were conducted in the MMSD Central Laboratory facility using standard methodology. Secchi disk readings were performed at each site by an MMSD aquatic biologist.

MMSD Research Vessel (RV) Pelagos



Secchi Disk

Photos: MMSD, Ken Wardius

Site Descriptions (Figure 1)

For this study Nearshore (NS) 27 and NS11 were examined separately due to geographic location. These sites are located east of the South Shore Wastewater Treatment Facility (SSWTP). They are relatively shallow water sites with depths of approximately 7 and 9 meters, respectively. "NS28, 12, and 13 represent a progression of sampling sites in the Milwaukee Harbor starting just downstream of the confluence of the Milwaukee, Menomonee, and Kinnickinnic Rivers and extending east to the main gap of the Milwaukee Harbor. These sites are all within the breakwall and average approximately 10 meters in depth. They have traditionally exhibited high phytoplankton abundances and nutrient levels due to significant influence of the Milwaukee, Menomonee, and Kinnickinnic Rivers. These rivers serve as major sources of nutrient loading to the lake" (MMSD 1997). NS14 is directly east of this site progression, approximately 1 mile from the main gap. It is approximately 16 meters in depth and data from this location are similar to other MMSD Nearshore deep water sites. NS10 is an offshore site and the deep water station. It has been designated as the "clean water site". Its' water chemistry and biological parameters are not influenced by the Milwaukee area rivers. NS10 is approximately 85 meters deep and located about 7 miles directly offshore. It is approximately 11 miles Northeast of the Milwaukee Harbor (MMSD 1997). NS1 and NS3 are offshore sites with depths of 25 meters and 23 meters, respectively. They are located approximately 12 and 20 miles (respectively) southeast of the Milwaukee harbor mouth. Phytoplankton abundance and nutrient levels are generally lower and more indicative of Lake Michigan than at sites within the harbor or located closer to shore.

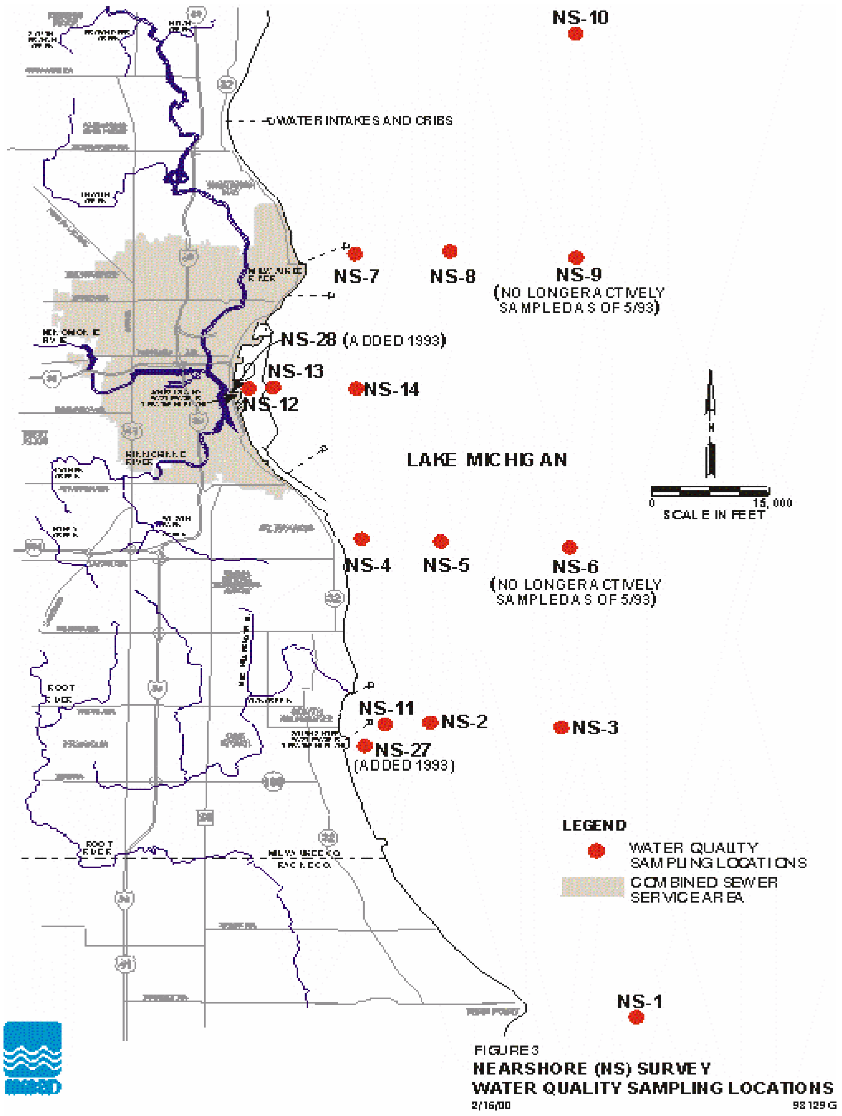


Figure 1

Additionally, inshore versus offshore differences are often apparent, influencing algal seasonality, species succession, and biomass (Munawar & Munawar, 1996). These differences can also contribute to trophic state, and some of the preceding sites were utilized to look at inshore/offshore divergence.

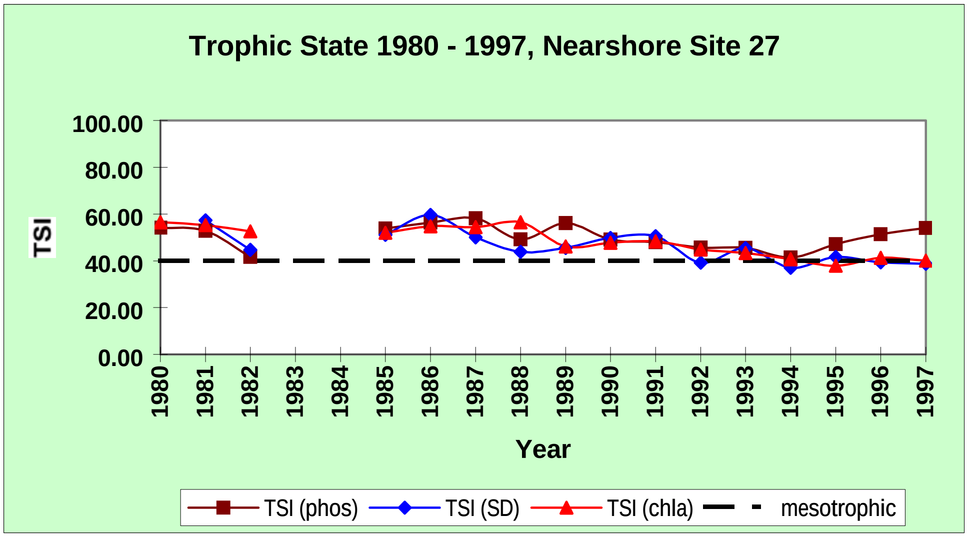
Results and Discussion:

Nearshore Sites 27 and 11

Nearshore (NS) site 27 is located approximately 0.30 miles from shore, directly east of the SSWWTP and south of the submerged SSWWTP outfall (**Figure 1**). This site was added to the Nearshore Survey in 1993, therefore biological (phytoplankton and zooplankton) data do not exist prior to 1993. NS27 was added to assess the impact of the SSWWTP effluent on Lake Michigan through the monitoring of various water quality data including the biological component. Since NS27 is regularly sampled as part of the South Shore Survey; chlorophyll, total phosphorus, and secchi disk data do exist and were utilized for portions of this report.

Nearshore site 11 is located approximately 1.00 mile from shore, east of the SSWWTP and in a direct easterly line from the outfall (**Figure 1**). This site has been regularly sampled as part of the Nearshore monitoring effort. Sampling at this site is also used to provide data and assess impact in regard to the SSWWTP effluent.

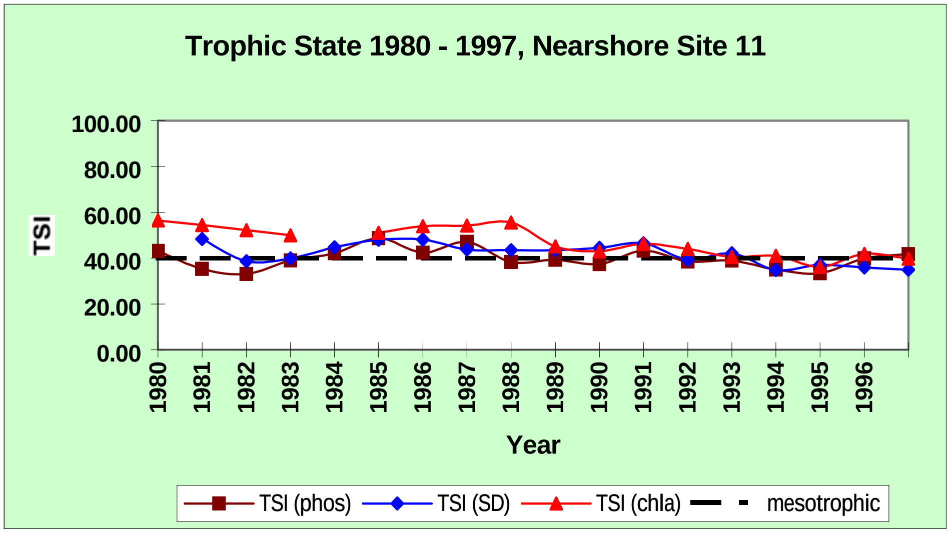
Figure 2



When the TSI of NS27 and NS11 for the years 1980 through 1997 **(Figures 2 and 3**) is examined, the two sites exhibit a trophic state between mesotrophy and eutrophy. Trophic state appears to be trending downward (toward mesotrophy) starting in the late 80's to early 90's. There is a spatial difference between these two sites; NS27 had values exclusively in the mesotrophic-eutrophic range until 1992 when the secchi disk TSI improved dropping just below the mesotrophic line (**Figure 2**). Conversely, NS11 had TSI values for phosphorus and secchi disk below the mesotrophic line (towards oligotrophy), on several occasions in the early 1980's (**Figure 3**) and more values at or below the mesotrophic line overall. There has been a definite improvement of trophic state at both sites with TSI values at NS11 and NS27 being mostly mesotrophic since 1992. The exception at NS27 is the phosphorus TSI which exhibited an upward trend towards eutrophy beginning in 1995 and increasing through 1997 (**Figure 2**). Phosphorus loading to the lake can increase with heightened precipitation; therefore if these years were "wet" years with a lot of precipitation or a higher number of flooding events, phosphorus content would increase due to surface runoff. Other sources of phosphorus loading are effluent from sewage treatment plants, atmospheric deposition, zebra mussels (can affect biological TP uptake, TP regeneration and availability), resuspension events and combined sewer overflows (although outside of the CSO area, due to the southerly flow of water from the Milwaukee Harbor, CSO effects may still be noted here).

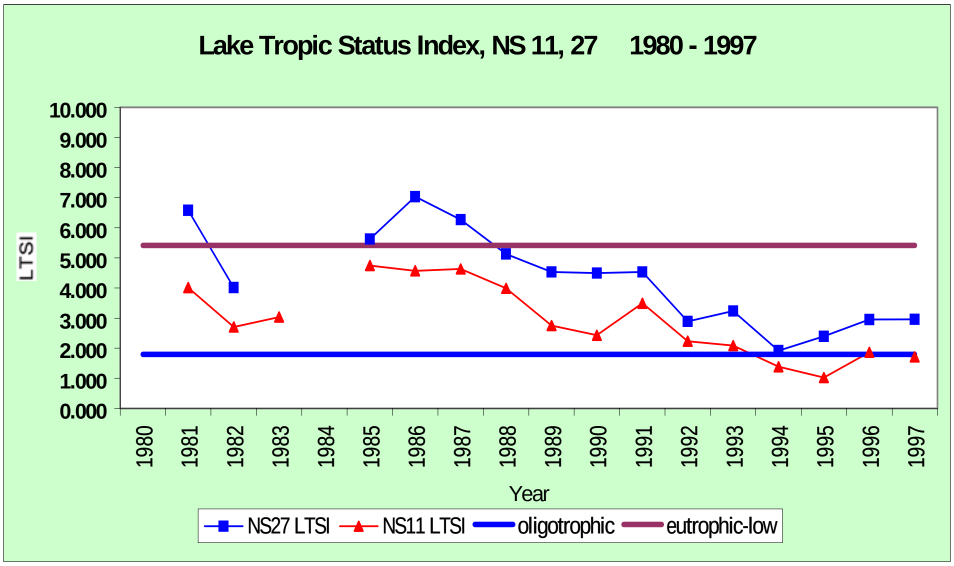
The overall improving trends in TSI values could indicate an improvement in nutrient loading to this area of the lake.

