Review of the Characteristics of Lake Shaokatan, MN

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A "Final Lake Shaokatan Phosphorus Total Maximum Daily Load [TMDL] Report" was released in December 2009 that discussed the development of the proposed phosphorus TMDL for Lake Shaokatan, MN to improve the eutrophication-related water quality of the lake (Schuler, 2009). Because the designation of a P TMDL for this waterbody will have a marked impact on the agricultural activities in the lake's watershed, it is paramount that those regulatory limitations have a sound technical basis. It is also important that there be a technically sound basis for a reasonable expectation that the implementation of such limits will effect the desired and anticipated improvement in water quality of the lake.

Normally, the year-to-year variations in weather, rainfall, runoff, and nutrient inputs, and lake responses to those variations necessitate an appropriately encompassing, several-year study of the lake and its watershed to adequately characterize the sources of P and quantify how contributions of P from those sources impact water quality. Such an understanding is essential for the development of a reliable TMDL sufficiently broad to have applicability to the range of conditions likely to occur. The Schuler (2009) TMDL was based on a limited set of data developed from routine monitoring for part of one year, 2005; the monitoring was not focused on collection of the necessary data for the development of a technically sound TMDL. It is therefore important to consider not only the adequacy of the technical approach used in the development of the TMDL, but also how representative the database used to establish the TMDL is of the broader range of normal conditions to which the TMDL will be applied over time.

We have undertaken a review of the technical foundation for the December 2009 draft P TMDL. One area of focus was the representativeness of the key weather-related and lake characteristics during the 2005 TMDL study period relative to those of other recent years; we have examined the data available for these aspects of Lake Shaokatan for the past 10 to 20 years. Another area of focus was the relationship between P load to the lake and the resultant eutrophication-related water quality. Schuler (2009) drew conclusions about that relationship based on the 2005 database and noted a number of key limitations in the data available. We have examined the relationship between P load and response from the 2005 database as well as from the results of the MPCA study in 2008, and some limited data collected in 2009. This has enabled us to consider how "normal" a year 2005 may have been to serve as a foundation for a TMDL, as well as how the load–response relationships for Lake Shaokatan compare to those in other waterbodies worldwide. It also provides insight into particular characteristics of Lake Shaokatan and its use of nutrients in the production of algae and aquatic macrophytes/rooted water weeds that call into question the appropriateness of a TMDL approach for regulating phosphorus input into this lake.

Watershed Rainfall

Precipitation pattern, intensity, and amount in the watershed and over the lake can affect the loading of P in ways that can affect its ability to stimulate the growth of algae and aquatic weeds. Greater rainfall amount and intensity can cause greater runoff of total P from the agricultural watershed. While for many waterbodies, much of the particulate P introduced in this way is unavailable to support algal growth, this may not be the case for Lake Shaokatan owing to the undefined but apparently substantial internal loading from sediments associated with aquatic weeds. High-intensity rainfall and wind, especially on the surface of this shallow lake, and boat traffic would also likely increase internal TP load, by stirring sediment into the water column. The impact of the increased P loads associated with precipitation on the growth of algae and aquatic plants in this lake depends to some extent on when they occur relative to the period of nuisance growth.

Figures 1 and 2 present the yearly average and monthly average rainfall values for the Lake Shaokatan watershed area for the past two decades; they show the variability in rainfall pattern and intensity in this watershed over that period. 2005 had the third-highest total rainfall in the past 20 years. Figure 3, the monthly average rainfalls during the 2003-2009 period, shows that the September 2005 rainfall was somewhat above normal for the same month in the other years. As illustrated in Figure 4, the large rainfall event on September 13 when 2.05 in. of rain fell, was largely responsible for that elevated monthly average.

Comparison of the tributary sampling dates (TMDL report, Appendix 1) with rainfall events in 2005 shows that 5 of the 28 samples collected for TP analysis at the stations equipped for continuous flow measurement (e.g., station 1–Co. Rd. 15) (see Figure 5) were collected on non-rainfall days. At the stations at which grab samples were collected (e.g., station 11–Bradley's tile), 3 of the 18 samples collected for TP analysis were collected on non-rainfall days. In general, except for a few non-rainfall sampling dates, the sampling appears to have targeted rainfall days when the rainfall date was preceded by several days with no rainfall. Also, on a couple of occasions, it appears that if samples had been collected early in what turned out to be a several-day rain period, another set of samples was also collected later in that rainfall period, ahead of the normal sampling interval regimen. This sampling scheme could tend to overestimate the actual P load from the watersheds of some of the areas studied.

Plots of the flow and TP data presented in the TMDL 2005 report for several of the lake's watershed sampling stations are presented in Appendix A. Also presented in those plots is the daily rainfall that was measured at the rainfall monitoring station located about 20 miles from the lake. Those plots show the complexity of these relationships and demonstrate that multiple years of detailed, year-round monitoring of the each of the lake's watershed components must be conducted to begin to adequately characterize the amount of TP exported from any particular watershed, the total annual TP and water loads to the lake, as well as the factors that influence those loads.

No information was provided in the TMDL on how the phosphorus load was calculated from the flow and concentration data from either the stations with continuous-flow measurements or from stations in which a staff-gage was read at the time the grab samples were collected. It will be important to examine the approach that was used to interpolate flow and TP concentrations between sampling dates in the computation of the P load.

Figure 1. Average Total Yearly Rainfall - Lake Shaokatan Watershed 1990 - 2009

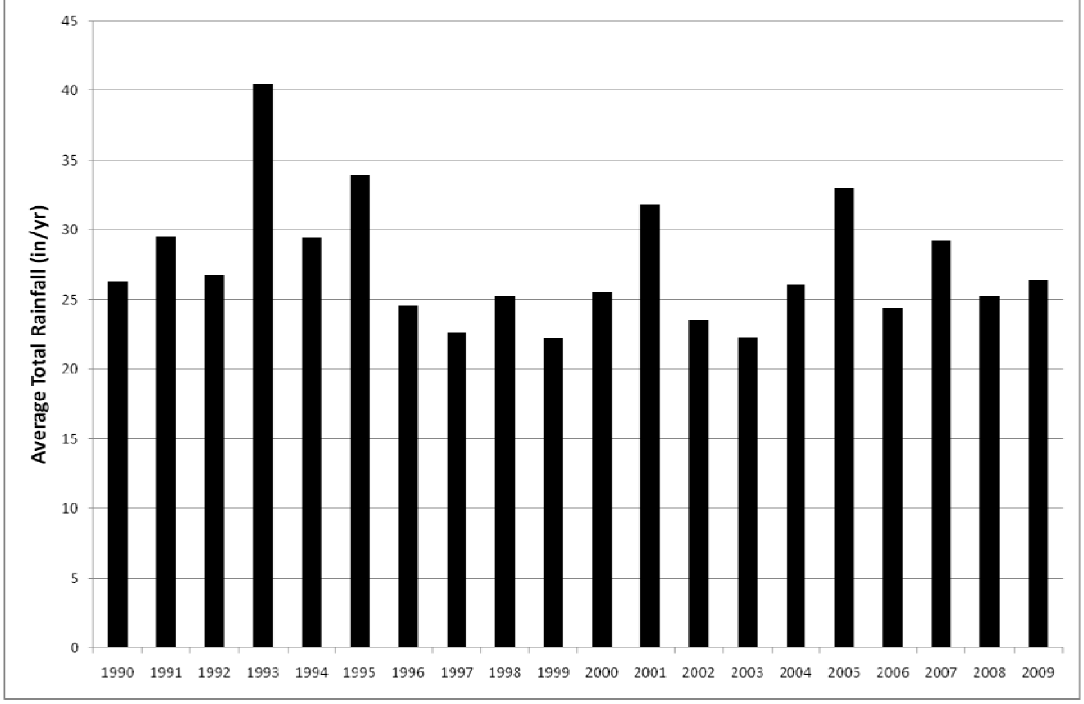
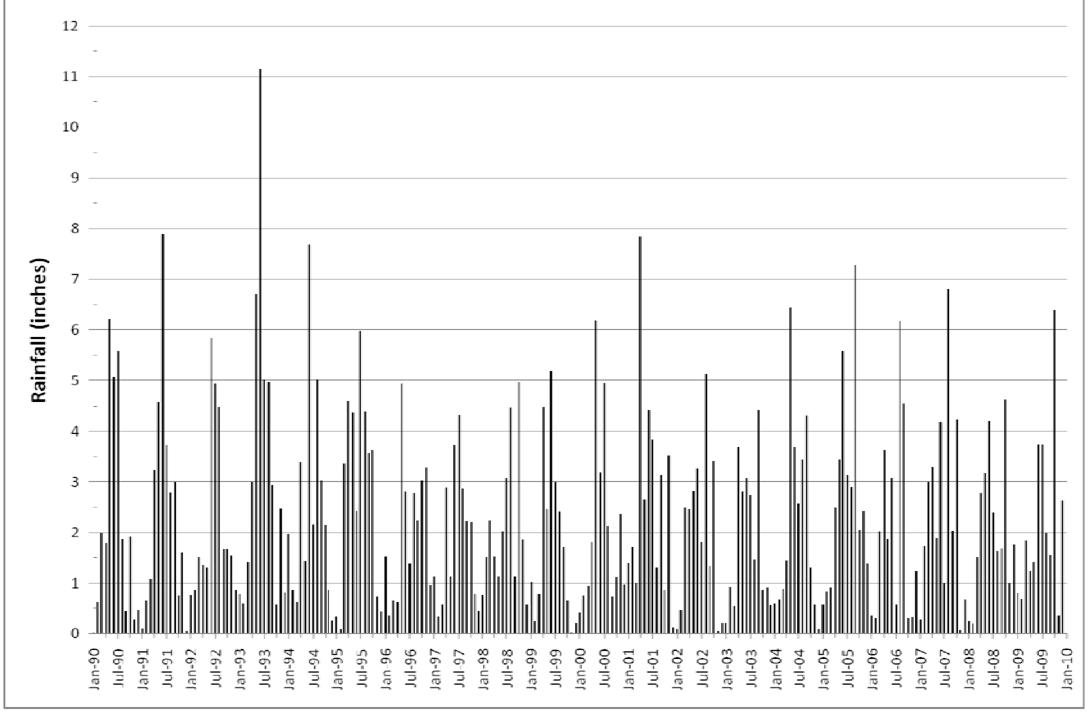


