PART 2

LM3-EUTRO

Chapter 4. Model Input and Field Data

2.4.1 Loading and Sediment-Water Interactions

2.4.1.1 Atmospheric Loads

Measurements were made at eight locations around Lake Michigan (Miller *et al.,* 2000; U.S. Environmental Protection Agency, 1997) and loads were calculated for total phosphorus, total Kjeldahl nitrogen (TKN), and nitrate (NO_3). Monthly total loads were available for March 1994 through October 1995 (Table 2.4.1). Table 2.4.1 shows the phosphorus loads for this period. In order to obtain a complete two-year record (necessary for model calibration and forecast simulations), January and February of 1994 were assumed to be the same as January and February of 1995, while November and December of 1995 were assumed to be the same as November and December of 1994. The total phosphorus loads were split between labile organic phosphorus (LOP) (67% of total phosphorus) and soluble reactive phosphorus (SRP) (33% of total phosphorus). All other forms were assumed to be insignificant. We assumed that the TKN atmospheric loading is split evenly between labile organic nitrogen (LON) and refractory organic nitrogen (RON) forms.

2.4.1.2 Tributary Loads

Loads from 11 monitored tributaries were calculated using the stratified Beale ratio estimator model (Hall and Robertson, 1998). Loads from 18 unmonitored tributaries (two of which represented portions of monitored tributaries) were also estimated based on results from monitored watersheds and individual watershed and flow attributes (Hall and Robertson, Part 7, Appendix 2). Monitored tributaries were sampled at sites as far downstream as possible to provide the most accurate load estimates. Composite samples were prepared from two depths at three points along a cross-sectional transect of the river. Most samples were taken during high flow

Table 2.4.1. 1994-1995 Monthly Atmospheric Total Phosphorus Loads

1994 Atmospheric Total Phosphorus Loads (kg/month)	
March	17552
April	34665
May	27465
June	14429
July	38184
August	38303
September	29908
October	17334
November	32418
December	7937
1995 Atmospheric Total Phosphorus Loads (kg/month)	
January	22748
February	8430
March	17552
April	34665
May	27465
June	14429
July	26457
August	39458
September	18893
October	43254

periods (Hall and Robertson, 1998). Loads provided in the original Great Lakes National Program Office (GLNPO) data set included chlorophyll *a*, dissolved organic carbon (DOC), particulate organic carbon (POC), total phosphorus, SRP, TKN, ammonia-N (NH_4), NO_3, and dissolved silica (DSi). Daily loads were provided in units of kg/d for the period of January 1, 1994 to December 1, 1995. Table 2.4.2 provides a summary of the total phosphorus loads for the 11 monitored tributaries.

Loads provided for each tributary were used to calculate additional parameters of interest. Chlorophyll *a* loads were converted to phytoplankton carbon by assuming a 40:1 carbon-to-chlorophyll ratio. This ratio was chosen to maintain consistency within the model (see Section 2.4.2.2). This carbon value was then converted into diatom carbon and non-diatom carbon by assuming that tributary phytoplankton populations were 75% diatom and 25% non-diatom (Allan, 1995). Labile particulate organic carbon (LOC) and refractory particulate organic carbon (ROC) were estimated by subtracting total algal carbon from POC and multiplying by 0.55 for LOC and 0.45 for ROC. Algal phosphorus was estimated by assuming a phosphorus:carbon ratio of 0.01 (algal carbon multiplied by .01). Organic phosphorus was taken to be total phosphorus minus the sum of algal phosphorus and SRP. From the estimate of organic phosphorus, dissolved organic phosphorus (DOP) was assumed to be 10% and LOP and refractory organic phosphorus (ROP) were both assumed to be 45%. Algal nitrogen was estimated using a nitrogen:carbon ratio of 0.2 (algal carbon multiplied by 0.2). Organic nitrogen was calculated as TKN minus the sum of algal nitrogen and NH_4. As in the case of phosphorus, dissolved organic nitrogen (DON) was represented by 10% of organic nitrogen, while labile organic nitrogen (LON) and refractory organic nitrogen (RON) were each represented as 45% of organic nitrogen.

2.4.1.3 Shoreline Erosion

Shoreline erosion, mainly along the western shore, contributes significantly to the solids concentration in Lake Michigan. The shoreline erosion estimates were based on the long-term, county-level estimates of Monteith and Sonzogni (1976). David Schwab, National Oceanic and Atmospheric Administration (NOAA), Great Lakes Environmental Research Laboratory (GLERL), Ann Arbor, Michigan, used these estimates to calculate erosion loads of coarse-

Table 2.4.2. Tributary Total Phosphorus Loads (kg/year)

River	1994	1995	Two-Year Average
Menominee	83753	127281	105517
Fox	562865	595991	579428
Sheboygan	28424	21703	25063
Milwaukee	33731	31320	32525
Calumet	44710	39782	42246
St. Joseph	275772	264341	270057
Kalamazoo	176318	137918	157118
Grand	663972	351250	507611
Muskegon	62490	43497	52993
Pere Marquette	34937	26828	30882
Manistique	25966	25367	25667
Total Monitored Tributaries	1992937	1665276	1829107
Total Unmonitored Tributaries	683544	650424	666984
Total	2676481	2315700	2496091

and fine-grained particles (personal communication). Organic carbon makes up a very small fraction of the bluff material (Monteith and Sonzogni, 1976) so we used a carbon fraction of 0.5% for the fine-grain material in estimating the POC erosion loads to the lake. We assume this POC is in the refractory form.

2.4.1.4 Sediment

A brief description of the sediment component of the model was previously provided in the model description section (Part 2, Chapter 3). A summary of the phosphorus fluxes, settled masses, and reported literature values can be found in Table 2.4.3.

Table 2.4.3. Sediment Masses, Fluxes, and Loads

State Variable	Mass Settled (kg/year)	Mass Recycled (kg/year)	Literature Comparison (kg/year)
Phosphorus	7 x 10^6	4 x 10^6	3.6-12 x 10^6* 1.1 x 10^6**

* Quigley and Robbins, 1986.
**Conley *et al.*, 1988.