Figure 3



The LTSI (**Figure 4**) showed similar trends with overall improvement in trophic state at both sites, beginning as early as 1988/89. The LTSI also illustrates a spatial difference between NS27 and NS11 with NS11 having consistently lower LTSI values and therefore, "better" trophic state. The LTSI rates NS11 as oligotrophic from 1994 to 1997 and NS27 as oligomesotrophic for the same time period. These values are an improvement over the TSI ratings, although an upward trend for 1995 – 1997 is still noted. Overall, the LTSI shows definite and improving trends at both NS11 and NS27.

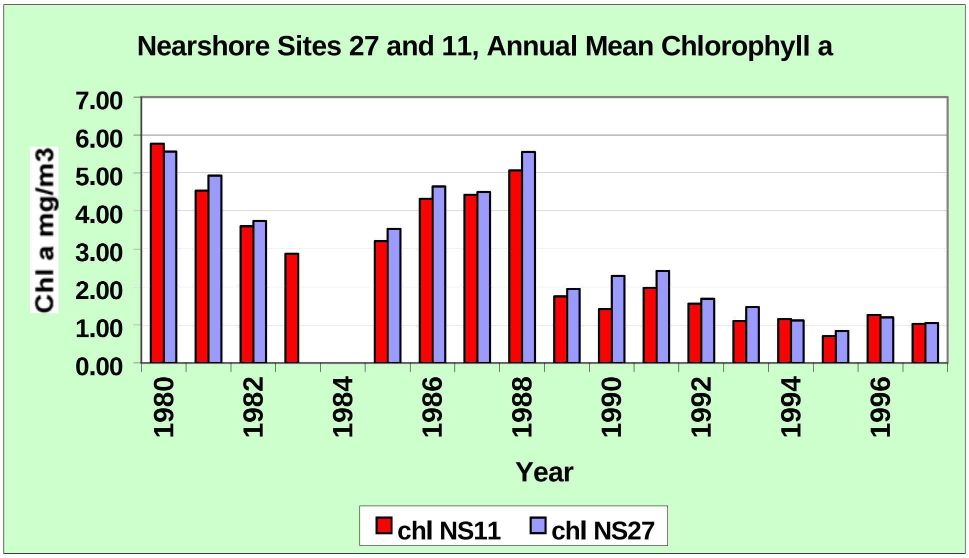
Figure 4



Temporally, trophic state at both sites has fluctuated over the 17 year period examined, with the greatest fluctuations occurring in the 1980's.

Chlorophyll is an important parameter to evaluate in regard to any study of surface water quality. Chlorophyll determinations give us a good idea of overall productivity as it relates to algal concentration. In fact chlorophyll concentrations have been significantly correlated with phytoplankton densities (Nicholls 1993). A closer examination of mean annual chlorophyll values (1980 – 1997) shows a dramatic drop in lake chlorophyll levels at NS27 and NS11 **(Figure 5**). Chlorophyll levels dropped significantly in 1989 (greater than a twofold decrease). These levels continued to

Figure 5



decrease through 1995. This drop in chlorophyll could be due to the invasion of zebra mussels into Lake Michigan. This exotic species first occurred in the Great Lakes in 1985 (Lake St. Clair, Lake Erie) and has become a dominant member of the nearshore benthic community (Berg 1996) and proceeded to quickly spread throughout the Great Lakes (USEPA, LaMP 2000). The MMSD Water Quality Research (WQR) staff first detected adult and immature (veligers) zebra mussels at the Milwaukee River flushing tunnel in August 1991. It is very likely that this invader was present in Southeastern Lake Michigan long before its detection by WQR staff in 1991. The overall drop in chlorophyll levels also substantiates the decreasing TSI trend for this parameter.

The driving force of these differences and other results could be due to many factors: temperature, thermal gradient, nutrient availability, circulation, turbulence, zooplankton predation, sampling and laboratory methodology, storm resuspension events, exotic species invasions and subsequent food web changes, etc. Zebra mussels have a direct effect on phytoplankton cell density in that their capacity to filter water is phenomenal. A single zebra mussel has a filtration capacity of 1 Liter per day and is capable of removing almost every microscopic aquatic plant (phytoplankton or algae) and animal (zooplankton). Zebra mussel colonies in Lake Erie have reached astounding densities of 70,000 per square meter, and experts estimate that Lake Erie's zebra mussel population filters the entire volume of the lake's western basin once a week. (Wisconsin Sea Grant 2000). In the Milwaukee area, zebra mussel densities have ranged between 2900 to 55,000 veligers per cubic meter (Wisconsin Sea Grant 1994). They can also have an “indirect effect on algal density and seasonal patterns” (DePinto et. al. 1999) by disrupting regular processes of the ecosystem (Heath 1995). Additionally, algal population densities can be affected by increased sediment-water phosphorus fluxes i.e., zebra mussels filter out phytoplankton and other similar sized particles; this material is either assimilated by the mussel or deposited to the bottom as fecal (or pseudo-fecal) material (DePinto et.al. 1999), thus making nutrients available to other organisms.

Zebra Mussels. Courtesy: USEPA, GLNPO

It is also possible that some sort of nutrient limitation is at work here. Nutrient limitation in terms of trophic state would affect algal biomass (decrease in chlorophyll concentration) and ultimately water clarity (improvement in secchi disk value). Studies have shown that declines in phosphorus inputs **and** the introduction of zebra mussels could have cumulative effects on algal population composition (Heath 1995, Nicholls 1993). Nicholls (1993) stated that it was "reasonable to expect that the effects of zebra mussel filtration would be greater in shallower nearshore areas in closer proximity to zebra mussel substrate". Additionally, Heath (et. al. 1995) stated that "the phytoplankton community is phosphorus limited if the TSI values calculated from total phosphorus equal the TSI values calculated from chlorophyll concentrations". **Figure 2** shows that TSI (TP) and TSI (Chl) for NS27 are very close with data being almost equal starting in 1990 and continuing through 1994. In 1995, the two data points diverge. This could indicate that NS27 was phosphorus limited until 1995. TSI values for chlorophyll and phosphorus at NS11 (**Figure 3**) begin to merge in 1991 and continue through 1993. In 1994 the two data points diverge. The relationship between TSI (TP) and TSI (Chl) is not as clearly defined at NS11 as at NS27 but enough similarities in the data exist to suggest that the potential for phosphorus limitation existed during these years. This data also shows that again, there are some spatial differences between these two nearshore sites, despite their proximity to each other.

Nearshore Sites 1, 3, 10, 12, 13, 14, and 28 (Results and Discussion con't)

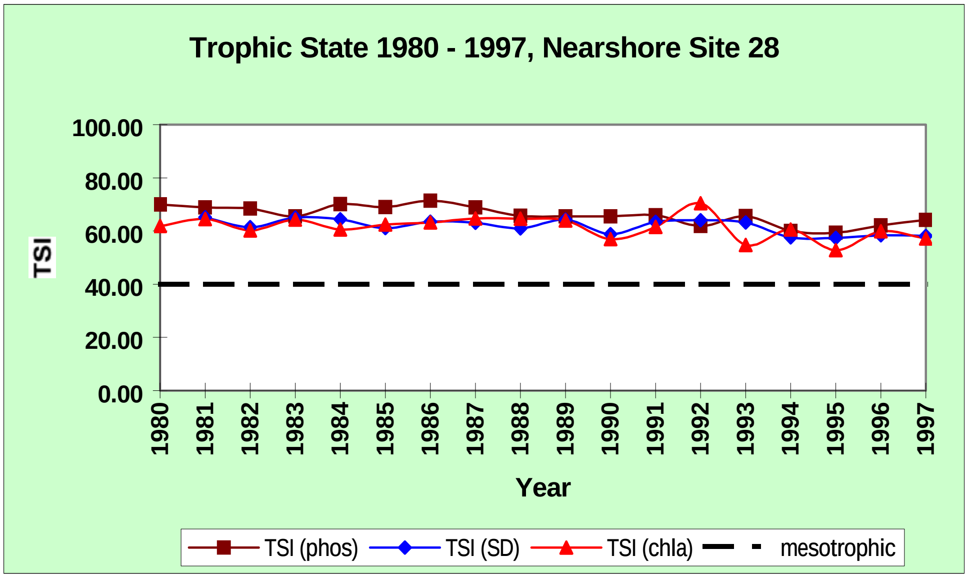
Nearshore Sites 28, 12, and 13 extend straight east from the confluence of the Milwaukee, Menomonee, and Kinnickinnic rivers to the main gap of the harbor breakwall (**Figure 1**). These sites are within close proximity to the Jones Island Wastewater Treatment Plant (JIWWTP) outfall. Since these sites follow a path from the rivers' confluence, improvements made during the MMSD Water Pollution Abatement Program (Deep Tunnel Project completed in mid 1993, fully operational 1994) could also be having a positive effect on water quality in these areas. With the Deep Tunnel completion, overflow events have been significantly reduced. This system has prevented more than 40 billion gallons of wastewater from entering Milwaukee area rivers and Lake Michigan since becoming operational in 1994 and has reduced overflow events from approximately 50 per year to an average of two (MMSD 2000). It follows then that nutritional inputs from these sources would also have been significantly reduced. The MMSD found that "phosphorus and fecal coliform bacteria have a major influence on water quality at all sites and that inside the CSO area, dissolved oxygen is a consistent variable determining bad and very bad water quality" (MMSD October 1997). The Deep Tunnel system not only keeps sanitary and combined sewage from entering the river systems and ultimately Lake Michigan, but also captures non-point pollutional material such as fertilizers, pet waste, street runoff etc. This system has significantly reduced loading of nutrients and suspended solids. These reductions should be reflected in improved water quality and subsequent improvements to the biological community.

Milwaukee Harbor and Breakwall: note loading from inner harbor/rivers (photo courtesy USGS)

NS28, 12 and 13 have historically exhibited high phytoplankton abundance's (consequently high chlorophyll values) and nutrient levels due to the significant contribution of nutrients by the rivers to the outer harbor and Lake Michigan. The rivers can actually function as a "seed" mechanism for phytoplankton in the harbor, not only in regard to nutrient input but also species richness and abundance. Stoermer (1985) noted that the Saginaw River had significant influence on the phytoplankton flora in Saginaw Bay. In contrast, NS14, 1, 3, and 10 are all located outside of the Milwaukee Harbor breakwall (**Figure 1**). Their locations and depths were discussed earlier in this report. With the exception of Site 14, these sites do not reside in an area that is significantly influenced by the 3 rivers with NS10 being located to the north of the harbor, NS1 and 3 to the south of the harbor, and NS14 directly east of the harbor.

The trophic state for NS28, 12, 13, 14, 1, 3, and 10 was examined for the years 1980 through 1997 using the TSI and LTSI. NS28, 12, and 13 will be discussed first and results are illustrated in **Figures 6 – 9**.