Figure 2. Monthly Average Rainfall Record for Lake Shaokatan 1990 - 2009



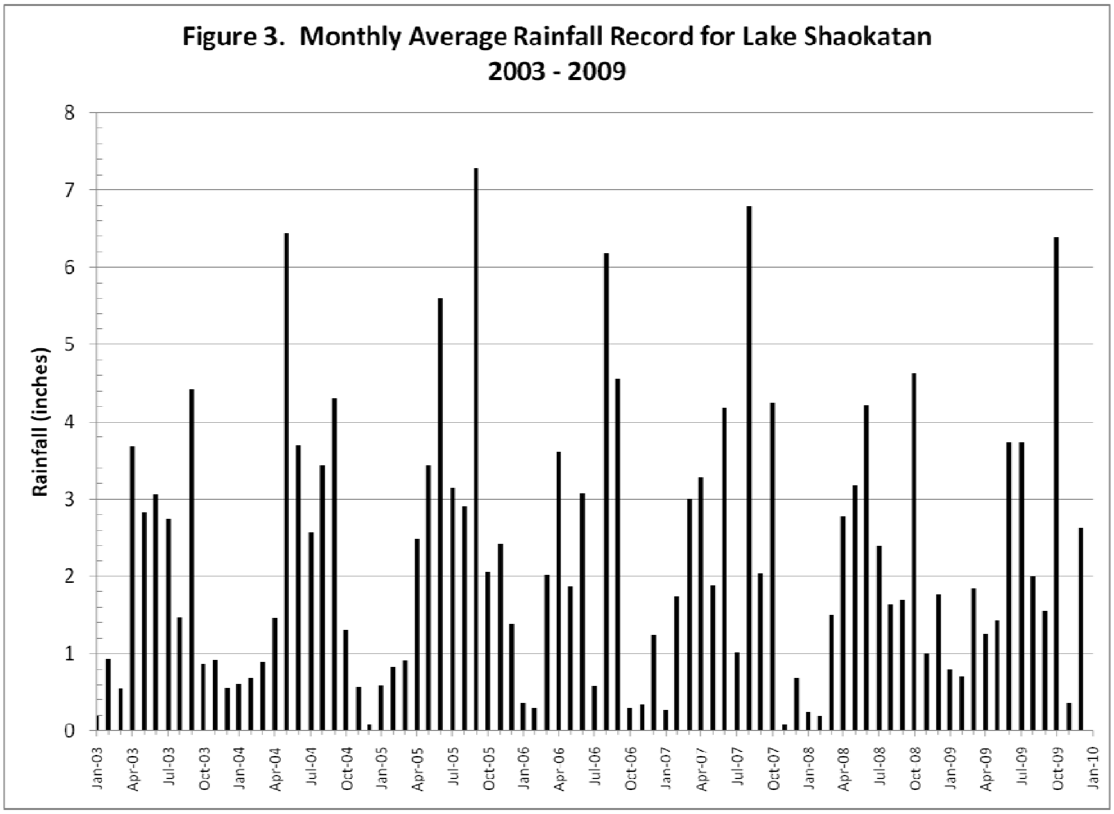


Figure 3. Monthly Average Rainfall Record for Lake Shaokatan
2003 - 2009
Rainfall (inches)
0
1
2
3
4
5
6
7
8
Jan-03
Apr-03
Jul-03
Oct-03
Jan-04
Apr-04
Jul-04
Oct-04
Jan-05
Apr-05
Jul-05
Oct-05
Jan-06
Apr-06
Jul-06
Oct-06
Jan-07
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Jul-09
Oct-09
Jan-10