2.4.2 Field Data

Large amounts of data were collected between April 1994 and October 1995 during eight sampling cruises (Table 2.4.4). Sampling stations were scattered throughout the lake (Figure 2.4.1). The data sets included lake nutrient concentrations; physical measurements such as solar radiation and temperature; and biological data related to phytoplankton, zooplankton, and fish communities in the lake. These data have been used to describe the current state-of-the-lake and to gain a better understanding of the lake as a whole and the processes affecting it. They were also useful in model calibration. Many of the samples collected were analyzed *in situ* or on the ship immediately following collection, while others were carefully preserved and sent out for analysis by several laboratories around the country. Detailed descriptions of sampling techniques and sample analyses used can be found in the Lake Michigan Mass Balance Project (LMMBP) Methods Compendium (U.S. Environmental Protection Agency, 1997).

Table 2.4.4. The LMMBP Sampling Cruises

Cruise Number	Start Date	End Date
Cruise 1	April 24, 1994	May 11, 1994
Cruise 2	June 17, 1994	June 26, 1994
Cruise 3	August 3, 1994	August 26, 1994
Cruise 4	October 14, 1994	November 7, 1994
Cruise 5	January 16, 1995	January 25, 1995
Cruise 6	March 23, 1995	April 18, 1995
Cruise 7	August 3, 1995	August 16, 1995
Cruise 8	September 16, 1995	October 13, 1995

All LMMBP data were subjected to rigorous water quality assurance (QA) procedures (U.S. Environmental Protection Agency, 2004). Once available to the modelers, data were examined for completeness and content. Any data which seemed suspect (unusually high or low values as compared to historical data, missing values or codes, etc.) were resubmitted to GLNPO for additional examination. Data which appeared reasonable and complete were subjected to a standardized data assessment protocol by individual modelers. This data assessment provided basic statistical information about the data (mean, minimum, maximum, median, standard deviation), identified outliers, and evaluated sample normality. In some cases, data averaging and grouping were necessary before adequate assessment could be performed. Once the data assessment was completed by the modeling team, data were imported into the modeling database and kept unchanged for the rest of the data evaluation, model development, and model validation. Summary statistics for the nutrient data are shown in Table 2.4.5. Due to the limited number of Green Bay samples, the table includes only the open lake statistics.

2.4.2.1 Open Lake Nutrient and Carbon Data

2.4.2.1.1 Total Phosphorus

Total phosphorus represented the sum of all phosphorus species in the sample, including the

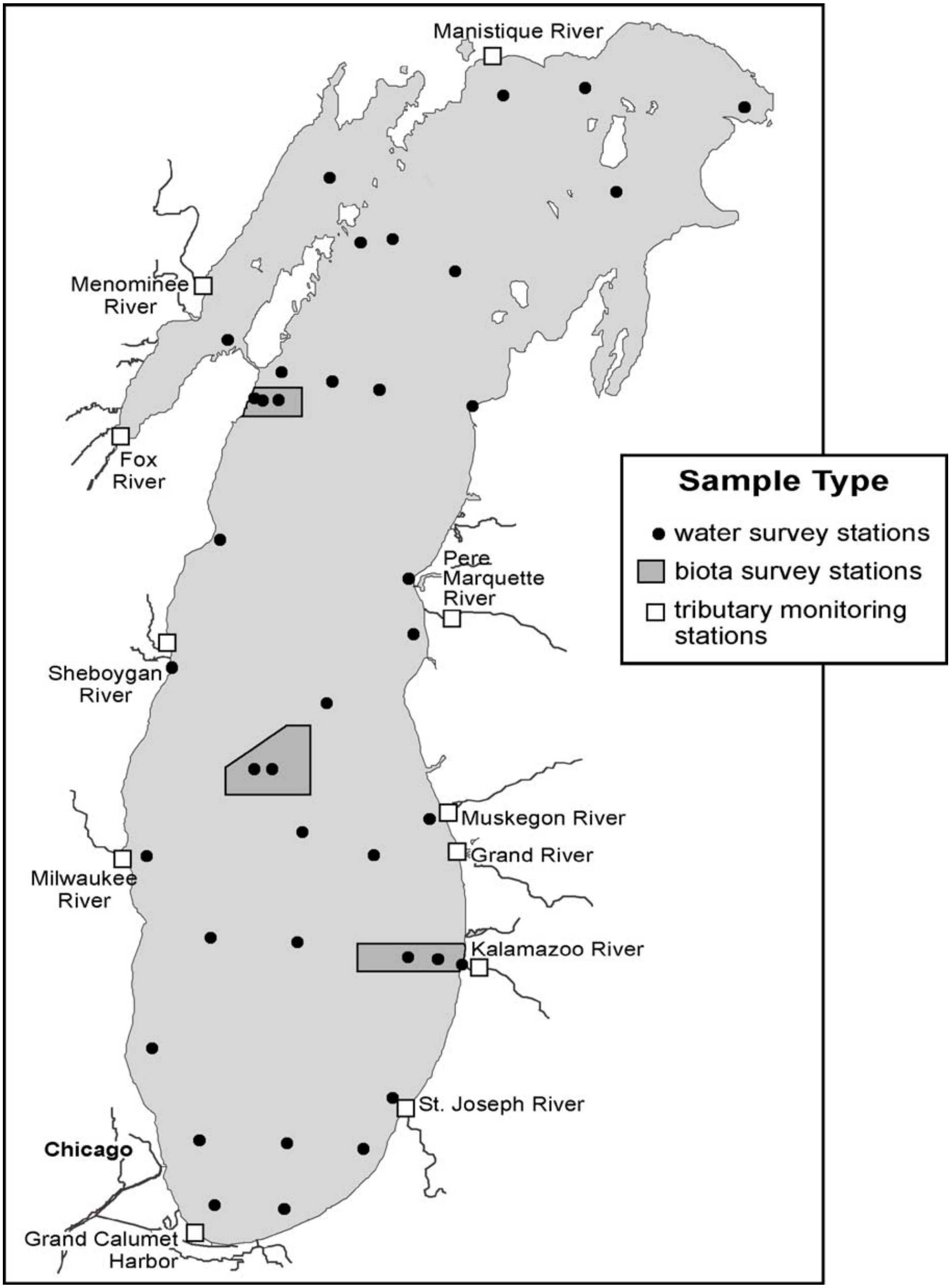

Figure 2.4.1. The LMMBP sampling locations.