Figure 6



These sites remain similar to each other in regard to trophic state – all being in the eutrophic range even though the trends at these sites are slightly downward, towards improved status. The exception to this is at NS12 where the TSI (TP) trend increased slightly. This is most likely due to the year 1995 when the highest TSI (TP) for all years was noted with a value of 72.13 (highly eutrophic) (**Table 2**). Interestingly, TSI (TP) data at NS28 and NS13 did not show this increase and actually decreased slightly. Given the location of NS12 (midway between NS28 and NS13) and the proximity of the three sites to each other, this is indeed a peculiar phenomenon.

One possible explanation for this is the water current patterns within the harbor. River flow patterns into the harbor have been shown to exhibit "mixing patterns concentrated in localized segments (gyre's) of the harbor" (Lee et. al, 1980). Additionally, due to the existence of these gyre's, actual retention time (usually 1 ½ to 2 days) can be greatly extended (Lee et. al. 1980). The retention of water potentially carrying higher nutrient content will serve to increase the concentration of the nutrient, particularly with little or no mixing of Lake Michigan water.

It is important to target the year 1992 as well. All three of these sites experienced a notable increase in the TSI (Chl). NS28 increased from 61.5 in 1991 to 70.4 in 1992, NS12 increased from 60.9 to 69.9, and NS13 increased from 58.6 to 69.0 (**Table 2**). Additionally, NS28 and

Figure 7

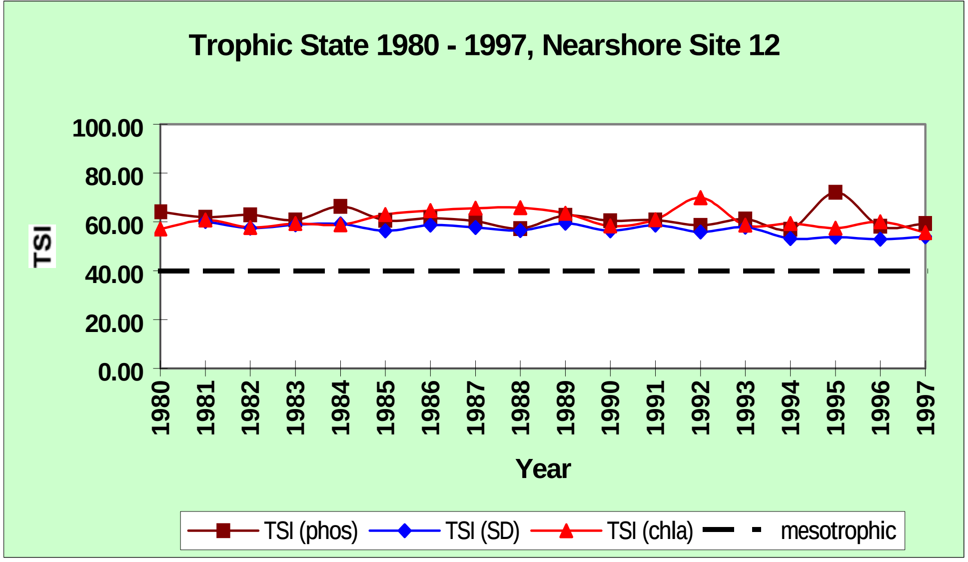
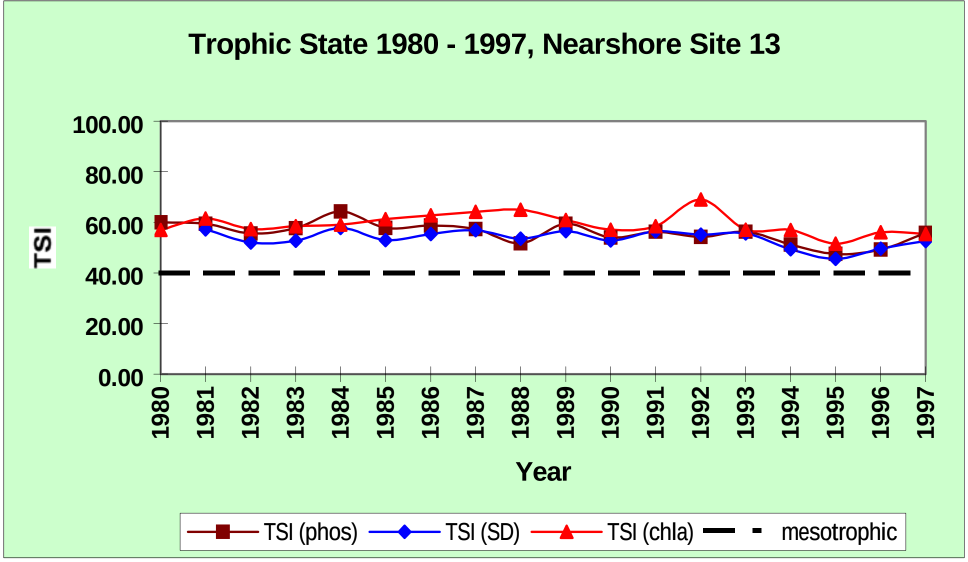


Figure 8

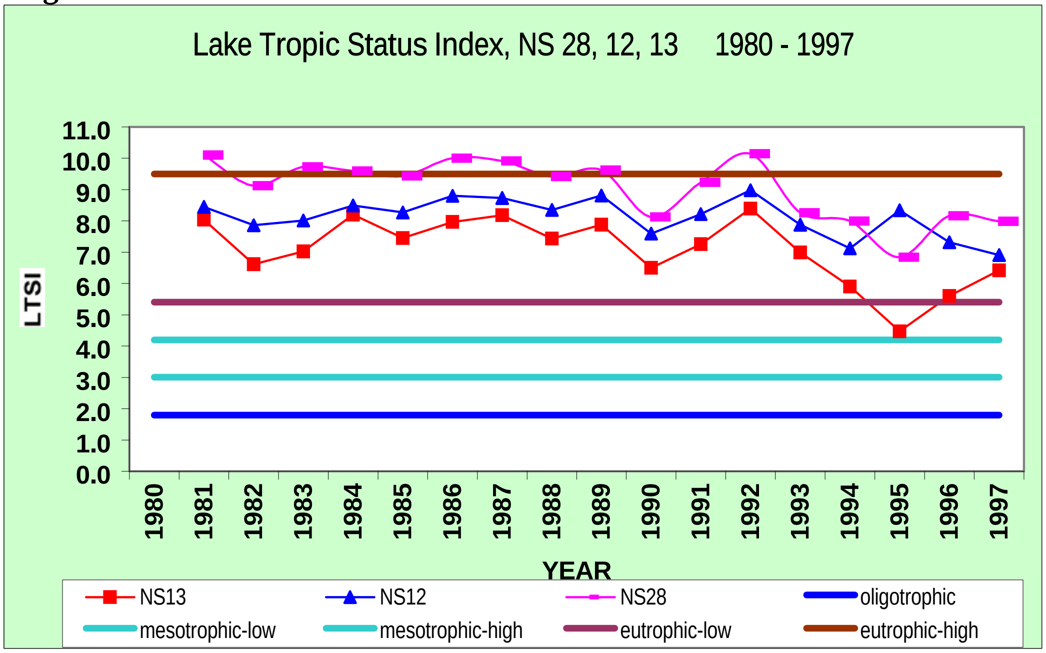


NS12 had the lowest TP values for the time period 1980 – 1992; NS13 had the third lowest TP values for the time period. Secchi disk readings for 1992 at all three sites also improved, with improvements to a greater degree at NS28 and NS12. Obviously, as algal biomass (production as measured by chlorophyll) increased, nutrients (TP) were utilized, and water clarity improved. The question is what caused algal biomass to increase so notably? It is possible that algal productivity was being limited by an essential micronutrient or by nitrogen or carbon; all of which are important to producing algal biomass. If a limiting nutrient suddenly becomes available the algal population will respond to this opportunity by increasing their numbers which will be measured through increased chlorophyll values.

The potential for some phosphorus limitation has sporadically existed throughout these years (**Table 2**). NS28 had similar TSI (TP) and TSI (Chl) values in 1983, 1989, and 1994. NS12 had similar values in 1981, 1983, 1989, 1991, and 1996. NS13 had similar values in 1981, 82, 83 1989, 1993 and 1997. Obviously, NS13 had many more occasions (6 years) for phosphorus limitation than NS28 (3 years). NS12 also had more occasions (5 years) for potential nutrient limitation than NS28. As discussed earlier, some spatial differences exist between these three inner harbor sites despite their proximity to each other and their containment within the harbor breakwall. For comparison purposes only, when the individual TSI's are averaged for all years we see that NS28 has slightly worse (higher) TSI values than NS12 and NS13 (**Table 2)** and the LTSI verifies this diminished trophic state. This could be due to a variety of factors. NS13 is located at the main gap of the Milwaukee Harbor and is strongly influenced by Lake Michigan water. Therefore, we would expect better values at this site. NS28 while still subject to Lake Michigan influence, is located within a relatively narrow area closest to the confluence of the three rivers, consequently, this site would be affected to a greater extent by river water quality than NS12 or NS13. NS12 is located approximately mid harbor and would be affected by lake water entrenchment and mixing but to a lessor extent than NS13.

The LTSI (**Figure 9**) also illustrates similarities and differences in trophic state between NS28, 12 and 13. NS28 had consistently higher LTSI values than NS12 or NS13. NS12 displayed consistently higher values than NS13. This illustrates the spatial differences between the 3 sites (despite their close proximity) and the influences of the Rivers and Lake Michigan on LTSI and trophic state in general. The LTSI also rates the 3 sites as consistently eutrophic and shows the same conflict in 1995 with LTSI's at NS28 and NS13 improving while LTSI at NS12 increased in eutrophic ranking. The LTSI also found the same increases at all 3 sites in 1992. The LTSI trend at NS28, 12 and 13 are improving toward lower eutrophic state with NS13 actually achieving a mesoeutrophic state in 1995.

Figure 9



Temporally, it is obvious from **Figures 6, 7, 8 and 9** that trophic state has fluctuated over the years 1980 to 1997 at all three sites and trophic state for all three indices has remained in the eutrophic range. Moreover, the LTSI at these three sites has fluctuated synchronously with the exception of 1995 as previously discussed. Both indices have indicated improvement in trophic state over time but still remain in a state of eutrophy.