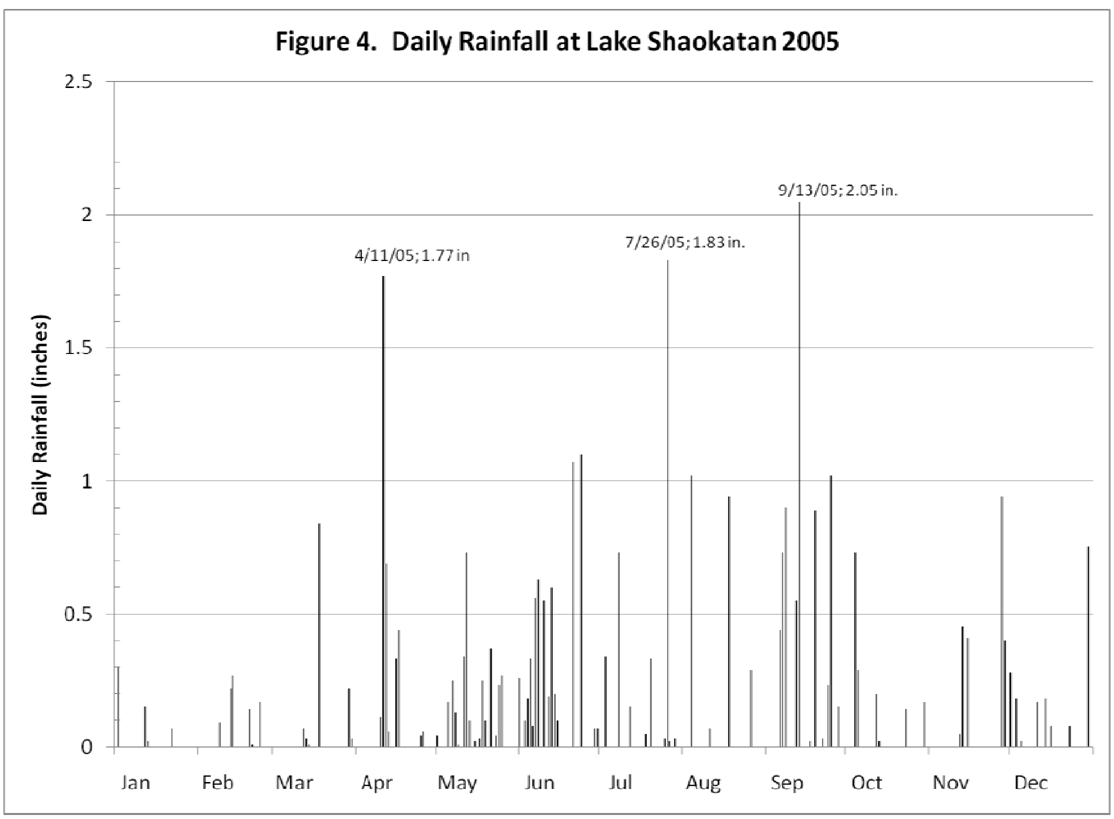
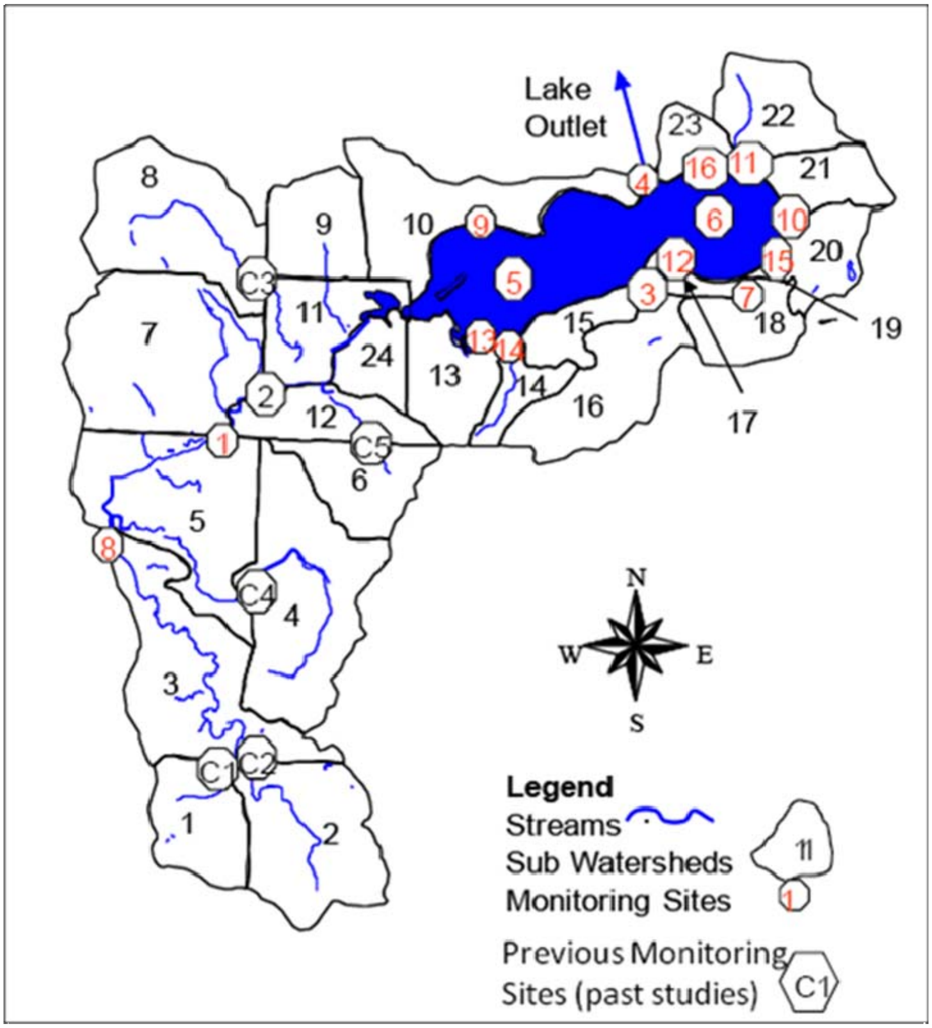


Figure 4. Daily Rainfall at Lake Shaokatan 2005
Daily Rainfall (inches)
0
0.5
1
1.5
2
2.5
4/11/05; 1.77 in
7/26/05; 1.83 in.
9/13/05; 2.05 in.
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

Figure 5. Lake Shaokatan Sampling Stations
(from the 2005 TMDL Original Report)



Figures 6 and 7 present the daily rainfall in the Lake Shaokatan watershed for 2008 and 2009, respectively; Figure 8 shows the two years' data side-by-side. With Figure 4, these figures show that during the period November through March, when no flow or TP measurements were made in the 2005 study period, appreciable rainfall occurred that could potentially impact the following summers' planktonic algal growth. The summer planktonic algal chlorophyll level in a waterbody can be significantly impacted by the TP load from the previous fall, winter, and early spring. This is especially true for a lake having a several-year hydraulic residence time and no outflow, such as is apparently typical of Lake Shaokatan in recent years.

Lake Elevation

Figure 9 shows the Lake Shaokatan water elevation record over the past decade. The lake's dam surface is at the 1776.6-ft elevation; when the water level reaches that elevation, water is discharged over the dam. The reported lake elevations for 2000 – 2009 were all below the top of the dam, although on August 21, 2006, the water level was almost at that level. The lake did not

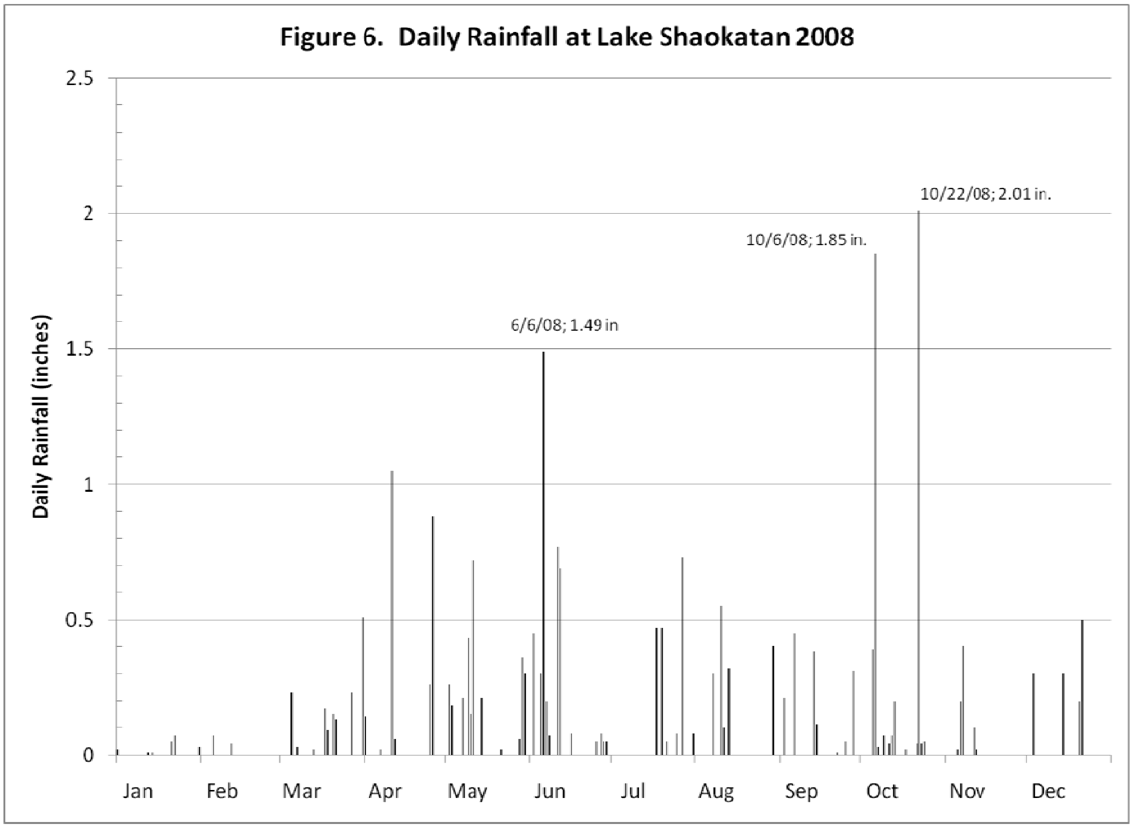


Figure 6. Daily Rainfall at Lake Shaokatan 2008
Daily Rainfall (inches)
2.5
2
1.5
1
0.5
0
10/22/08; 2.01 in.
10/6/08; 1.85 in.
6/6/08; 1.49 in
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