Table 2.4.5. The LMMBP Open Lake Nutrient Data Summary Statistics

	Number of Samples	Minimum	Maximum	Median	Mean	Standard Deviation	Outliers*
Nitrate	847	0.01	0.45	0.28	0.27	0.064	None
SRP	504	0.0	6.70	0.60	0.71	0.69	19
Total Phosphorus	846	1.8	28.7	4.6	5.0	2.1	31
DSi	847	0.038	2.11	0.52	0.54	0.29	10
TKN	845	0.01	0.43	0.15	0.16	0.07	10
NH_4	505	0.0	0.30	0.01	0.02	0.03	13
POC	363	36.15	989.26	201.7	203.0	92.0	6
DOC	364	1.05	2.9	1.54	1.55	0.19	9

Note: POC, SRP, and total phosphorus are expressed in µg/L, all others are in mg/L.
*Larger than twice the standard deviation.

phosphorus dissolved in the water; phosphorus sorbed to particles such as iron, calcium, and magnesium; and the phosphorus contained within the phytoplankton, zooplankton, and detrital particles. Large spatial and temporal changes were not expected in the lake over the project years (1994-1995) because of the conservative nature of total phosphorus. Changes were typically limited to particulate settling and incoming and outgoing loads. It appeared that the LMMBP data verified this, suggesting small, if any, changes in concentration and no apparent nearshore/offshore or north/south trends in the lake. Seasonal trends were observed, with complete mixing early in the year and slightly higher total phosphorus in surface waters during the spring/early summer bloom. Total phosphorus was lower in the surface waters later in the summer, possibly due to settling out of the algal phosphorus. Higher concentrations were observed at the bottom. On a few occasions, unexpectedly high total phosphorus values were observed. These may result from local inputs (tributary) or natural or sediment disturbances during sampling.

2.4.2.1.2 Dissolved Phosphorus

Dissolved phosphorus was defined as the concentration of phosphorus found in a sample after filtration through a membrane filter. SRP, the preferred form of phosphorus used by algae, was some portion of dissolved phosphorus. A general seasonal concentration trend in dissolved phosphorus was observed on a lake-wide basis. Early in spring, the concentration was relatively low, with values just above 2 µg/L. There was a slight increase in early summer, followed by a decrease in summer to a level frequently below detection limits. Dissolved phosphorus increased in the fall and the pattern repeated for the following year.

2.4.2.1.3 Soluble Reactive Phosphorus

SRP is one of the most important nutrients because it is widely considered to be the driving force for algal primary productivity in Lake Michigan (Tarapchak and Nalewajko, 1987). There has been considerable discussion in the literature about the meaning, measurement, and role of SRP, but most agree that SRP levels can be used to predict algal growth (Tarapchak and Nalewajko, 1987). SRP was not analyzed for samples collected during the first three cruises and the majority of the data from the other five cruises fell below the detection limit of 1 µg/L (U.S. Environmental Protection Agency, 1997). The remarkably good correlation between SRP and dissolved phosphorus, which was previously discussed, was useful in making estimates of SRP for the first two cruises. However, because of the lack of actual SRP data, we did not speculate about trends in the lake. This weakness in this important data set made the analysis and subsequent modeling exercise difficult.

2.4.2.1.4 Nitrate

Nitrate analysis methods actually measure the sum of NO_3 and nitrite (NO_2). Nitrite values were assumed to be low enough to be considered negligible. No obvious nitrate spatial trends were observed (nearshore versus offshore or northern basin versus southern basin), but it appeared that the concentration, on average, was slightly lower in the summer than in the winter. This was probably due to the uptake of dissolved nitrogen during phytoplankton production in the summer.

2.4.2.1.5 Ammonia

Ammonia is the most reduced nitrogen form and is, therefore, the most available for algal uptake. It occurred in the lake at very low concentrations, often below the detection limit of 20 µg N/L. Though the data set was incomplete because no samples for ammonia analysis were taken during the first three sampling cruises, no obvious spatial or temporal trends were observed.

2.4.2.1.6 Total Kjeldahl Nitrogen

TKN is a measure of all of the reduced nitrogen present in the water, including organic nitrogen (particulate and dissolved) and ammonia. No spatial or temporal trends were observed for the TKN values but noticeably higher values were observed throughout the lake during the August 1994 cruise.

2.4.2.1.7 Dissolved Silica

Only the dissolved form of silica (DSi) was measured in this study. A reasonably good representation of the open lake concentration could be constructed. Silica concentrations followed a distinct pattern, with highest observed values occurring uniformly in the lake early in the year. The silica was depleted during the spring and summer by diatom consumption in the epilimnion, while silica increased in the lake's hypolimnion during this part of the year, mainly due to diatom settling and detrital silica (Laird *et al.*, 1988). Toward the end of the summer and early fall, silica, in the strongly stratified epilimnion, decreased to approximately 0.2 mg/L, while it was greater than 1 mg/L in the hypolimnion. This seasonal trend was observed for both project years. No obvious differences could be observed between the Michigan or Wisconsin shores or between the southern and northern parts of the lake. Epilimnion values tended to be higher during the summer in shallow nearshore sites than in deeper open lake sites.

2.4.2.1.8 Dissolved Organic Carbon

DOC remained remarkably constant in Lake Michigan over the two-year period. We observed few spatial or temporal trends in the lake, although significantly higher and lower concentrations were observed at individual stations in the lake.

2.4.2.1.9 Particulate Organic Carbon

As expected, there was a large variation in POC concentrations in the lake. Typical concentrations for the open lake ranged from 100 to 300 µg/L. In Lake Michigan, POC consisted mainly of phytoplankton carbon, detrital carbon, and to a lesser extent, zooplankton carbon. High POC was strongly related to the timing and locations of phytoplankton blooms. In general, POC was higher in the euphotic zone during the warmer summer months. Early in the spring, POC was higher in the nearshore, probably due to higher temperatures which resulted in early spring phytoplankton production.

2.4.2.1.10 Green Bay Nutrient Data

While Lake Michigan is classified as an oligotrophic system, Green Bay is eutrophic and has drastically different properties than the Lake Michigan proper. Green Bay exhibited much higher concentrations of nutrients and large phytoplankton and zooplankton populations (and, thus, higher carbon concentrations). Most state variables had a concentration gradient, with highest levels (several times higher than the open lake) close to the Fox River mouth and lowest concentrations close to the confluence with the lake. This gradient was especially prominent for phosphorus, phytoplankton, and carbon. During the LMMBP (1994-1995), Green Bay was only sampled in two locations (Figure 2.4.1). This lack of data complicated the estimation of many state variables. Available historical data and scaling of open lake data were used to estimate concentrations in many instances (Bierman *et al.*, 1992; DeStasio and Richman, 1998; Sager and Richman, 1991).