TABLE 2: TROPHIC STATE INDEX VALUES by YEAR: 1980 – 1997

Site	Year	TSI (TP)	TSI (SD)	TSI (Chl)	Average All years	Site	TSI (TP)	TSI (SD)	TSI (Chl)	Average All years	Site	TSI (TP)	TSI (SD)	TSI (Chl)	Average All years	Site	TSI (TP)	TSI (SD)	TSI (Chl)	Average All years
NS1	1980	37.43		56.51	TSI(TP) 36.9 TSI(SD) 35.2 TSI (Chl) 46.6	NS3	40.23		54.19	TSI(TP) 36.0 TSI(SD) 33.9 TSI (Chl) 46.4	NS10	30.65		45.99	TSI(TP) 36.2 TSI(SD) 32.3 TSI (Chl) 43.3	NS14	39.62		54.15	TSI(TP) 39.1 TSI(SD) 40.6 TSI (Chl) 48.7
	1981	25.91	38.66	50.51			35.10	35.96	49.68			24.40	32.03	47.16			33.94	42.78	54.00	
	1982	32.77	30.61	53.25			30.20	33.50	54.56			25.69	31.70	44.88			40.04	40.51	54.93	
	1983	42.65	28.56	51.78			36.78	30.32	49.63			37.27	35.56	43.97			46.79	44.52	54.25	
	1984	40.31	44.08				40.31	23.40				36.52	27.76				47.99	45.45	55.15	
	1985	44.74	38.53	49.40			39.23	35.43	48.46			49.17	32.61	44.94			44.27	42.72	50.09	
	1986	31.10	37.92	51.06			31.63	35.53	50.43			35.40	30.40	44.12			40.91	42.65	51.45	
	1987	44.48	36.45	49.42			38.25	35.26	47.45			51.30	32.35	43.25			42.38	42.36	50.93	
	1988	31.75	35.43	55.65			29.03	35.03	54.62			31.02	33.21	50.12			41.30	39.83	52.46	
	1989	31.02	39.03	41.96			30.06	38.69	40.68			24.87	34.71	35.85			35.83	42.77	43.36	
	1990	37.74	28.98	30.49			36.78	30.23	30.81			32.77	30.80	31.21			31.12	37.65	37.27	
	1991	37.27	41.93	41.15			35.74	40.28	40.11			38.54	37.34	34.62			37.05	42.45	43.78	
	1992	33.42	33.44	47.07			29.86	33.44	48.34			33.73	33.44	41.55			32.88	40.15	54.62	
	1993	39.67	35.61	46.55			36.06	38.20	47.62			34.97	31.92	45.96			37.94	41.70	49.20	
	1994	39.91	33.65	43.19			42.75	37.03	43.48			39.58	32.83	43.97			36.18	36.29	43.43	
	1995	34.48	33.10	39.20			33.42	33.79	41.83			44.38	32.98	40.49			35.08	35.64	40.14	
	1996	35.74	34.78	46.48			38.54	31.29	47.14			42.03	33.17	50.68			38.27	37.41	46.34	
	1997	43.88	27.37	38.97			44.67	29.51	39.43			39.77	27.32	47.10			41.69	36.16	40.66	
NS28	1980	70.00		61.87	TSI(TP) 66.0 TSI(SD) 61.8 TSI (Chl) 61.4	NS12	64.12		57.10	TSI(TP) 61.4 TSI(SD) 56.9 TSI (Chl) 60.9	NS13	59.98		56.94	TSI(TP) 55.9 TSI(SD) 53.7 TSI (Chl) 59.4					
	1981	68.92	65.17	64.56			61.96	60.18	60.77			59.46	57.28	61.47						
	1982	68.50	61.48	60.26			62.87	57.51	57.73			55.59	52.08	57.37						
	1983	65.48	65.04	64.29			60.78	58.85	59.31			57.72	52.67	58.48						
	1984	70.11	64.42	60.56			66.29	59.13	58.82			64.27	57.77	59.03						
	1985	69.00	61.09	62.43			60.63	56.41	62.95			57.85	52.97	61.27						
	1986	71.45	63.52	63.22			61.50	58.72	64.62			58.69	55.39	62.73						
	1987	68.87	63.03	64.68			60.25	57.77	65.61			57.33	56.92	64.19						
	1988	65.67	61.04	64.59			57.15	56.42	65.86			51.65	53.49	64.99						
	1989	65.49	64.33	63.97			62.63	59.38	63.47			59.44	56.48	60.89						
	1990	65.46	58.78	57.00			60.41	56.32	58.29			53.97	52.89	57.06						
	1991	65.97	63.37	61.51			60.77	58.69	60.88			56.28	56.45	58.55						
	1992	61.90	64.03	70.39			58.57	55.83	69.88			54.27	55.12	69.05						
	1993	65.63	63.23	54.82			61.22	57.88	58.73			56.36	55.65	57.10						
	1994	60.06	57.60	60.55			57.01	53.13	59.36			51.24	49.33	57.01						
	1995	59.32	57.44	52.80			72.13	53.79	57.41			47.55	45.53	51.54						
	1996	62.10	58.34	59.87			58.18	52.92	60.10			49.27	49.55	56.02						
	1997	64.22	58.19	57.21			59.34	53.94	55.64			55.85	52.57	55.40						

The TSI trends at NS14 show definite improvement in trophic state (**Figure 10**), with TSI (TP) and TSI (SD) moving below the mesotrophic line. TSI (Chl) which consistently had values in the eutrophic low to mid 50's improved in 1989 and generally continued to improve through 1997 with values being mostly in the mid 40's. The exceptions are 1992 and 1993 when the TSI (Chl) had a trophic state value of approximately 55 and 49 respectfully, placing this TSI in the eutrophic range. The other TSI's did not experience this increase.

Figure 10

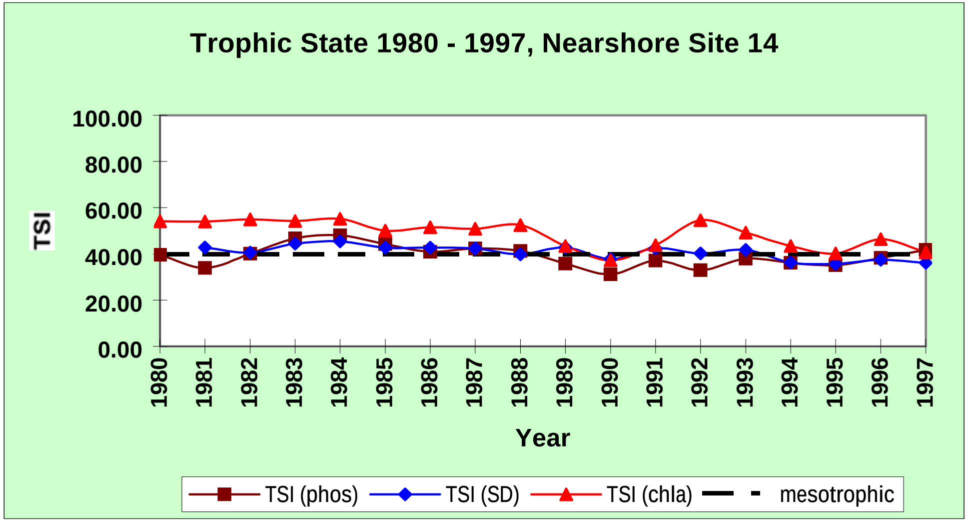
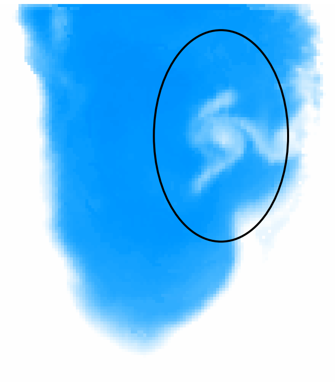


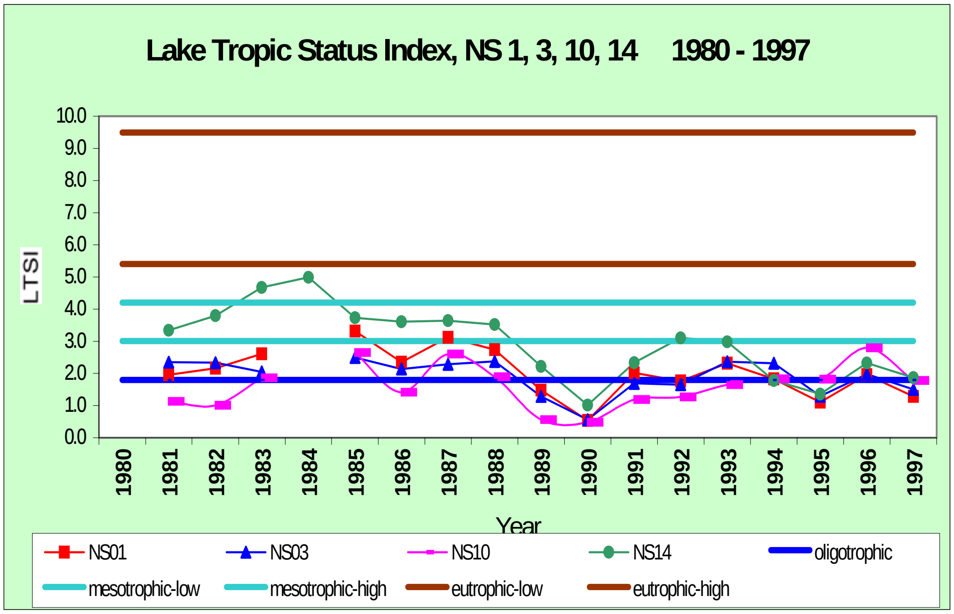
Figure 10 also illustrates the fluctuation of the various trophic state indices over time. This site also experienced a significant increase in the 1992 TSI (Chl), rising from a mesotrophic 44 to a eutrophic 55. The other TSI indices did not experience this increase and in fact, decreased. **Figure 10** shows that the only year for potential phosphorus limitation (as defined by approximately equal TSI (TP) and TSI (Chl)) was 1997 when the TSI (TP) was 42 and the TSI (Chl) value was 41. Possibilities for the elevated 1992 and 1993 TSI (Chl) are; precipitation, nutrient limitations in 1991 which once alleviated contributed to rapid algal growth, decreased zooplankton predation, increasing phytoplankton populations from the rivers, zebra mussel excretion of soluble reactive phosphorus (SRP) and other nutrients causing a spike in phytoplankton activity and subsequent chlorophyll concentration, light penetration and availability, resuspension of sediment materials, upwelling, the Lake Michigan sediment plume, and other episodic events.

Southern Lake Michigan



A major storm in Lake Michigan with 30 – 40 mph winds and 20 ft. waves initiated the plume captured in this image. This event is transporting huge quantities of resuspended (sediment) material offshore. PHOTO: EEGLE project (NOAA).

Figure 11



The LTSI at Nearshore 14 shows definite improvement with values dropping from mesotrophic to oligomestrophic values and even oligotrophic status (**Figure 11).** NS14 shows a definite decreasing trend in the LTSI indicating improving trophic state.

The TSI at NS1, NS3, and NS10 for the years 1980 – 1997 generally shows a trophic state between mesotrophy and oligotrophy (**Figures 12, 13, 14**) and generally improving or steady trends. The TSI for total phosphorus is the exception, having a definitive to slight increase at all three sites (**Figures 12, 13, 14**). In fact, averages for the 1980's decade vs. the 1990's decade clearly illustrate an increase of this TSI (**Table 3**) with the largest increase occurring at NS10. At NS1, the trophic state index (**Figure 12, Table 2)** for total phosphorus was at or below the mesotrophic line for almost all of the 17 year period, rising above the 40 mark on only 4 occasions: 1983, 1985, 1987, and 1997. At NS3, the TSI **(Figure 13, Table 2)** for total phosphorus was above mesotrophic line in 1980, 1984, 1994 and 1997 NS10 total phosphorus TSI **(Figure 14, Table 2)** was above the mesotrophic line in 1985, 1987, 1995 and 1996.