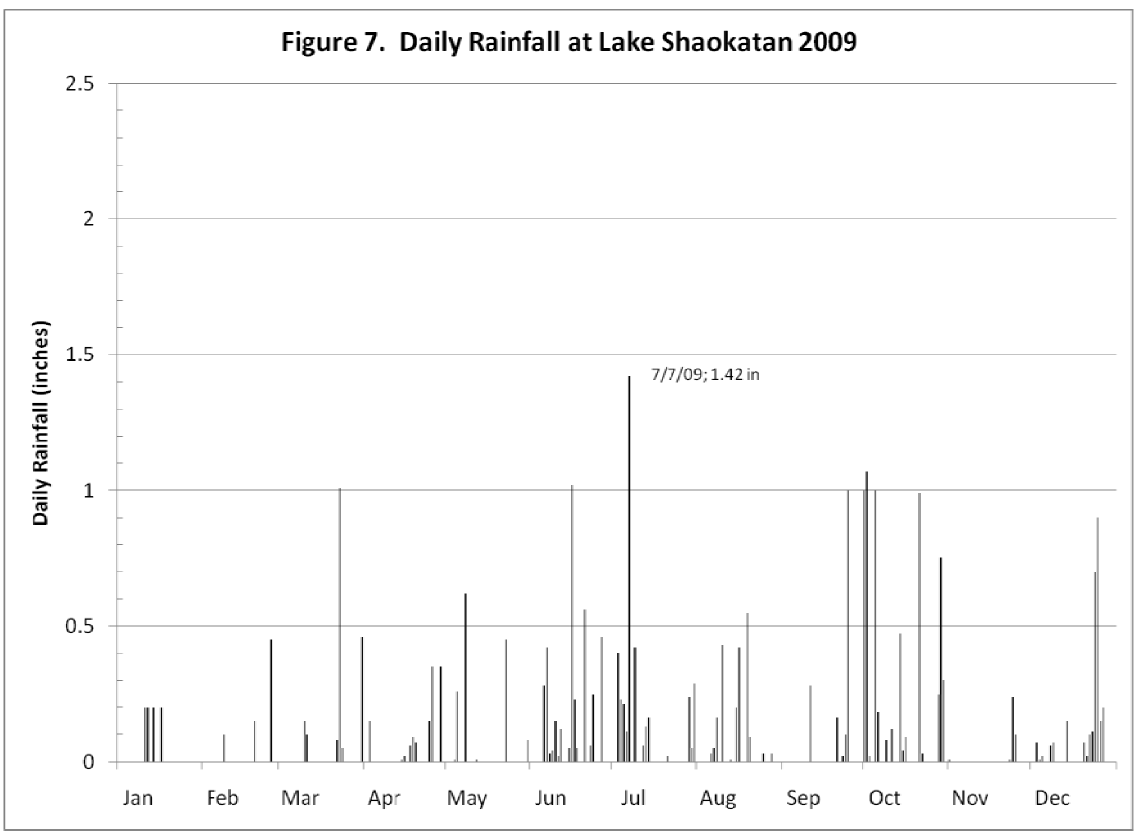


Figure 7. Daily Rainfall at Lake Shaokatan 2009
Daily Rainfall (inches)
2.5
2
1.5
1
0.5
0
7/7/09; 1.42 in
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

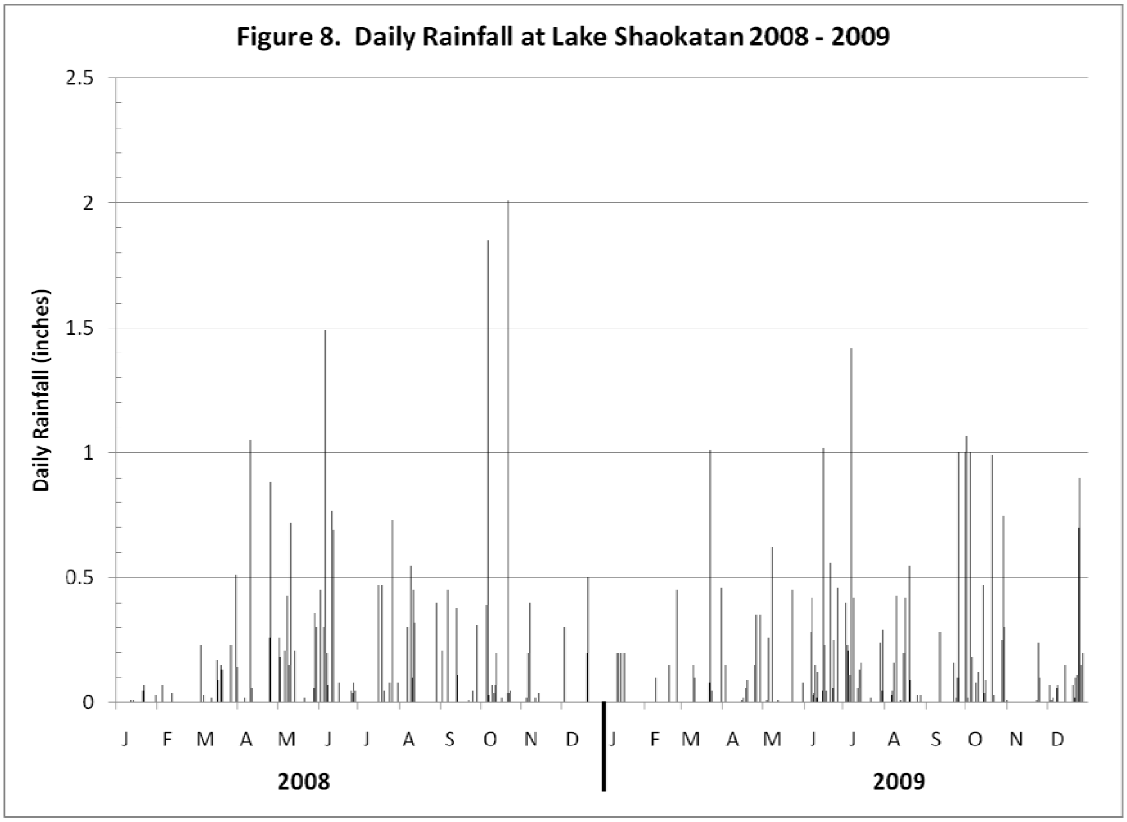


Figure 8. Daily Rainfall at Lake Shaokatan 2008 - 2009
Daily Rainfall (inches)
2.5
2
1.5
1
0.5
0
J F M A M J J A S O N D J F M A M J J A S O N D
2008
2009