2.4.2.2 Plankton

2.4.2.2.1 Phytoplankton

Data were collected during eight cruises between April 1994 and October 1995. Samples represented composites of 1, 5, 10, and 20 m sub-samples. Data were communicated by group densities and biovolumes (diatoms, "all else" (primarily flagellates), greens, non-nitrogen fixers, and nitrogen-fixers) and species densities and biovolumes. Sampling stations were distributed through the lake (Figure 2.4.1).

Sampled phytoplankton populations differed in overall density and biovolume in 1994 and 1995. Diatoms and "all else" occurred in higher numbers in 1994 than 1995, while greens and blue-greens occurred in similar numbers during both years. This density difference was reflected in the 1994 and 1995 biovolume data. Overall, phytoplankton biovolume was much higher in 1994 as a result of higher diatom and "all else" biovolume. This finding could be the result of sampling which was not evenly divided across the calendar year, with 1994 being spring-weighted and 1995 being fall-weighted.

Blue-green algae (non-nitrogen fixers and nitrogen-fixers categories) dominated the samples in the total number of cells present. Blue-greens were the dominant cell type present in all months. Peak densities of blue-greens occurred in August-October 1994 and August-September 1995. Peak densities of diatoms were observed in May-June 1994 and April-August 1995. "All else" category phytoplankton peaked in number in May-June 1994, again in October-November 1994, and then remained stable throughout the 1995 sampling months.

Diatoms dominated phytoplankton biovolume in April-June 1994 and again in January-August 1995. "All else" phytoplankton dominated total biovolume in October 1994, November 1994, and September 1995. Diatoms and "all else" contributed similarly to total phytoplankton biovolume in August 1994 and October 1995. Green algae and blue-green algae contributed slightly more to total biovolume in August-October 1994 and August-October 1995 but never contributed more than approximately 20% and 15%, respectively. In general, diatoms and "all else" composed >75% of the total phytoplankton biovolume every month, while the blue-greens contributed approximately 6% of the phytoplankton biomass.

Average sizes for each phytoplankton category further supported the biovolume data. Diatoms averaged 898.6 μm^3/cell, "all else" 574.3 μm^3/cell, greens 374.4 μm^3/cell, non-nitrogen fixers 12.2 μm^3/cell and nitrogen-fixers 167.7 μm^3/cell. Because total carbon content was expressed as a function of cell biovolume and diatoms and "all else" dominated the total biovolume of the epilimnetic waters, it was safe to assume that the major phytoplankton carbon source would be the diatom and "all else" phytoplankton categories. The blue-greens, although high in numbers, made up an insignificant percentage of phytoplankton carbon mass.

2.4.2.2.2 Chlorophyll a

Chlorophyll *a* data were provided by GLNPO for the 1994-1995 LMMBP field season. Data were collected using a Seabird fluorometer and calibrated to extracted chlorophyll *a* data. Due to laboratory error, extracted chlorophyll *a* data from all cruises except Cruise 8 (September-October 1995) were declared invalid. Thus, Seabird data for the 1994-1995 sampling season were calibrated with fall 1995 and 1997 extracted chlorophyll *a* data (Goldsmith, 1999). This was accepted as the best alternative, and the chlorophyll *a* profiles generated from the calibrated data generally agreed with trends and overall concentration levels expected for the lake.

Raw, station-specific chlorophyll *a* data files contained information such as station code and location, date, time, depth of measurement, chlorophyll *a* (mg/L), and percent transmissivity. Most chlorophyll *a* depth profile measurements were taken in 0.1-0.5 m increments, although occasionally only 1 m increments were provided. Some level of "cleaning" was required for all files. All data with depth measurements less than or equal to zero meters were discarded in the analysis, as were data reporting a measurement of -0.18. Both of these values were utilized as data flags by GLNPO. In addition, chlorophyll *a* data near the surface or bottom were frequently reported as a long-series of identical measurements. The chlorophyll *a* profile used in the analysis included the last of these "repeats" and its coordinating depth if the repeats occurred at surface depths, or the first of the "repeats" and coordinating depth if occurring at lake bottom. These repeating values were likely the result of equipment limitations and sampling error (hitting bottom, etc.) and could not be deemed reliable.

2.4.2.2.3 Phytoplankton Carbon

The eutrophication model required phytoplankton to be expressed as carbon and divided into diatom and non-diatom classes. Multiple data transformations were necessary to satisfy these requirements. The determination of which approach should be used to estimate phytoplankton carbon was a complicated first step. The LMMBP data set included phytoplankton biovolume data from 0-20 m integrated samples as well as chlorophyll *a* depth profiles. Biovolume data could be converted to phytoplankton carbon using equations published by Strathmann (1967) and Rocha and Duncan (1985). While this approach is generally accepted in the scientific community, some researchers question whether it is possible to avoid propagating error using this method (Sicko-Goad *et al*., 1984). In calculating biovolume, organism dimensions are measured and then multiplied to yield cubic volume. Any measurement error is, thus, cubed and then further compounded by inclusion of the erroneous value in the volume-to-carbon equation. The microscopic nature of phytoplankton makes some degree of measurement error inevitable. Another issue was the presence of vacuoles and thick walls in some phytoplankton species. These would be included in a microscopic measurement of an organism as biovolume but contribute relatively little to the carbon content of the organisms (Sicko-Goad *et al*., 1984). In addition to methodological difficulties, the limitation of phytoplankton biovolume data to integrated samples from the top 20 m of the water column made it difficult to estimate phytoplankton carbon for discrete depths and deeper waters using these data.

Another method of estimating phytoplankton carbon is converting chlorophyll *a* using a carbon-to-chlorophyll *a* ratio. This approach also has shortcomings. Carbon-to-chlorophyll ratios may vary with species and light and nutrient conditions. Some researchers have found that the variation was greatest under nutrient limitation, a common occurrence in Lake Michigan (Riemann *et al*., 1989). The chlorophyll *a* calibration difficulties encountered during the LMMBP, and discussed earlier, further complicated the issue, as the chlorophyll *a* data set was not as reliable as desired. The LMMBP chlorophyll *a* data set, however, was quite thorough and any error contained within it as a result of actual measurement or calibration was probably consistent across the entire data set. The chlorophyll *a* data set also lent itself to comparison with the large volume of historical data from Lake Michigan, as well as measurements taken in Green Bay as part of the Green Bay Mass Balance Project (GBMBP) modeling effort (Bierman *et al*., 1992).