Figure 12

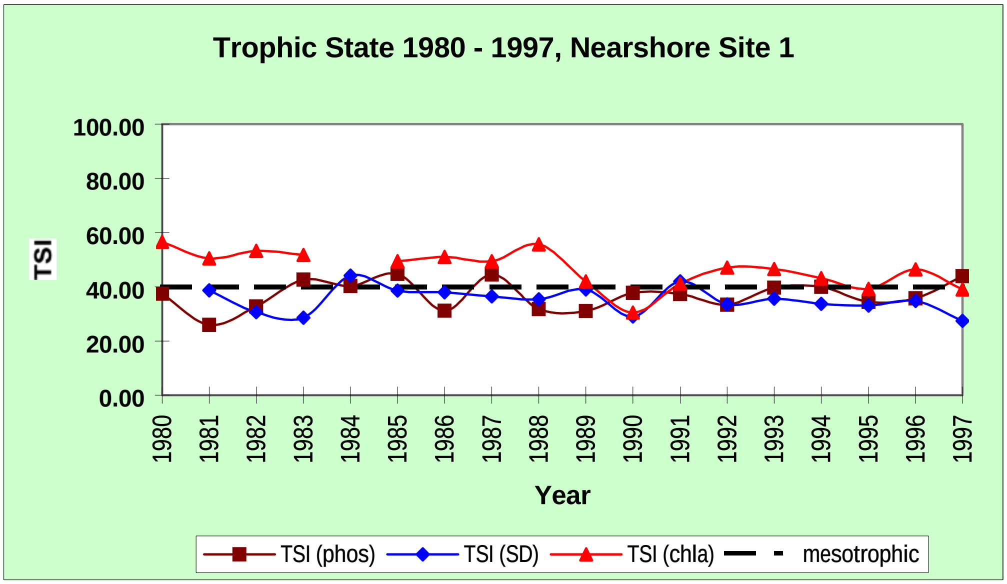


Figure 13

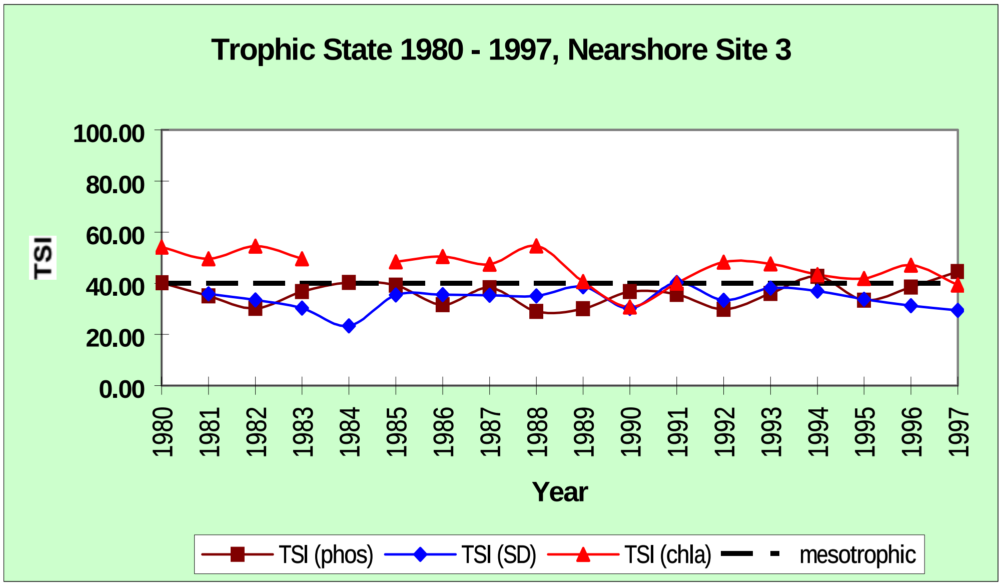


Figure 14

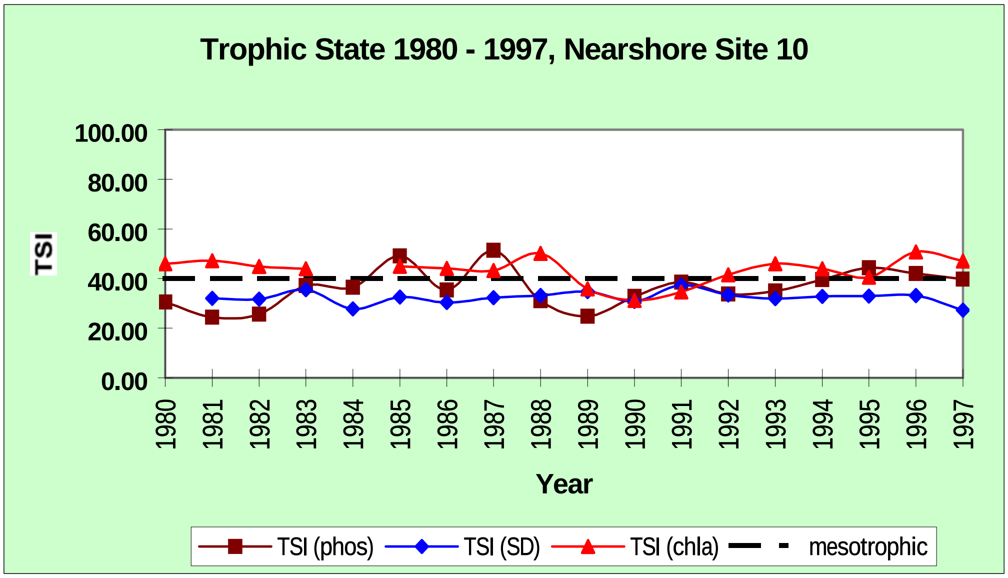


Table 3 Average TSI (TP) values comparing 1980's to 1990's

		TSI (TP)		*TSI (TP)*		*TSI (TP)*
NS1	1980's	36.22	***NS3***	35.08	***NS10***	34.63
	1990's	37.76		37.23		38.22

These increased phosphorus concentrations could be due to normal variation in water quality data. Fluctuations of data over time are common. It is important to be sure that an analysis is not based on a low or high period, but rather the overall trend. This is why long term environmental monitoring is critical. The increased phosphorus concentrations could also be due to erosion, sediment recycling and resuspension effects, the southern Lake Michigan sediment plume, upwelling, and other episodic events, which promote the mixing of sediment into the water column. The Lake

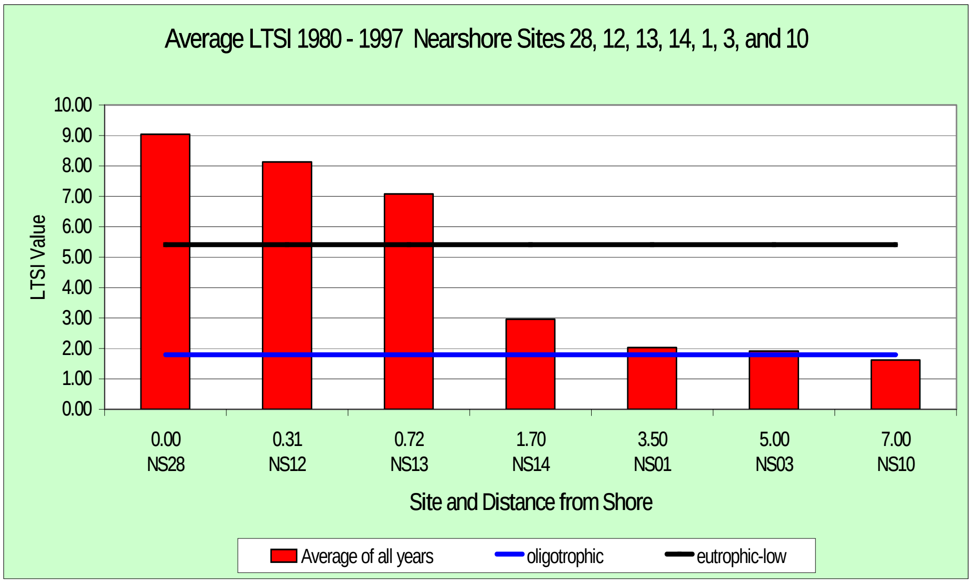
Sediment plume due to erosion. PHOTO Courtesy GLNPO.

Michigan sediment plume is estimated to be up to 12 miles wide and 200 miles long. It appears in the spring of each year usually with the first big storm after the ice cover is gone from the lake. It is suspected to have a profound impact on the ecology of Lake Michigan and may be a major mechanism for resuspending and transporting both nutrient and contaminants in the lake (NOAA Oct. 97)

The LTSI at NS1, 3, and 10 for the years 1980 – 1997 show a consistent trophic state between oligomesotrophic and oligotrophic (**Figure 11**). The trend at NS1 and NS3 has been toward improved status. The LTSI trend as NS10 is increasing toward a less desirable status; however, the trend is still contained within the oligotrophic range. The NS10 LTSI trend could be indicative of general water quality degradation to the open waters of Lake Michigan and based on previous discussion could partly be due increasing phosphorus levels.

The spatial differences between all sites are nicely illustrated in **Figure 15** with NS14 having the highest LTSI values of the outer sites followed by NS1, NS3 and NS10 with the lowest LTSI in general. NS28 had the highest LTSI of the inner sites followed by NS12 and NS13 respectively.

Figure 15



This is as one would expect, **Figure 15** graphically represents all sites in relation to their respective distances from shore (and therefore pollutional sources) and LTSI average values. The spatial difference and progression of degrading trophic state is most likely due to the influence of Harbor and the three area rivers on trophic state.

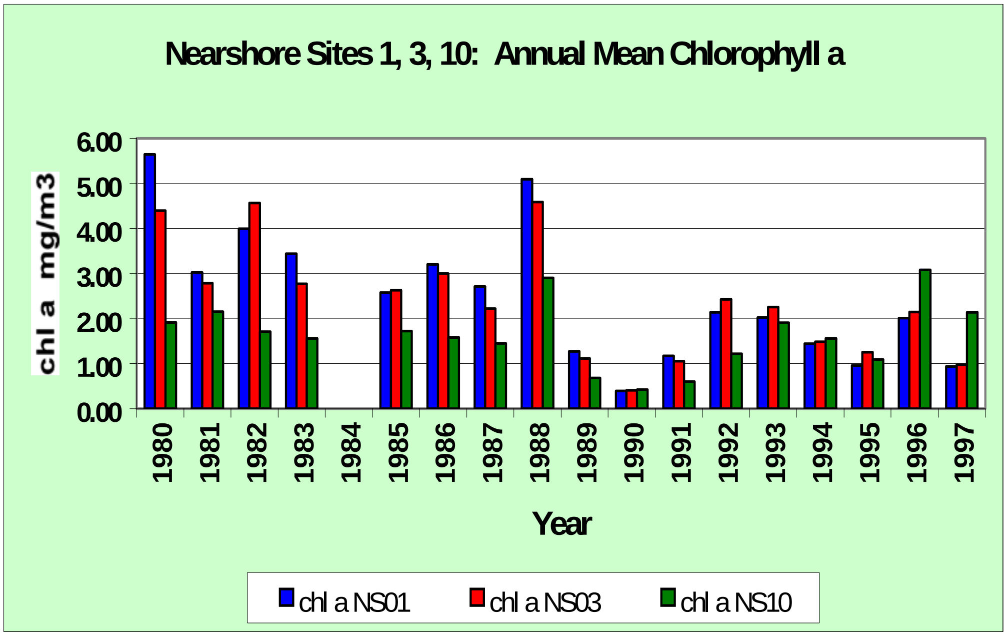
Chlorophyll

Chlorophyll concentration has been significantly correlated with phytoplankton cell density (Nicholls 1993) and is an important parameter to consider when evaluating algal populations or surface water quality. Many factors affect the planktonic community, which have the ability to respond very quickly. This response can be evaluated using chlorophyll data as an indication of algal biomass. Potential factors that impact surface water quality and therefore the phytoplankton are; exotic species effects and subsequent food web (and nutrient) implications, temperature, thermal gradient, light penetration and availability, nutrient availability, turbulence, water circulation patterns, episodic events (resuspension and recycling of nutrients, erosion etc.), zooplankton predation, and sampling methodology. Other impacts to surface water quality are; organic chemical contamination, metal toxicity, potential silica limitation to diatoms, algal production and related regulation of carbon flow in the aquatic system (Epplett, 2000) and bacterial competition for nutrients. In regard to nutrient availability and recycling of phosphorus from the sediments: it has long been accepted that productivity in the Great Lakes is limited by phosphorus (Cotner 1997, Partnership for Saginaw Bay 2000) because of the extremely low concentrations present in the water column. It is also known that phosphorus is recycled into the aquatic system through sediment resuspension events, dissolution, readsorption at the sediment/water interface, and that zebra mussels may potentially control ecosystem function by providing nutrients at a rapid rate through pseudo-fecal inputs (Heath 1995). DePinto (1999) noted that in Lake Erie beginning in 1988 and especially in 1989-90, there was a decrease in phytoplankton biomass with **no decrease in phosphorus load.** He further stated that the only logical hypothesis was the additional loss of algal biomass due to zebra mussel activity. Effler (1998) found that zebra mussels contributed to phosphorus dynamics alterations in a system by significantly enhancing the amount of soluble reactive phosphorus in the water column without a change in total phosphorus concentration. All of these factors affect algal biomass (chlorophyll).