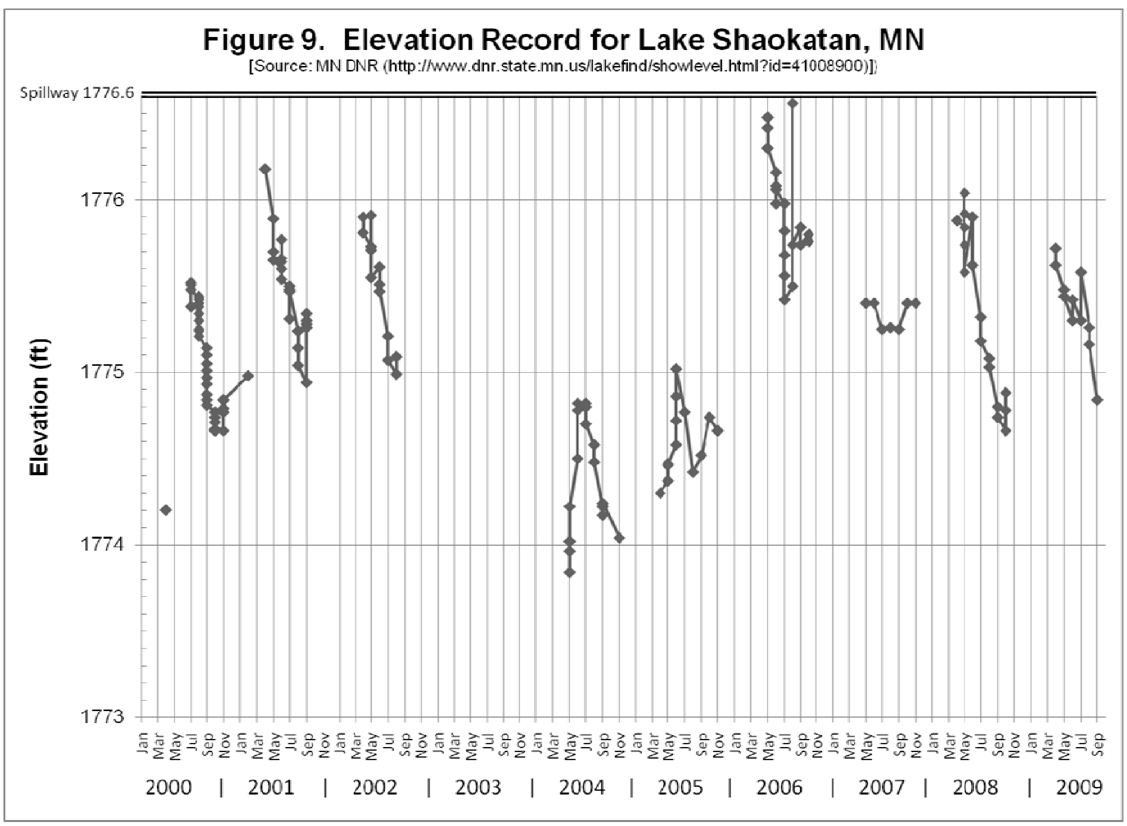
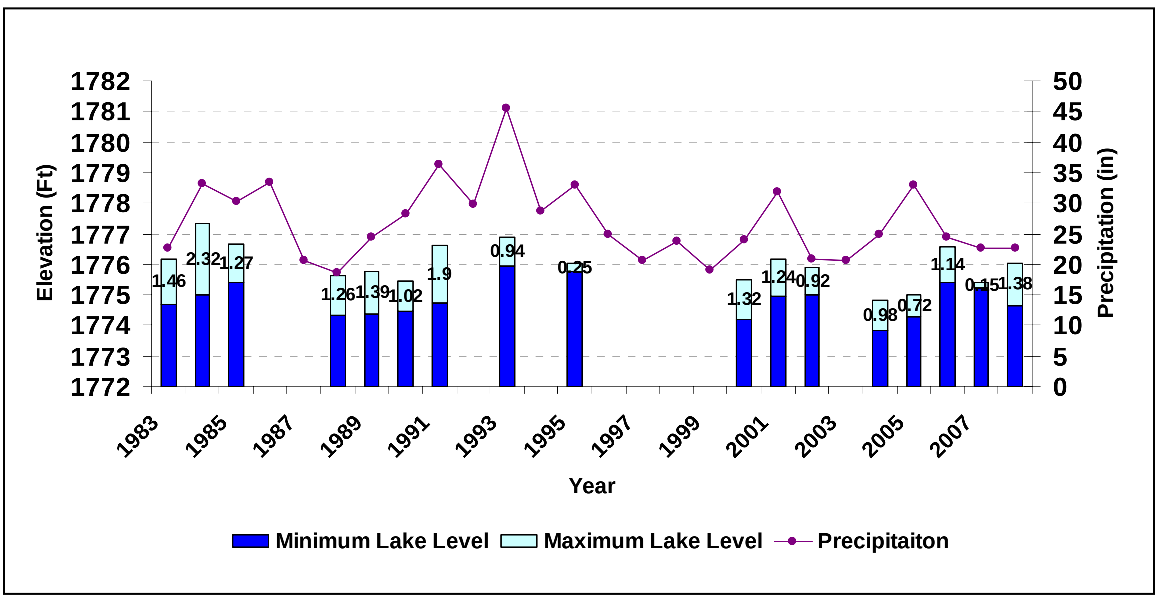


Figure 9. Elevation Record for Lake Shaokatan, MN
[Source: MN DNR (http://www.dnr.state.mn.us/lakefind/showlevel.html?id=41008900)]
Spillway 1776.6
Elevation (ft)
1776
1775
1774
1773
2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009

discharge water during this period, a condition that increases the hydraulic residence time of the waterbody. The hydraulic residence time ("filling time") of a lake can be computed by dividing the volume of the lake water by the annual inflow. As discussed subsequently, it is a key factor in affecting how nutrients added to the lake from the watershed and from internal cycling are utilized by algae and aquatic plants. Greater flushing of water through Lake Shaokatan would lead to lower TP and chlorophyll in the lake as there would be less time for algal development from the nutrients introduced, and greater flushing of internally derived nutrients. In this decade, the water levels in 2004 and 2005 were notably below those of the other years reported. Such a sustained and comparatively low water level in the year prior to and during the 2005 TMDL monitoring year, with no outflow from the lake, would be expected to result in somewhat nutrient behavior/cycling in the lake and atypical couplings between phosphorus load and planktonic algal growth in 2005. This will be examined further subsequently.

Figure 10, which is from the MPCA 2009 report, shows the lake level combined with rainfall data. As expected, the lake level responds to increased rainfall. Low precipitation in 2002 and 2003 resulted in the low lake levels in 2004-2005; increased rainfall in 2006 resulted in a substantially higher lake elevation in 2007.

Figure 10. Annual Precipitation, Maximum, and Minimum Water Levels in Lake Shaokotan[1]