A cruise-by-cruse comparison of biovolume and chlorophyll *a* derived carbon data for the entire lake was made (Figure 2.4.2). Chlorophyll *a* values from the top 20 m of the water column were averaged and converted to carbon using several commonly cited carbon-to-chlorophyll *a* ratios (35:1, 40:1, and 50:1) (Riemann *et al*., 1989; Montagnes *et al*., 1994; Cloern *et al*., 1995). Visual analysis of the results presented in Figure 2.4.2 suggested that a 40:1 carbon-to-chlorophyll ratio provided the best fit with biovolume carbon data over all eight sampling cruises. It was our belief that this chlorophyll *a* carbon estimation approach provided the greatest consistency among integrated 0-20 m samples, deeper water samples, and Green Bay estimates, and it provided the best fit to biovolume carbon estimation methods.

The 40:1 carbon-to-chlorophyll relationship was used to generate carbon values for model fitting exercises. Chlorophyll *a* values for each station and cruise were converted to carbon at each depth along the depth profile, and then separate average carbon values were calculated for the 0-10 m and 11-20 m intervals. Diatom/non-diatom proportions were taken from the corresponding 0-20 m phytoplankton biovolume data and used to divide the total average carbon value into diatom and non-diatom categories. Estimates of phytoplankton carbon deeper in the water column were also calculated from chlorophyll *a* data. Set depths of 25 m and 40 m were chosen, and the total depth between 50 m and the bottom for each station was split into thirds, and the midpoint of each third was used for carbon estimation. When total depth was less than 65 m, a few set depths were used instead (50 m, 60 m, etc.). Occasionally, an additional depth was added to allow better representation of the deep chlorophyll layer. Phytoplankton carbon at these depths was estimated

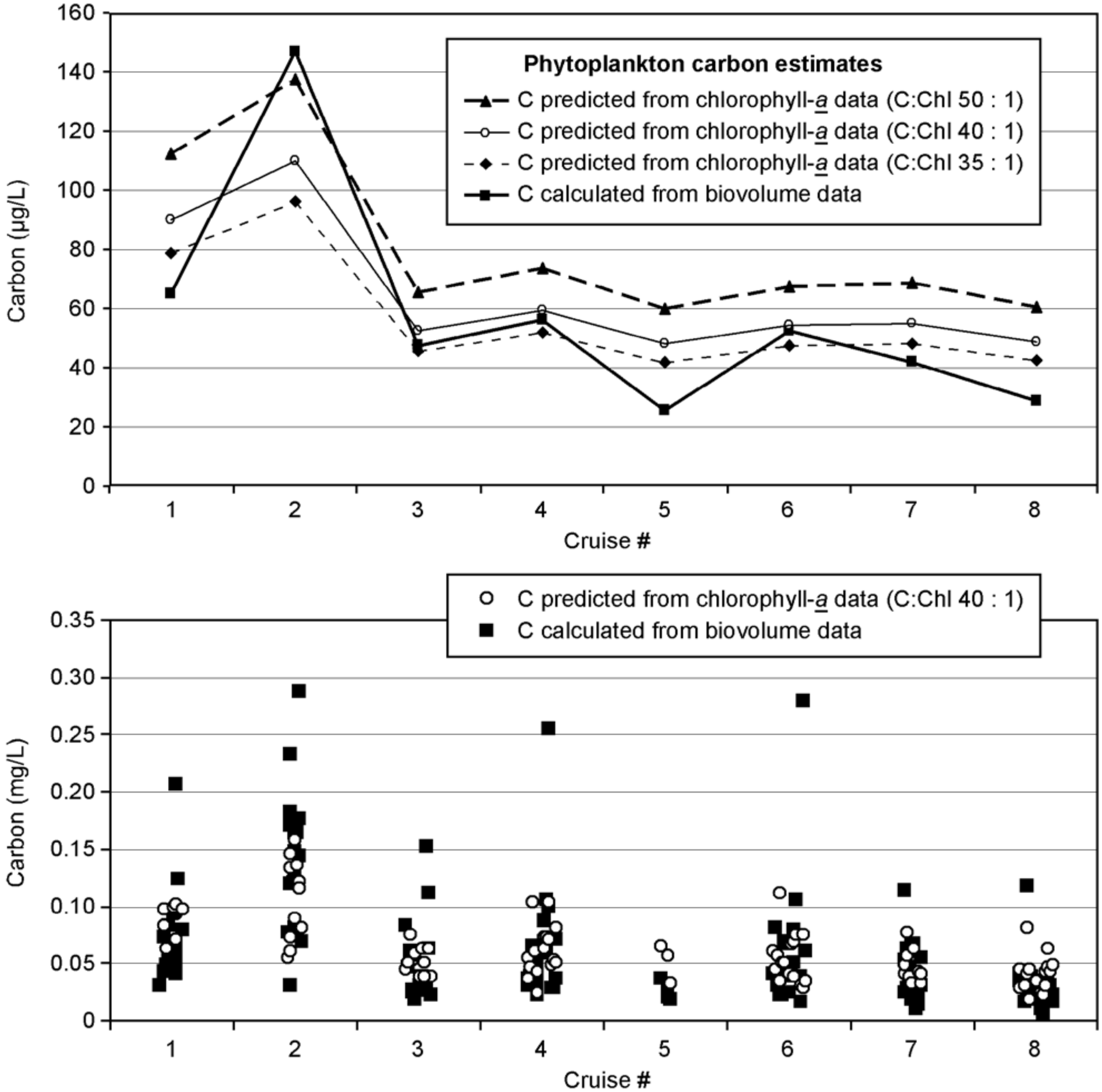

Figure 2.4.2. Lake-wide phytoplankton carbon calculated from biovolume data and carbon-to-chlorophyll *a* ratios for the eight LMMBP cruises.

by again assuming a carbon:chlorophyll ratio of 40:1. Total carbon was then split into diatom and non-diatom carbon using station- and cruise-specific 0-20 m diatom proportions. Biovolume data were not available for many stations and some station/cruise combinations and cruise average diatom proportions were used in these instances.

2.4.2.2.4 Zooplankton

Zooplankton were collected with plankton net tows from 20 m to the surface. At stations that were less than 20 m in depth, the zooplankton tow was done from 1 m above the bottom to the surface. Data were communicated by group densities and biovolumes (*Bythotrephes*, carnivores, detrivores, *Dreissena* veligers, herbivores, and *Mysis*) and species densities and biovolumes. Sampling stations were distributed throughout the lake.