As a side note, quagga mussels are another exotic species that were introduced to the Great Lakes about the same time as the zebra mussels; they infest deeper (profundal) areas, may be able to out compete zebra mussels, and while the ecological implications are not yet understood, it has the potential to significantly alter ecosystems (Mills 1999), especially benthic productivity. It is expected to eventually colonize the upper Great Lakes. Future studies of Lake Michigan productivity should take the effects of this exotic species into account.

Annual mean chlorophyll data are presented in **Figures 16, 17, and 18**.

Figure 16



Lake chlorophyll levels at NS1, 3, 10 and 14 (**Figures 16 & 17**) experienced a significant drop in 1989 (similar to NS27 and 11), decreasing in value threefold. Chlorophyll concentration at NS1 and 14 never returned to pre 1989 levels (except 1992 at NS14). NS10 did eventually return to pre 1989 levels and NS3 began to approximate pre 1989 levels.

Figure 17

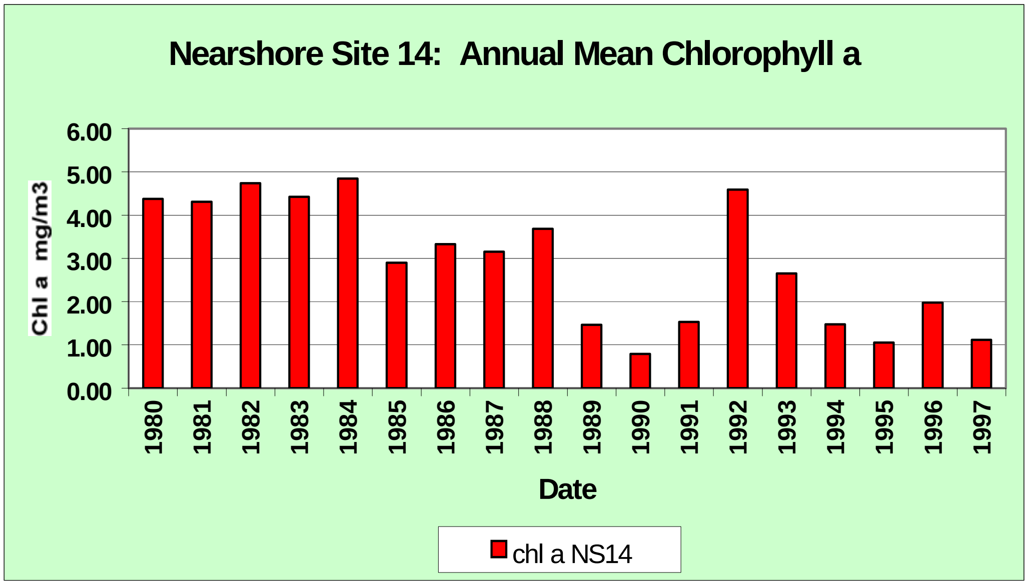
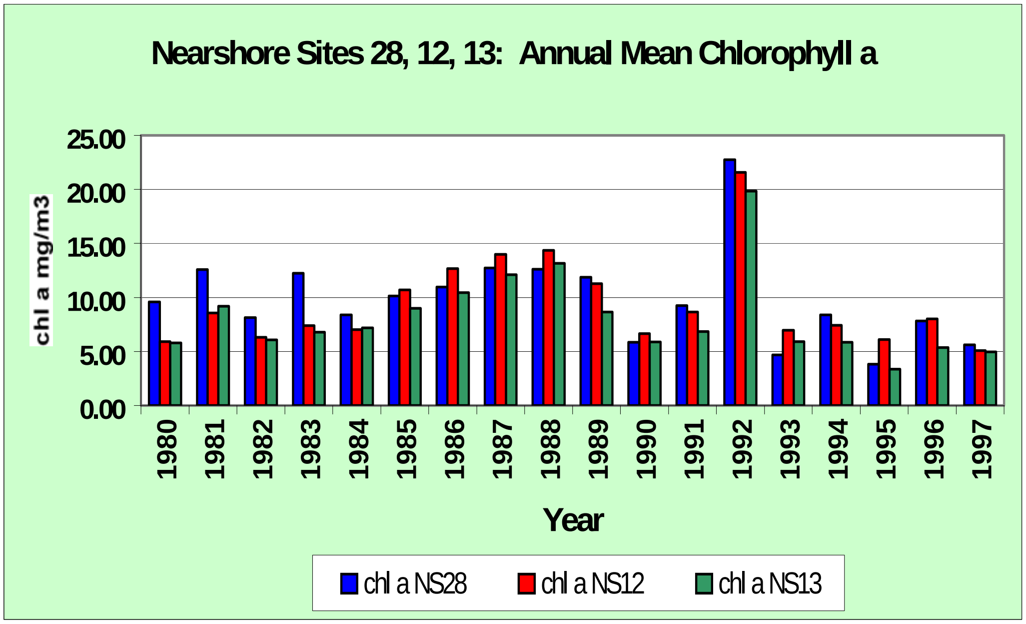


Figure 18



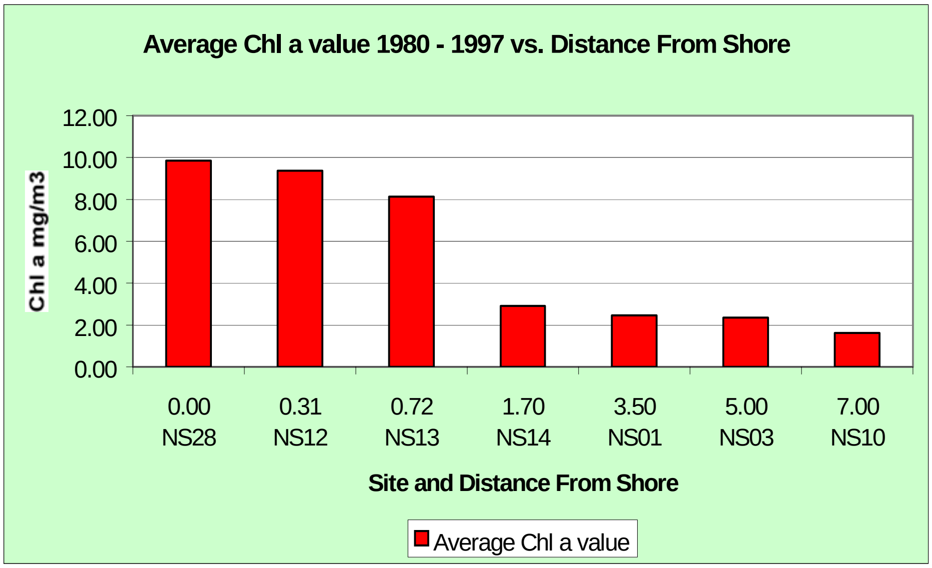
NS28, 12, and 13 also experienced a drop in chlorophyll level in 1989 but to a much lessor extent and chlorophyll did return to pre 1989 values. It is important to note that in 1992, all 3 of these sites experienced a significant increase in chlorophyll production; at least 2 times greater than the year previous and higher than any other annual average from 1980 to 1997. This increase was also noted at NS14 (approximately 2 times) and NS1 and 3 (approximately 1 time).

The considerable 1992 spike in chlorophyll concentration could be caused by many factors, certainly increased productivity by phytoplankton is the key and therefore, many of the factors affecting phytoplankton activity subsequently affect lake chlorophyll levels. Another factor potentially impacting annual mean chlorophyll values is the number of surveys performed in a particular year. Fewer surveys were obtained in 1992 than other yearly periods, ultimately affecting the yearly averages. However, chlorophyll values in June and July at the Inner Harbor sites were extremely high (20 to 48 mg/m^3), therefore driving the annual means upward.

Nitrogen and phosphorus are well known essential nutrients for algal productivity. They act much like fertilizers on lawns and can promote excessive algal growth. Nitrogen is generally not considered to be a limiting growth factor in Lake Michigan. However phosphorus has historically caused problems with excessive algal growth especially in Lake Erie (Ohio Lake Erie

Commission 1998). Lake Michigan is considered to be a phosphorus limited oligotrophic lake (Cotner 1997). Phosphorus is also known to be recycled through the pseudo-feces of zebra mussels. Time and resource constraints do not allow an investigation of MMSD data for phosphorus and nitrogen levels as they relate to chlorophyll and phytoplankton production at this time but these factors should be investigated in the future.

Figure 19



Spatially chlorophyll at NS1, 3, 10 and 14 is very different from NS28, 12 and 13 (**Figure 19**). Average chlorophyll values at these three inner harbor sites was generally 2 to 3 times higher, indicating a much more productive (nutrient rich) environment. This is not surprising based on previous discussion and also is consistent with TSI and LTSI evaluations.

General Conclusions and Summary:

This report represents a first attempt at analyzing the enormous surface water quality database (using several typical surface water quality variables monitored by the MMSD Water Quality Research Department). Another informative and useful method of evaluation is to compare species of phytoplankton between sites and major taxonomic groups, but limited time and resources prevents us from achieving this goal at the present time. Hopefully, this biological analysis can be completed in the future, thereby providing us with more answers and a more in depth analysis of “what’s really happening out there”.

Obviously differences exist between sites with the most notable being inner harbor versus outside sites with NS14 exhibiting characteristics of both regions. The inner harbor is a highly productive environment, subsequently the phytoplankton community (and ultimately chlorophyll) will be reflective of the various ecological consequences of heightened productivity and exposure to both point and non-point source pollution. Trophic state was drastically different at Inner Harbor locations versus outside sites. All of the Inner Harbor sites were rated as eutrophic to highly eutrophic while the outside sites were rated as mesotrophic to oligotrophic. These trophic state conditions are consistent with the literature; Vollenweider (1974) summarized the offshore regions of Lake Michigan as being oligotrophic while the inshore regions were classified as eutrophic. Welling (1980) and Wujek (1981) found inshore regions of southern Lake Michigan as eutrophic to mesotrophic. This is probably a factor of the heightened nutritional input that the Inner Harbor receives from point and non-point source pollution. The combination of nutrient additions coming from streams and recirculation of nutrients from the bottom sediments causes considerably more productivity than the waters of the open lakes (Stoermer 1978).

A major difference between inner harbor and outside sites was the magnitude of chlorophyll concentration. This variable was much higher at the inner harbor sites. Chlorophyll has been significantly correlated with phytoplankton density (Nicholls 1993) and higher inshore chlorophyll concentrations are a common phenomenon in the Great Lakes (Nicholls 1993). These differences could also be attributed to the increased nutrients available from the area rivers.

A few words should be devoted to the importance of algal productivity and composition to trophic state. In a lake system such as Lake Michigan, the greatest contributor to primary production is the phytoplanktonic community. These small plants form the basis of the food chain and play an extremely important role in the overall biological makeup of the lake. This community is complex; varying not only by season but also by many other biological, chemical and physical factors, and can be reflective of the systems "relative health. Reynolds (1984) stated that more than one factor ultimately determines algal activity. Tortell (2000) suggested that competitive interactions among algal taxa are influenced by their ability to assimilate inorganic carbon. Ultimately, the factors that "drive" algal populations, productivity, and competition, also control trophic state.

In analyzing the data presented in this report (general summary of results – **Table 4**) it seems that both trophic indices utilized indicated that trophic state was improving. The USEPA found trophic status in the southern portion of Lake Michigan to be improving (USEPA 1998). NS10 however, did not experience improvement. This is curious but not surprising since NS10 is outside of the influence of the Milwaukee Harbor and Rivers. If improvements to the inner harbor sites were indeed due to remediations within this area, then these affects would not be noted at NS10, which would still remain reflective of Lake Michigan trophic condition in general. NS10 was still in an oligotrophic state. Chlorophyll decreased at all nearshore sites, however at NS10, chlorophyll eventually increased again, returning to pre 1989 levels.