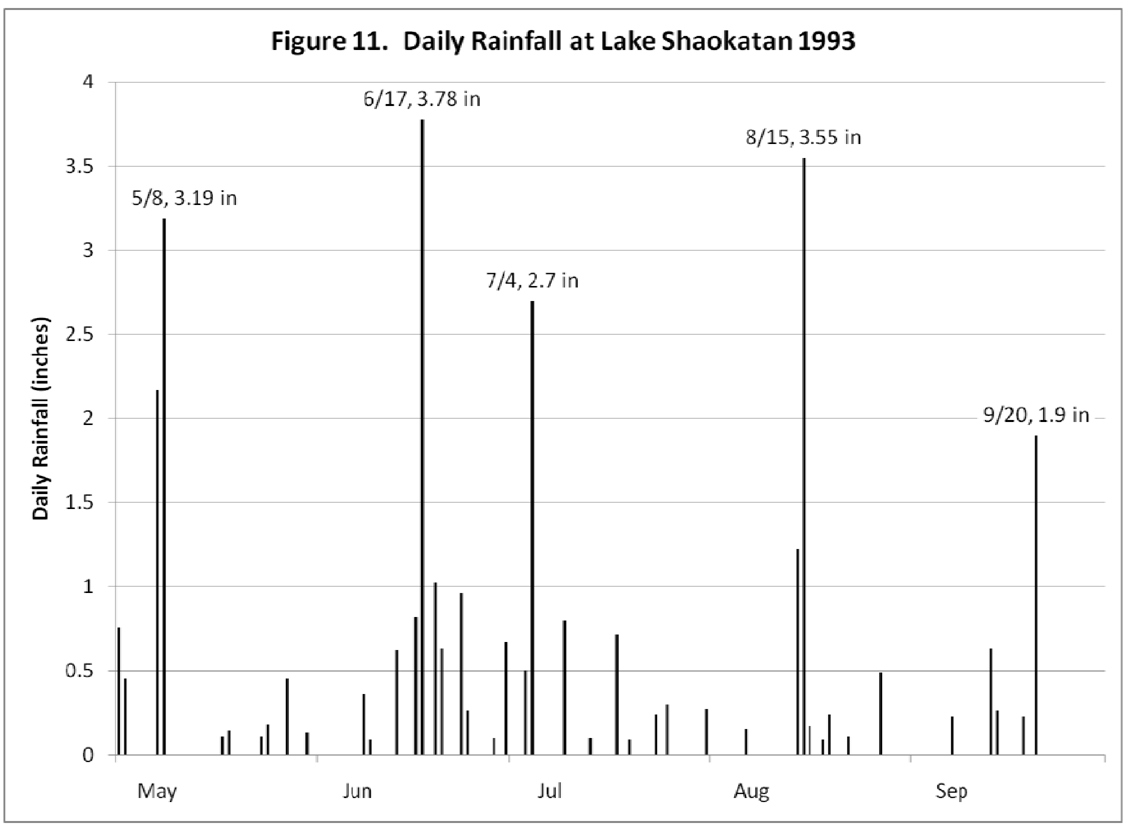


[1] (Figure 8 from MPCA and MN DNR, "2008 Sentinel Lake Assessment Report Lake Shaokotan (41-0089), Lincoln County, Minnesota," Minnesota Pollution Control Agency, St. Paul, MN, July (2009). www.pca.state.mn.us/water/lakereport.html

1993 Rainfall/Flushing
Figure 11 presents the daily rainfall in the Lake Shaokatan area during 1993. 1993 was, by far, the wettest of the years reported, with a total rainfall of 40.07 inches. It was followed by two years of elevated rainfall levels of 30.36 inches and 35.43 inches. T. Dritz (personal communication) stated, "*Not only was 1993 a very wet year but if I remember right there were some big storms with heavy downpours making soil loss more likely.*"

By comparison, according to W. Formo (personal communication) the TMDL study year of *"2005 was the eighth highest rainfall in history with 33.75 inches of rain. Consecutive years of rainfall with over 30 inches of rainfall have happened three times in history 1905-1906, and 1993-"* While as shown in Figure 10 water flowed over the dam in 1993, it has not flowed over the dam in subsequent years, even with the occurrence of higher than usual rainfall in 1995, 2001, and 2005. Thus, it is indeed rare that Lake Shaokatan watershed receives sufficient rainfall/runoff to cause lake water to flow over the dam to flush the lake.

The appendix to the first TMDL report indicates that the hydraulic residence time computed for 2005 was 2.2 years. However it is not clear that that value considered the rainfall data from the fall of 2004, or winter and early spring of 2005 since apparently no flow measurements were made during those periods.



Lake Total P Concentration
Figure 12 presents the TP concentration data for Lake Shaokatan for 1985 - 2009. While data were sparse prior to the early 1990s, there appeared to have been a progressive decrease in concentration of total P in the lake between 1991 and 1995 when sampling was suspended. This decrease occurred following implementation of P input reduction measures by the agricultural interests in the late 1980s. Sampling was resumed in the early 2000s, and, with the exception of elevated concentrations in September 2005, TP concentrations and patterns were about the same each year of the ensuing decade. The concentration of TP is seen to increase over the summer, apparently due to aquatic weed pumping of P from the sediments and other sediment release of P, rainfall runoff that occurs in the summer, as well as tile drainage discharges.

As shown in Figure 12, the proposed TMDL water quality target for TP is 81 µg/L (with the MPCA 10% margin of safety). The total P in the lake during the 2000s was consistently greater than the TMDL water quality target, especially in late summer, as it had been in earlier years. The TP in the lake tended to be below the target concentration in early summer followed by ever-increasing concentrations over the summer. That pattern apparently reflects the pumping of P from the sediments into the water column by aquatic macrophytes (weeds). That phenomenon appears to have led to the TMDL report’s statement that about 50% of the total P load is derived from the internal P load. The major peak in the TP concentration in 2005 reflects the greater external and internal P loads, especially associated with the September 2005 precipitation event.

Figure 13 presents the TP concentrations in Lake Shaokatan along with the rainfall data reported for 1991–2009. Associated with the elevated rainfall in September 2005 was an elevation in TP concentration. In 2008 the elevated TP in July was associated with elevated rainfall in June-July. The July 21, 2009 sample with the elevated TP concentration followed a major rainfall event on July 7, 2009. This apparent association of TP in the lake with rainfall events could be due to increased runoff that transports more TP from the watershed, to direct deposition of TP on the lake surface in the precipitation, and to increased stirring of the water column and sediments due to storm-associated wind conditions. Table 7 in the TMDL report indicates that an estimated 3 to 11 % of the TP annual load comes from deposition directly on the lake’s surface.

For some lakes geese can be an important source of nutrients; geese feed in the fields and release nutrients into the lake in their fecal matter. Ducks feed in the lake facilitating the cycling and release of nutrients from the sediment to the water column. According to T. Dritz (personal communication, 2010) with regard to ducks and geese in Lake Shaokatan:
“*In the summer there is maybe a couple of dozen ducks and geese on the lake. During the fall there are large flocks on the lake as smaller water bodies freeze over.*”

The “total phosphorus” measured in a water is composed of dissolved “soluble” orthophosphate (OP) as well as particulate forms of phosphorus that are in cells of algae and other planktonic organisms in the water, organic and inorganic P stirred up from the sediments or introduced to the lake from the watershed, and possibly some aquatic weed fragments especially in lake summer. Rooted aquatic weeds can use sediment-associated P for growth which, as noted above, serves to “pump” phosphorus from the sediment into the water column. Soluble orthophosphate is the portion of the total P that is readily available to support the growth of planktonic algae.

Figure 12. Total P Concentrations in Lake Shaokatan 1985 - 2009 (Station 41-0089)