Zooplankton species level analyses revealed that several species had high average abundances. *Conochilus unicornis, Polyarthra vulgaris, Polyarthra major, Dreissena* veliger, copepod nauplii, *Keratella cochlearis, Synchaeta, Kellicottia longispina,* and *Diaptomus* copepodites all occurred at average densities greater than 5,000/m^3. Of these organisms, only *Dreissena*, copepod nauplii, and *Diaptomus* are not rotifers. Other species were found in virtually all of the samples and were well distributed throughout the lake, regardless of season. These included copepod nauplii, *Cyclops* copepodites, *Diaptomus* copepodites, *Diaptomus minutus, Keratella cochlearis, Synchaeta, Cyclops bicuspidatus, Diaptomus ashlandi, Kellicottia longispina,* and *Polyarthra vulgaris.*

Zooplankton were further divided into groups by class (rotifer, copepod, and cladocera). As suggested by the species level data, rotifers dominated the overall zooplankton abundance, although copepods were more important in early spring and winter (April-June 1994, January-May 1995). Rotifer abundance peaked in July-August 1994 and July-August 1995 while copepods seemed to peak in August of both years. Cladocerans experienced a brief but significant peak in number in mid-August and September of each year. Total zooplankton abundance peaked at 400,000 organisms/m^3 in 1994 and 700,000 organisms/m^3 in 1995. This annual difference may be the result of differential reproductive success between years or the timing of sampling, as discussed for the phytoplankton data.

Copepods overwhelmingly dominated zooplankton biomass throughout most of the year, with peaks from August to mid-October 1994 and August to September 1995. Cladocerans did experience seasonal peaks, however, in which they accounted for most of the zooplankton biomass present in the lake over a very short period of time. These cladoceran biomass peaks coincided with peaks in the *Daphnia galeata* population at the sampling stations. The peaks occurred in mid-August 1994 and early-August 1995, with a smaller peak in October 1995. Rotifer biomass was always quite low despite peaks in abundance and generally high numbers. Overall, total zooplankton biomass peaked in the 225,000 to 275,000 mg/m^3 range in August 1994 and August 1995.

In order to better understand the impact of zooplankton on phytoplankton populations, trends of carnivorous species versus herbivorous species were examined. Detrivores and *Dreissena* did account for 10-30% of the total zooplankton abundance during several sampling months, but no biomass data were available for these organisms. Carnivores accounted for less than 25% of the total zooplankton biomass and abundance during all months sampled. Carnivore abundance and biomass, in fact, were relatively static, with only small peaks in each observed in August of 1994 (around 46,000 mg/m^3 and 12,000 organisms/m^3) and 1995 (around 48,000 mg/m^3 and 4,000 organisms/m^3). Herbivore abundance increased from April 1994 to August 1994 and then began to decline. The same abundance peak was observed in 1995, but with a slight resurgence in October of 1995. Herbivore biomass increased from April 1994 through August 1994 and slowly declined through December 1994. Herbivore biomass began to increase again in April 1995 and followed a similar pattern to that of 1994 over the rest of 1995. Herbivore abundance peaked at approximately 210,000 organisms/m^3 in 1994 and 275,000 organisms/m^3 in 1995, while biomass peaked at around 225,000 mg/m^3 both years.

Differences in carnivore and herbivore abundance and biomass among sampling stations were analyzed using a one-way ANOVA. No significant differences were found among stations for herbivore abundance or biomass, but significant differences did exist among stations for carnivore abundance and biomass. Statistical differences in carnivore biomass arose primarily from a difference between Stations 47M and MB19M. Carnivore abundance differed between many stations and Station GB24M. This was not unexpected since GB24M is located in Green Bay rather than the open lake.

2.4.2.2.5 Zooplankton Carbon

LMMBP zooplankton data were provided as dry weight biomasses (mg/m^3). Data corresponding to herbivorous species were extracted from the data set for further analysis. Herbivorous species were selected because their grazing activities directly impacted phytoplankton and were, thus, important to the eutrophication model. Herbivore data were converted to units of g/L and then converted to carbon by assuming that carbon accounted for 50% of the dry weight (Baudouin and Ravera, 1972; Hessen, 1990; Andersen and Hessen, 1991). Carbon data were incorporated into the model with accompanying station and date information. No zooplankton carbon values were estimated for segments below 20 m due to the lack of applicable LMMBP or historical data.

2.4.3 Initial Conditions

The model simulation started in January 1994, but no field data were available until late April 2004. Seasonal changes of the state variables were much larger than changes (increases or decreases) over a one-year period. We, therefore, based our initial conditions for the nutrients, carbon, and plankton on January 1995 (LMMBP Cruise 5) field data. The carbon estimates were derived from the LMMBP chlorophyll *a* data for the 41 segments in the LM2 model. Level 2 segmentation is detailed in Figure 2.4.3. A 40:1 carbon:chlorophyll *a* ratio was assumed and used throughout. Diatom/non-diatom proportions were taken from the 0-20 m phytoplankton biovolume data wherever possible, and the same diatom/non-diatom proportions were maintained throughout the water column. When insufficient phytoplankton biovolume data existed (as was the case for many segments in Cruise 5), a cruise average value (52% diatoms) was used. When no chlorophyll *a* profiles were available for a given segment for Cruise 5, values from neighboring segments were used. In general, if no values were available for segments 4, 5, and 6, the average of total phytoplankton carbon for segments 1, 2, and 3 were used (diatom/non-diatom carbon proportions were assigned later based on segment specifics). If values were available for segment 6 but 4 and 5 were missing, segment 6 values were assigned to segment 5 and segment 3 values were assigned to segment 4. These estimated surface segment values were then mirrored throughout the water column.

Inadequate Green Bay data existed to follow the previously described approach for assigning initial conditions. After review of the LMMBP chlorophyll *a* profiles available for Green Bay stations, January chlorophyll *a* was estimated to be 1 µg/L for segments 7 and 8, 2 µg/L for segment 9, and 3 µg/L for segment 10. Using Green Bay specific diatom/non-diatom proportions estimated from the literature and a 40:1 carbon-to-chlorophyll ratio, these values were converted to diatom and non-diatom carbon initial conditions (Sager and Richman, 1991; DeStasio and Richman, 1998). Values for deeper segments mirrored the surface values.