General Summary of Results 1980 – 1997

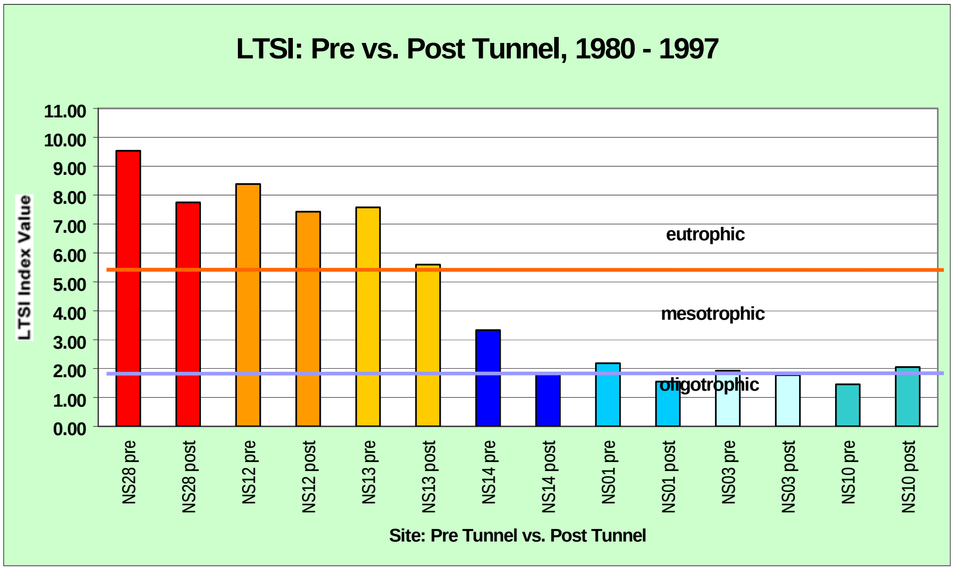
Table 4

Site	*TSI*	*LTSI*	*Chl*	*Comments*
NS27	Improving to mesotrophic	Improving to meso - oligotrophic	Decreasing	
NS11	Improving to mesotrophic	Improving to oligotrophic	Decreasing	
NS28	Improving, still eutrophic	Improving from high eutrophic to eutrophic	Decreasing	Significant increase in chlorophyll in 1992
NS12	Slight improvement still eutrophic	Improving, to mid eutrophic	Decreasing	Significant increase in chlorophyll in 1992
NS13	Improving still eutrophic	Improving, mid eutrophic to low eutrophic	Decreasing	Significant increase in chlorophyll in 1992
NS14	Improving eutrophic to mesotrophic	Improving meso-eutrophic to meso-oligotrophic	Decreasing	Significant increase in chlorophyll in 1992
NS1	Improving trend mesotrophic / meso eutrophic to low mesotrophic / mesotrophic	Improving oligo-mesotrophic to oligotrophic	Decreasing	
NS3	Improving to steady trend, mesotrophic	Improving oligo-mesotrophic to oligotrophic	Overall decease if 1980's vs. 1990's	Chlorophyll at times approximated pre 1989 levels
NS10	TSI(TP) increasing trend to mesotrophic, other TSI's approximately no change to slight improvement	Increasing trend from mid oligotrophic to high oligotrophic	Decreased then returned to pre 1989 levels	Slight degradation in trophic state at this site.

The Deep Tunnel and Potential Water Quality Improvements:

Improvements made to the MMSD combined sewer overflow and sanitary sewer overflow system (deep tunnel project completed in mid 1993, fully operational 1994) could also be having a positive effect on water quality in these areas. With the completion of the deep tunnel, overflow events have been significantly reduced. This system has prevented more than 40 billion gallons of wastewater from entering Milwaukee area rivers and Lake Michigan since becoming operational in 1994 and has reduced overflow events from approximately 50 per year to an average of two (MMSD 2000). It follows then that nutritional inputs from these sources would also have been significantly reduced. The MMSD found that “phosphorus and fecal coliform bacteria have a major influence on water quality at all sites and that inside the CSO area, dissolved oxygen is a consistent variable determining bad and very bad water quality” (MMSD October 1997). The deep tunnel system not only keeps sanitary and combined sewage from entering the river systems and ultimately Lake Michigan, but also captures non-point pollutional material such as fertilizers, pet waste, street runoff etc. In fact, LTSI pre vs. post tunnel data (**Figure 20**) show distinct improvement at all sites except NS10, with NS3 experiencing a slight improvement in trophic state. NS13 actually moved from highly eutrophic 7.58 LTSI to a slightly eutrophic 5.60 LTSI. NS14 improved from a mesotrophic 3.33 LTSI to a highly oligomesotrophic 1.83 (oligotrophy = 1.80 and less). NS1 improved from a mesotrophic 2.19 to an oligotrophic 1.54. In contrast, NS10 experienced a slight degradation in trophic state. NS10 is unaffected by Milwaukee area rivers and harbor water quality and could be reflecting a general trend for Lake Michigan. Additionally, due to the physical location of NS3, the impact from Milwaukee area water quality is probably minimal. General current patterns have a tendency to follow the lake shoreline in a southerly direction, therefore NS1 would more likely be affected by changes in Milwaukee area water quality.

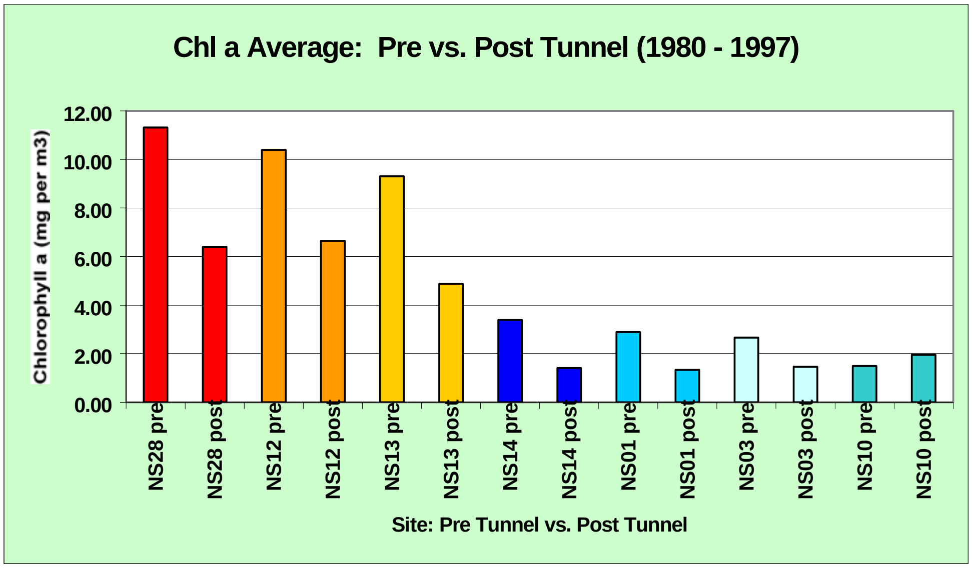
Figure 20



When the average chlorophyll pre v. post tunnel data (**Figure 21**) are compared; the same general trends are exhibited. Distinct improvement at all Nearshore sites, except NS10 which experienced an increase in chlorophyll values. This is consistent with trophic state data. The deep tunnel system could be a significant contributor to this reduction in algal biomass since algal growth and productivity are controlled by nutrient and light availability.

Improvements to both chlorophyll and trophic state could be due to other factors as well. Certainly, zebra mussels with their incredible filtration capabilities could be removing nutrients as well as solid particulates (and algal cells) which in turn would limit algal biomass (through reduced nutrient availability and removal of the cells themselves from the water column) and improve secchi disk readings (by removing fine and suspended particulates from the water column).

Figure 21



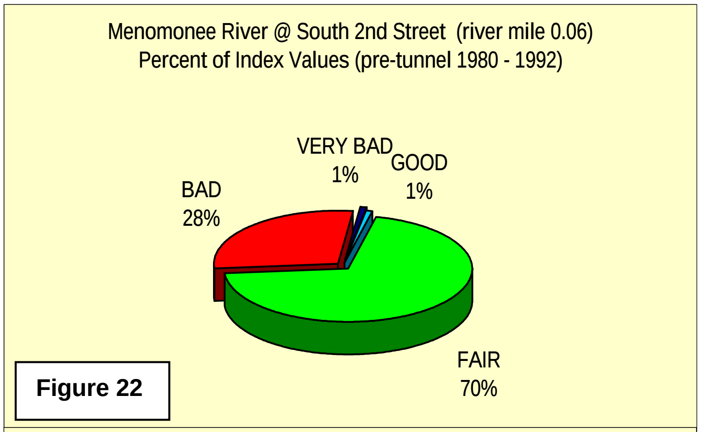


Figure 22

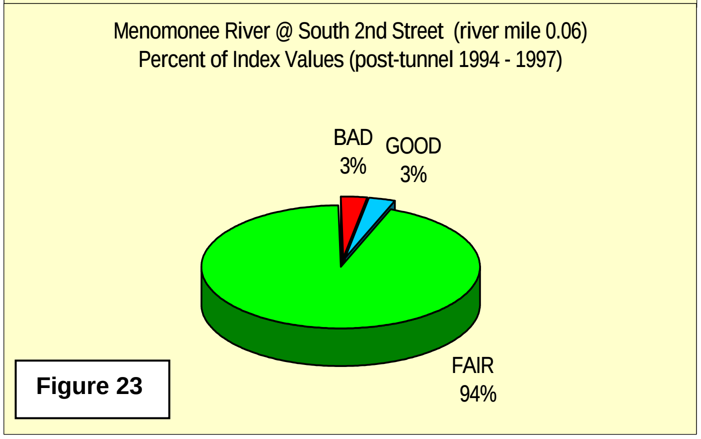


Figure 23

Figures 22 – 27 graphically illustrate the overall improvement to the Milwaukee, Menomonee, and Kinnickinnic Rivers, pre vs. post tunnel, utilizing the MMSD Water Quality Index (WQI).

The MMSD WQI is a rapid assessment tool developed by MMSD staff to aid in the presentation and interpretation of surface water quality data (further information see MMSD 1994 and MMSD 1997). The WQI is an effective tool for documenting relative changes in water quality over time, providing a “snapshot” of water quality and a means to compare different locations over space and time. Although the MMSD WQI has been calculated for each MMSD River site, the preceding sites were chosen for the following reasons.

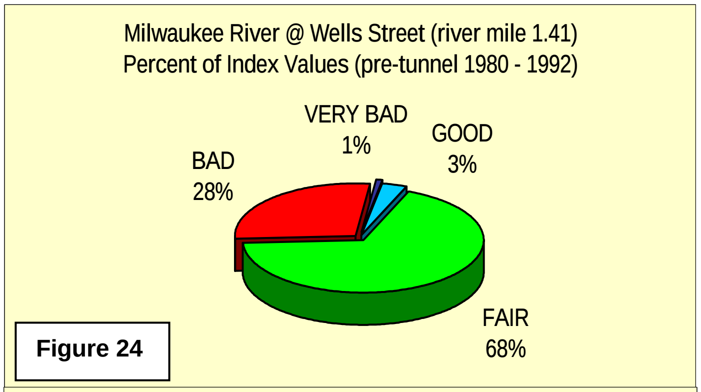


Figure 24

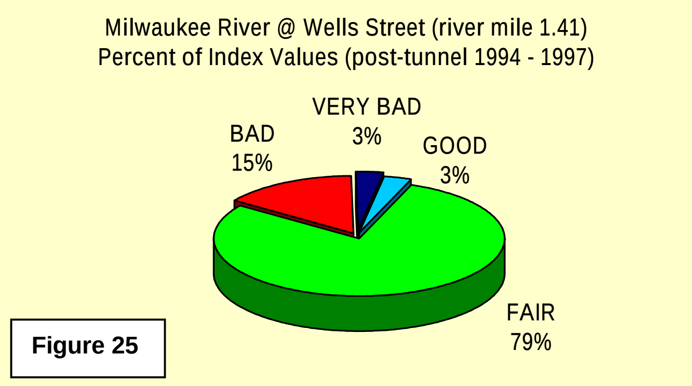


Figure 25

- RI 17 (Menomonee River at 2nd Street); this is the last monitoring site on the Menomonee River prior to the confluence with Milwaukee River. This site would reflect the pollutional load of the Menomonee River to Lake Michigan.