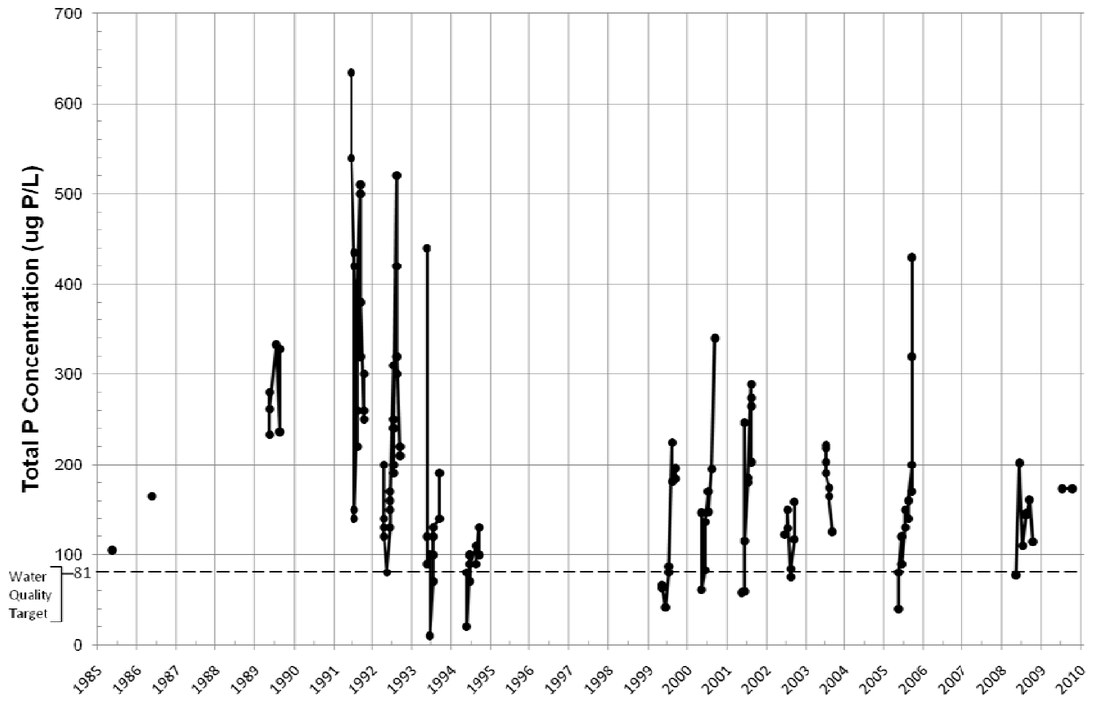
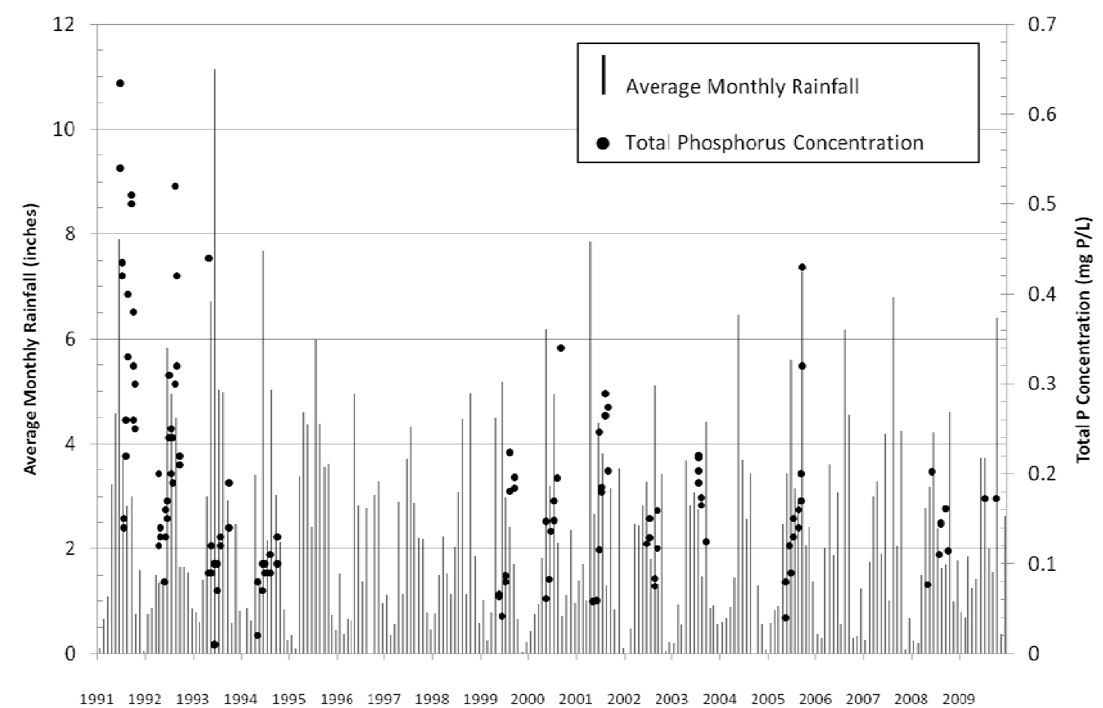


Figure 13. Total Phosphorus Concentrations in Lake Shaokatan and Average Monthly Rainfall 1991 - 2009



Only some of the particulate P may solubilize and become available to algae. Figure 14 presents the concentrations of OP measured in Lake Shaokatan over the period 1991 through 2009. It shows a dramatic decrease in the OP concentration in the lake between 1991 and 1992, associated with P control efforts in the watershed. While measurements of OP have been few, essentially all concentrations of OP reported since mid-1992 have been below the TMDL water quality target; one of the measurements made in 2009 (October 13) was greater than the target level.

Figure 14. Ortho P Concentrations in Lake Shaokatan 1991 - 2009 (Station 41-0089)

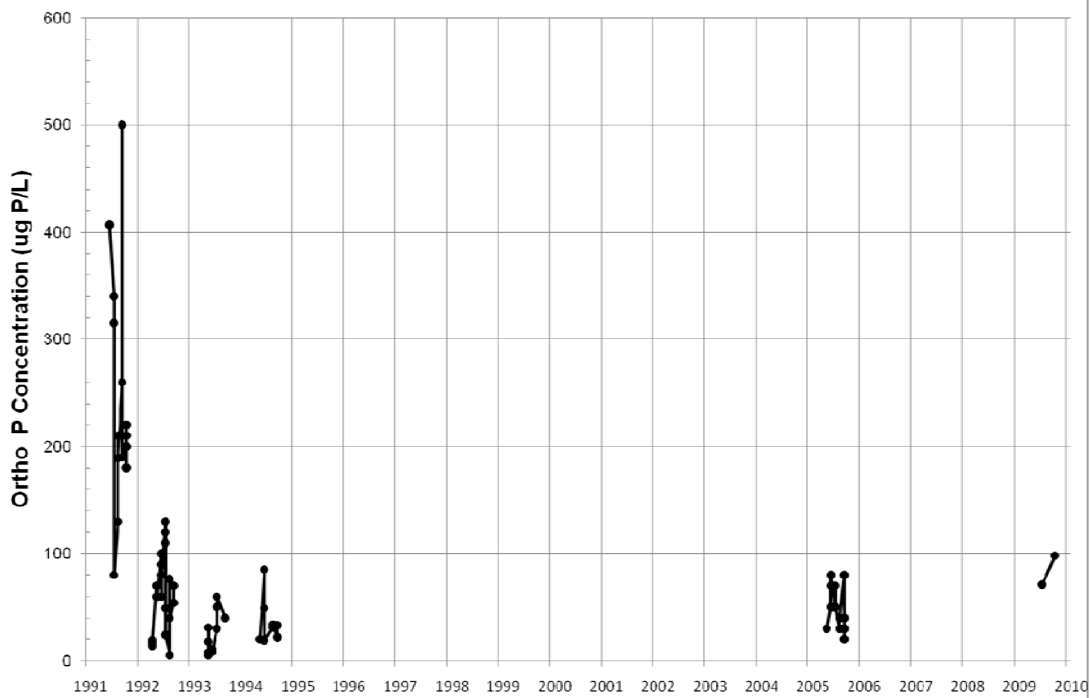


Figure 15 shows the lake's TP and the OP concentrations plotted together. While there is comparatively little OP data, this figure illustrates that when OP was measured it accounted for only a small portion of the total P; essentially all of the phosphorus has been in particulate P forms.

Figure 16 compares the daily rainfall in the Lake Shaokatan area in 1993 (the wettest year on record) with TP and soluble P concentrations measured in the lake. The sampling of the lake during the summer was inadequate to show a discernable pattern between the high rainfall in the watershed and in-lake TP and OP. However, the plot does show that there was readily measureable soluble ortho P as well as particulate P in the lake. This is to be expected with high rainfall runoff periods. It is also likely that the elevated particulate P is derived, at least in part, from soil erosion and would not be available to support algal growth.