Carbon data for zooplankton collected from waters 0-20 m depth in January 1995 (Cruise 5), March 1995, and April 1994 and 1995 (Cruises 1 and 6) were examined in order to estimate initial conditions for the lake. No zooplankton samples existed for several surface segments within the lake and most estimates for these segments follow from estimated values of neighboring segments. Carbon values varied with segment, but, generally, the same value was assigned to the 0-10 m, 10-20 m, and 20-30 m segments within each surface segment sector, and a value of 150% of this 0-10 m carbon value was assigned to the 30-50 m depth segment. The bottom segment (50 m maximum depth) was assigned a carbon value equal to the 0-10 m carbon value.

Many of the non-biological field measured variables did not directly relate to the state variables used in the model. As a result, assumptions were made and calculations were performed to determine the appropriate initial conditions for the modeled state variables. Table 2.4.6 lists the field measurements and modeled state variables for the nutrients and carbon. Specific assumptions and calculations used in estimating these model state variables from field

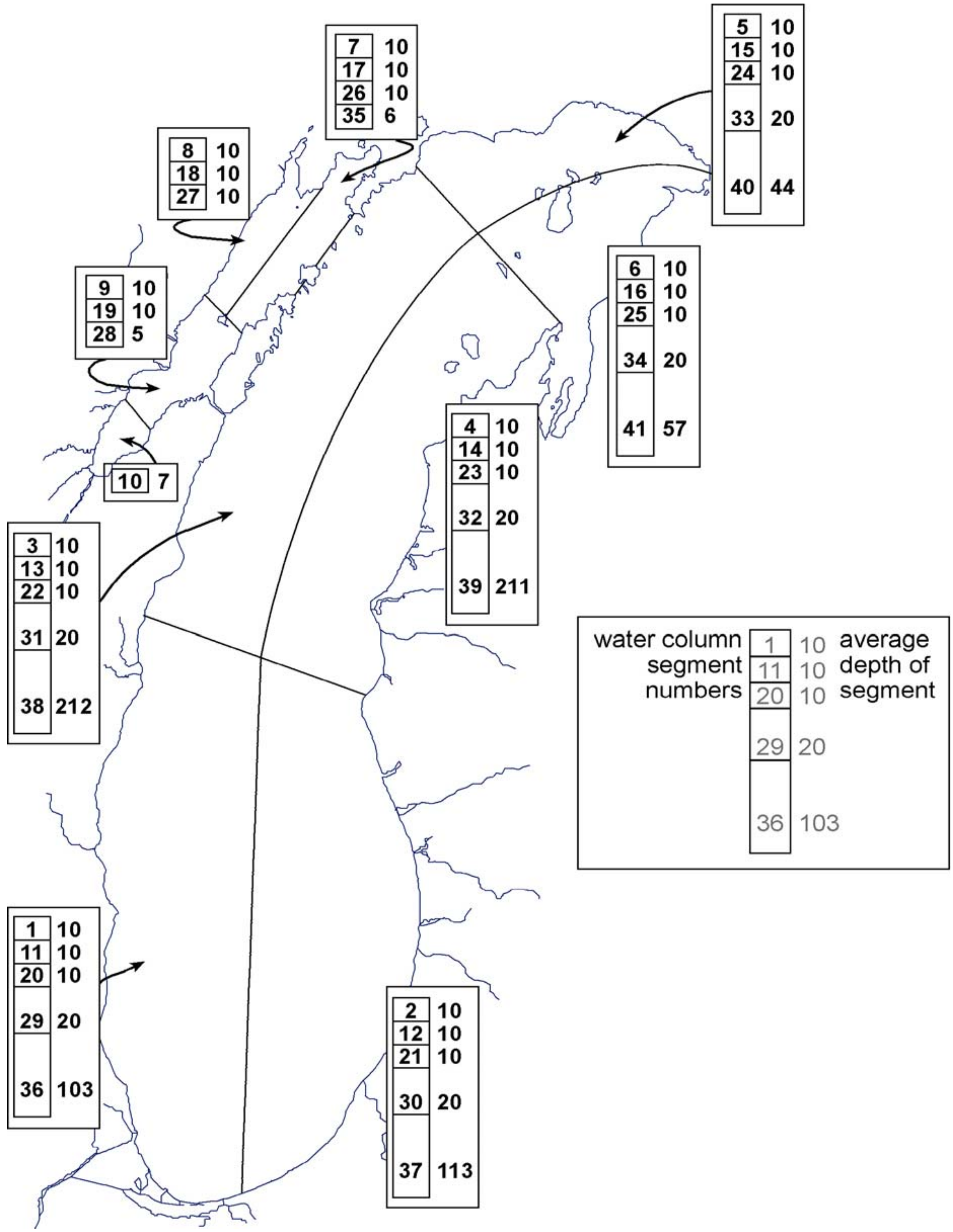

Figure 2.4.3. Level 2 model segmentation for LM3-Eutro.

Table 2.4.6. Relationship of Field Measurements and Model State Variables

Variable	Field Measurements	Model State Variable
Phosphorus	Total Phosphorus Dissolved Phosphorus Soluble Reactive (SRP)	Labile Organic (LOP) Refractory Organic (ROP) Soluble Reactive (SRP) Dissolved Organic (DOP)
Nitrogen	Total Kjeldahl (TKN) Ammonium (NH_4) Nitrate (NO_3)	Labile Organic (LON) Refractory (RON) Dissolved Organic (DON) Ammonium (NH_4) Nitrate (NO_3)
Silica	Dissolved (DSi)	Dissolved (DSi) Biogenic (BSi)
Carbon	Particulate Organic (POC) Dissolved Organic (DOC)	Labile Organic (LOC) Refractory Organic (ROC) Dissolved Organic (DOC)

measurements can be found in Appendix 2.4.1. It was assumed that the particulate forms for carbon, phosphorus, and nitrogen were split evenly between the labile and refractory forms. It was also assumed that the DON was insignificant.

2.4.4 Parameter Estimation

One of the most challenging tasks in the model development process was the estimation of the different model coefficients. A limitation of this project was the lack of field and laboratory experiments to determine values for the many coefficients. Some physical data were available for model coefficient estimation, and these instances are detailed below. In addition, the use of primary productivity experiments to assist with the estimation of production-related coefficients will be discussed. Values for all other parameters were obtained initially from the literature, with further refinement *via* calibration.

2.4.4.1 Physical Measurements

2.4.4.1.1 Secchi Disk

Secchi disk measurements were performed during the eight sampling cruises in 1994-1995 to obtain an estimate of water clarity. Cruise averages for all available stations were calculated and are shown in Figure 2.4.4. Secchi disk values were used in an empirical equation (Thomann and Mueller, 1987) to estimate the light extinction coefficients used in the eutrophication model.