- RI 07 (Milwaukee River at Wells Street); this is the last monitoring site on the Milwaukee River prior to the confluence of the Menomonee River. This site would reflect the pollutional load of the Milwaukee River to Lake Michigan.

- RI 14 (Kinnickinnic River at 1st Street); this is the last site sampled with minimal dilutional effect from Lake Michigan. This site would reflect the pollutional load of the Kinnickinnic River to Lake Michigan.

Obviously these pie charts all illustrate a rather dramatic improvement in water quality when comparing pre vs. post Deep Tunnel data. The largest improvement occurred in the “Fair” category with increase of WQI rankings in this area and a concurrent decrease of WQI rankings in the “Bad” category. The most notable improvements were at RI 17 (Menomonee River at 2nd). This site experienced an improvement from 28% “Bad” WQI rankings for pre tunnel years to 3% “Bad” WQI rankings for the post tunnel years (fair ratings increased from 70% to 94%).

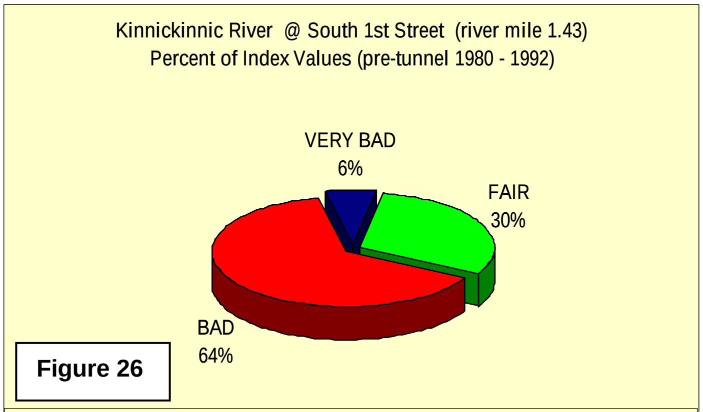


Figure 26

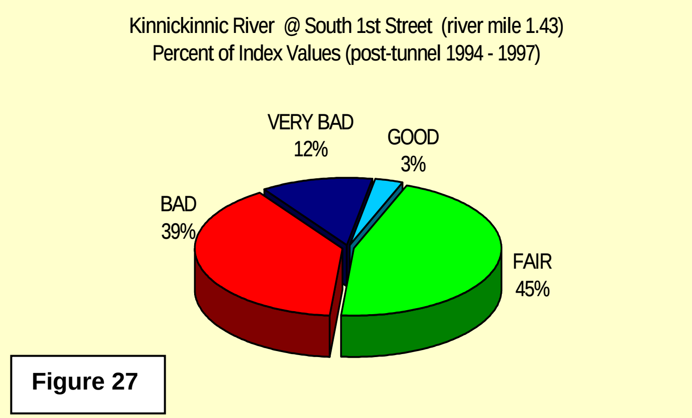
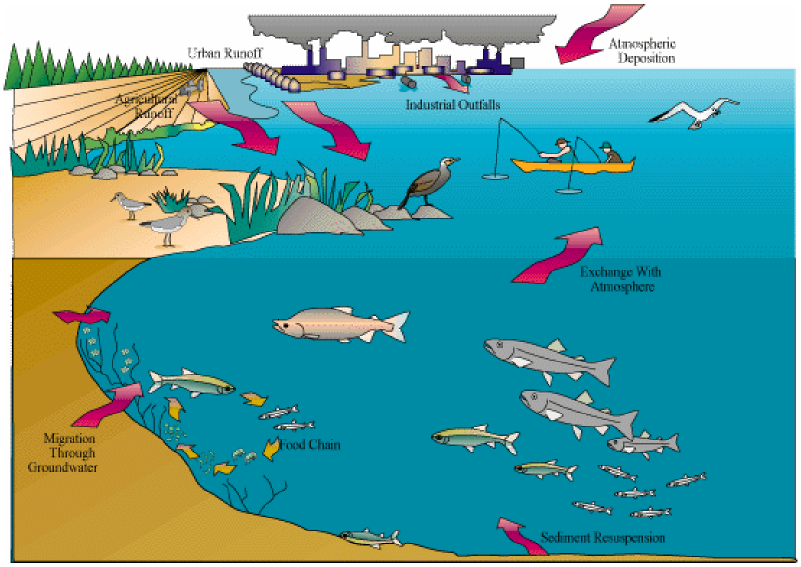


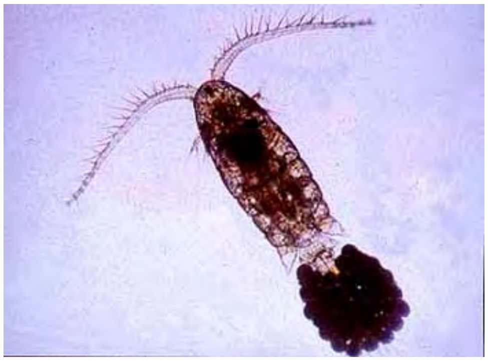
Figure 27

WQI data definitely show an improvement to surface water quality of the 3 major Milwaukee area rivers when comparing pre to post deep tunnel data. With this improvement to surface water quality in the rivers, we would expect to see a concurrent improvement to water quality in the Milwaukee Harbor. An analysis of the biological community (phytoplankton species) would substantiate improvements to water quality in the Milwaukee Harbor and Nearshore water of Lake Michigan.



Sources and Pathways of Pollution (USEPA, Great Lakes Atlas 1995)

Why is it critical to evaluate and continue to monitor water quality? While seemingly plentiful, clean water is a resource at risk (USEPA 1996). The Great Lakes are the largest system of fresh, surface water on earth, containing roughly 19 percent of the world supply. Lake Michigan is the second largest of the Great Lakes. It has an average residence time of 99 years (time it takes for water entering the system to leave the system). Lake Michigan receives water and nutrients from a 45,600 square-mile watershed (USEPA, 1994). Therefore, influences that we exert now will still impact this system a lifetime from now and we are still “paying for” perturbations exerted a lifetime ago. The phytoplanktonic community is one of the first groups to respond to environmental disturbances and are “the most abundant life forms in the open waters of lakes; converting the energy of sunlight and chemical nutrients found in the surrounding waters to biomass via photosynthesis. Phytoplankton are the primary food for zooplankton, the most common animals in open lake environments. Zooplankton form the second link in the food chain of the open waters. These animals swim and drift in the open water, feeding by straining food particles (phytoplankton) they come in contact with. Planktivorous fish form the third link in the open water food chain, feeding on zooplankton. These fish, in turn, fall prey to the larger fish which in turn fall prey to raptors such as osprey and bald eagles and other top predators (humans, terns, cormorants, etc.)” (USEPA 1994). Ultimately, when various stressors affect the phytoplankton population, the human population is also affected. The stressors come in the form of habitat destruction, altered species compositions (exotic species effects), sedimentation, nutrient inputs, air emissions, land development, agriculture and agricultural practices, surface run off, temperature changes, competition for food and other life sustaining substances, increased predation and grazing etc. “These impacts on biological diversity affect multiple systems and tend to be less reversible than other stresses” (USEPA 1994). Many of the changes in species composition in the Great Lakes over the last 200 years have largely been the result of human activities (USEPA, Great Lakes Atlas 1995). Stoermer (1998) stated; “Indeed it is probably fair to say that large-scale population-based studies of algae have been reduced at precisely the time when they might be most valuable”.



Zooplankton (Copepod):
Photo by Carol Eunmi Lee,
life.bio.sunysb.edu/marinebio/plankton

“The integrity of the Great Lakes ecosystem has been and continues to be compromised. Contaminated sediments in the lakes produce health problems. Contaminants are reaching the lakes through the air from places within and far beyond the basin. Drinking water must be extensively treated. Swimming must often be prohibited and beaches closed. Fish in the Great Lakes are contaminated with persistent toxic substances; these fish pose a threat to the health

Photo: MMSD, Ken Wardius

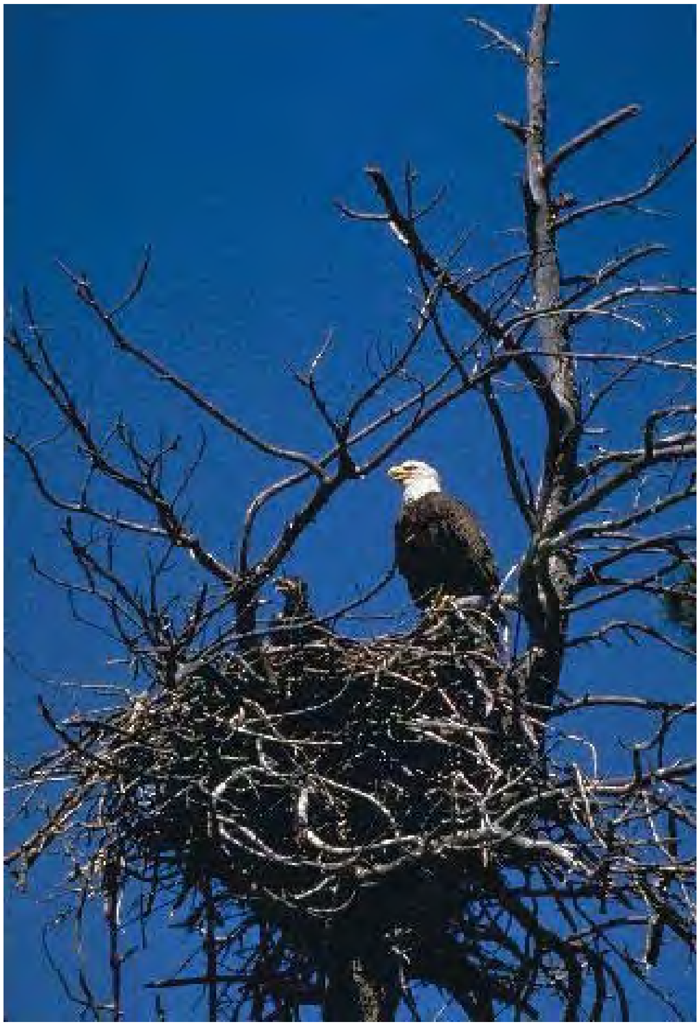


Photo Courtesy: USEPA, GLNPO

of those who eat them and to their unborn children. Increasing urbanization is adversely affecting water quality; as a result of human activities, alien invasive species are entering the lakes and causing billions of dollars in damages and massive aquatic ecosystem disruption. **Moreover, the public lacks the information to identify sources of contamination, or judge the adequacy of remedial and preventive programs"** (International Joint Commission, 2000). The District's surface water quality monitoring program provides the data necessary to dispense water quality information to the public. Moreover, due to the long-term nature of the District's water quality monitoring program (and data), problems, which are inherent with other programs, are not exhibited. These problems include difficulties with trend analysis and interpretation, difficulties tracing and examining causes and pathways of pollution, and difficulties determining effects of exotic species, nonpoint source pollution, point source pollution, episodic events, watercourse and other improvements, etc. These lapses in monitoring ultimately affect the quality of infrastructure management decisions and our ability to adequately address the education of and concerns of the public. Continued long term water quality monitoring improves the effectiveness of protecting our water resources for the public's many uses and future generations. In the words of the International Joint Commission: "Every delay in achieving this purpose carries a price (in regard to restoring and maintaining the integrity of Great Lakes Basin Ecosystem and to coordinated monitoring and surveillance programs necessary to fulfill commitments under the Great Lakes Water Quality Agreement). With time the price will grow heavier, and the line between delay and outright failure will be stretched thinner. Governments need to show a new sense of urgency and a commitment to action in restoring and protecting the Great Lakes" (International Joint Commission 2000).

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