2.4.4.1.2 Solar Radiation and Temperature

Primary productivity was strongly affected by both available light (solar radiation) and temperature. As part of the output of the hydrodynamics model (Princeton Ocean Model [POM]) used to generate Lake Michigan hydrodynamic parameters, lake-wide short wave solar radiation and temperature data were generated (Schwab and Beletsky, 1998). Solar radiation was one of the forcing functions driving the phytoplankton growth. In the model, it was referred to as incident solar light intensity (I_o).

2.4.4.2 Primary Production Estimates

The rates at which phytoplankton grow and utilize available nutrients are among the most important and complex processes in any eutrophication model. Primary productivity laboratory experiments were conducted as part of the LMMBP. However, due to the difficulty in converting laboratory production rates into reasonable *in situ* primary production information, the model production rates were generated using coefficients gleaned from published literature and the model calibration process (Table 2.4.7). The laboratory primary production experiments were used to verify the overall production rates in the model (Figure 2.5.2). Laboratory productivity data were provided by GLNPO for the 1994-1995 project field season. The ^{14}C incubation productivity determination method was utilized. This method calls for the inoculation of water sub-samples with ^{13}C radiotracer followed by incubation at varying light intensities for two to four hours. Sub-samples were filtered and radioactivity

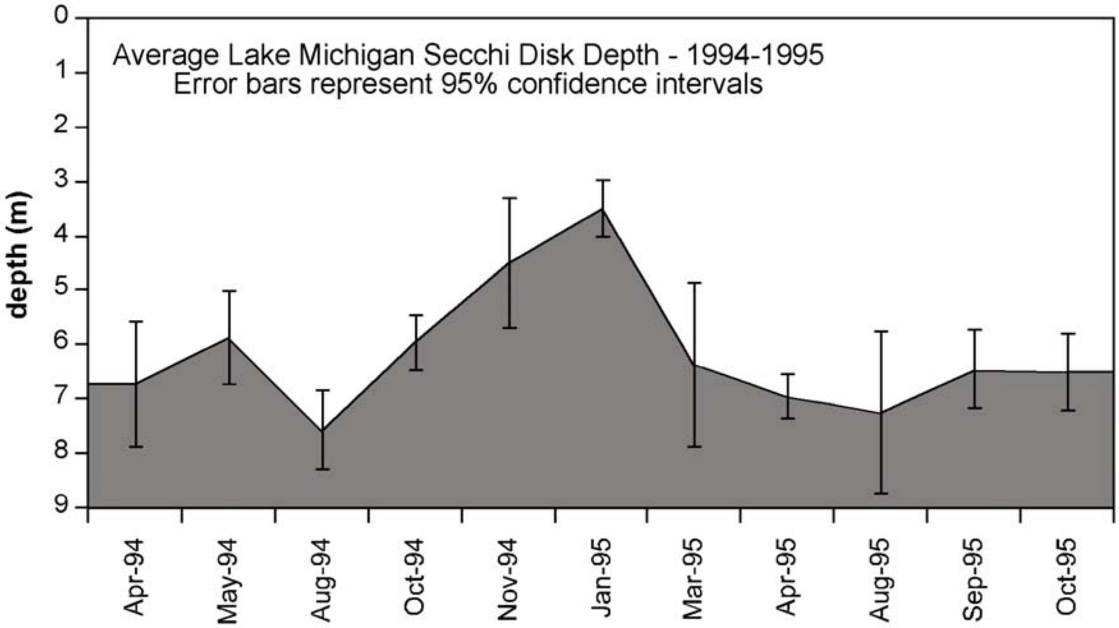

Figure 2.4.4. Lake-wide Secchi depths for the eight LMMBP cruises.

Table 2.4.7. Important LM3 Model Coefficients

Parameter	Unit	Value	Literature Values	Description
CCHLD	No Unit	40	10-100[2,3,4]	Carbon:chlorophyll ratio (diatoms)
CCHLG	No Unit	40	10-100[1-4]	Carbon:chlorophyll ratio (non-diatoms)
KHPD	µg/L	0.5	0.5 - 1.0[2,3,4]	Phosphorus half-saturation coefficients for diatoms
KHPG	µg/L	0.5	0.5 - 1.0[1-4]	Phosphorus half-saturation coefficients for non-diatoms
KHSD	mg/L	0.03	0.03 - 0.06[2,3,4]	Si half-saturation coefficient for diatoms
PMD	1/day	2.5	0.58 - 8.0[2,3,4]	Diatom growth coefficient
PMG	1/day	2.1	0.58 - 8.0[1-4]	Non-diatom growth coefficient
TMD		20	20[2,3,4]	Optimum diatom growth temperature
TMG		20	20[1-4]	Optimum non-diatom growth temperature

[1]Rodgers and Salisbury, 1981
[2]Di Toro and Connolly, 1980
[3]Bowie *et al.*, 1985
[4]Thomann and Di Toro, 1975

of algal cells was measured (U.S. Environmental Protection Agency, 1997). Measured radioactivity should be proportional to the amount of carbon fixed by the algae. Other variables used in calculating the final productivity estimate include light intensity, length of incubation, temperature, and basic information about carbon and chlorophyll levels in the water samples. Variables reported included station code, date, sample depth, temperature, sample identification number, productivity results (mg C/L/h), total incubation time and incubation light level ($mE/m^2/s$). Each station was sampled several times from April 1994 to October 1995, and 12 sub-samples were incubated (at different light intensities) for each station/date/depth combination. Discrete and integrated samples were collected, and efforts were made to include hypolimnetic samples during stratification.

Most of the analysis effort was devoted to determine how productivity changes with light, temperature, phytoplankton carbon, chlorophyll *a,* etc., and to compare these changes with the output of the model equation. Data appeared to follow typical irradiance versus production curves, with production increasing with increasing light levels and then reaching a plateau. Limited light ranges, however, prevented determination of the presence/absence or degree of light inhibition. For purposes of further analysis of laboratory versus model productivity predictions, optimum light levels were designated. For each set of experiments, optimum light was taken to be that light at which maximum production (mgC/L/h) was reported.

There was some degree of uncertainty associated with all estimates of phytoplankton production derived from incubation experiments. It is well-known that results from short experiments (< 6 hours) are frequently higher than those estimated from longer experiments (24 hours). It is generally believed that short-term ^{14}C incubations measure something between gross and net production (Fahnenstiel and Scavia, 1987). This is a factor which must be considered when comparing laboratory data to predictions from model equations.

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