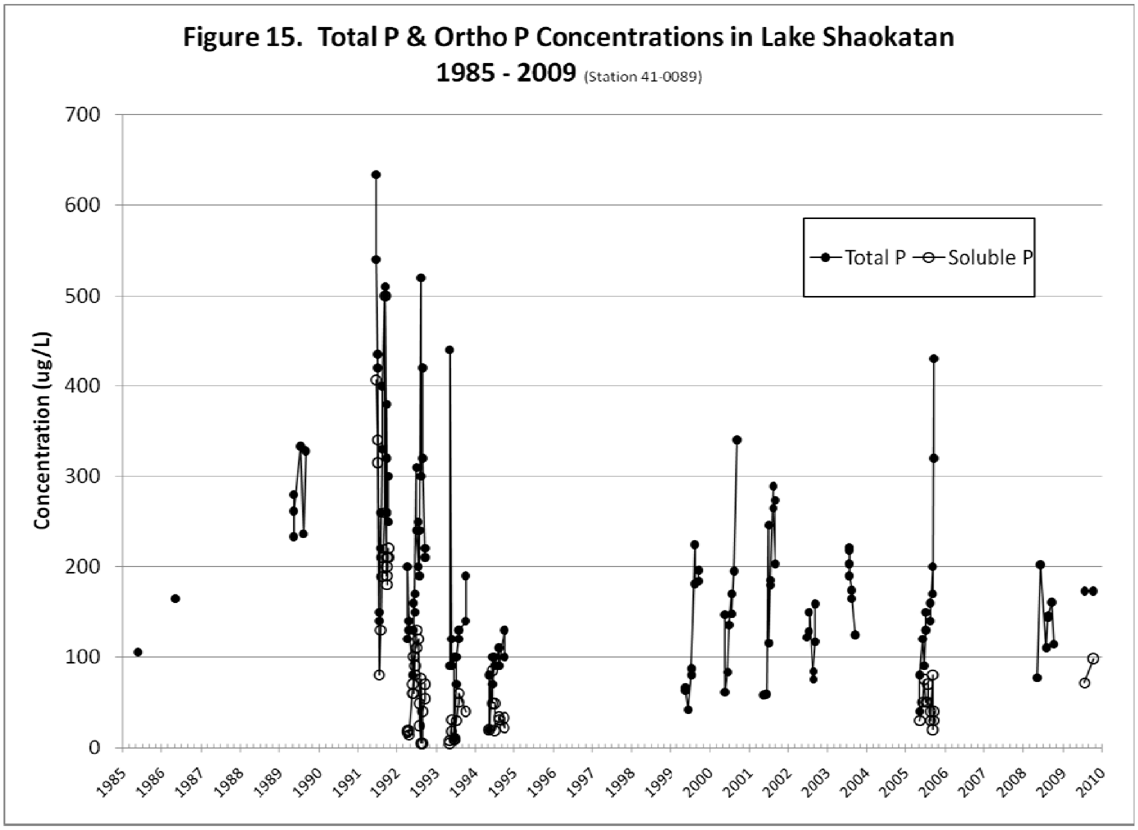


Figure 15. Total P & Ortho P Concentrations in Lake Shaokatan
1985 - 2009 (Station 41-0089)
Concentration (ug/L)
Total P
Soluble P
700
600
500
400
300
200
100
0
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010

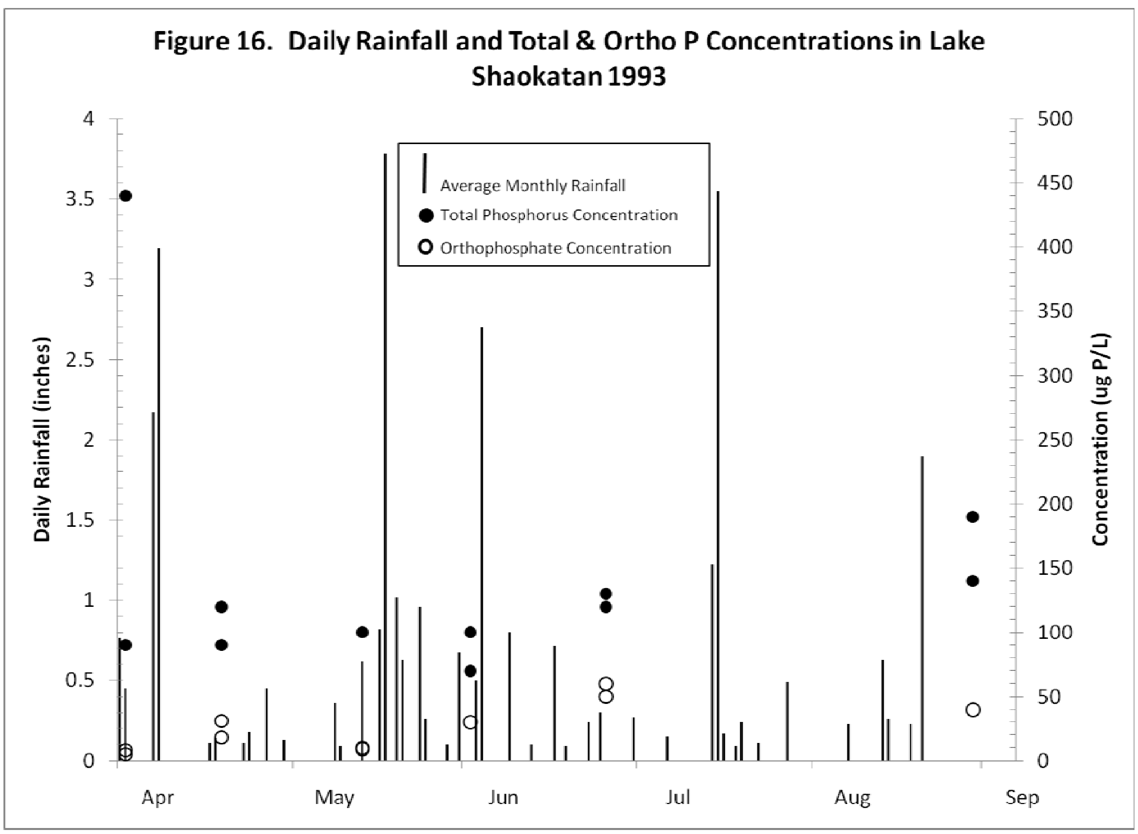


Figure 16. Daily Rainfall and Total & Ortho P Concentrations in Lake Shaokatan 1993
Daily Rainfall (inches)
Concentration (ug P/L)
Average Monthly Rainfall
Total Phosphorus Concentration
Orthophosphate Concentration
4
3.5
3
2.5
2
1.5
1
0.5
0
500
450
400
350
300
250
200
150
100
50
0
Apr
May
Jun
Jul
Aug
Sep

It was stated in the TMDL report (page 16) that the 1993 rainfall, which led to flushing of the lake, greatly improved the lake's water quality. While Figure 3 in the TMDL report showed that the TP in 1994 was just over the proposed TMDL water quality target of 81 µg/L, no eutrophication-related water quality response parameters were measured in the lake during 1994 to quantitatively substantiate that impression. As discussed elsewhere, TP concentration is not a good indicator of eutrophication-related water quality, and in this case could be indicative of the higher input of erosional material brought into the lake with the elevated rainfall. If that was the case, one may expect that Secchi depth may have been lower during the summer of 1994 than would be expected if the water clarity were controlled by planktonic algal chlorophyll.

Lake Chlorophyll Concentration Data
Figure 17 presents the planktonic algal chlorophyll data for Lake Shaokatan during the period 1985-2009; Figure 18 focuses on the more recent, 1999-2009, period. In most years monitored, chlorophyll concentrations were quite low in the spring and early summer, and increased substantially by the August/September samplings. As was seen with TP concentrations, the peak concentrations of chlorophyll were notably lower in the years after the 1992 monitoring and appeared to be associated with the P load reductions from agricultural sources that occurred at that time. Planktonic algal chlorophyll concentrations have, however, continued to reach the exceedingly high levels of 150 to more than 200 µg/L in late summer/fall. Such levels are indicative of severe algal scum; it is difficult to reliably sample such scum and properly analyze such samples. The range and pattern of planktonic algal chlorophyll concentrations during the 2000s, including the 2005 TMDL monitoring period, have generally been similar year to year. There were only two chlorophyll measurements in Lake Shaokatan reported for 2009; the concentrations were 16.1 µg/L on July 21 and 4.11 µg/L on October 13. While a lower chlorophyll concentration was not unusual for July, it is not possible to determine whether the low concentration reported for the October sample was indicative of overall lower algal growth during that summer/fall or whether the commonly found spike in chlorophyll in the fall was missed due to an inadequate sampling regimen.

The proposed TMDL water quality target value for chlorophyll is 30 µg/L. Figures C and D show that in the summer/fall of essentially each year in which data were collected, chlorophyll levels exceeded that target value by several-fold. As noted above, the chlorophyll concentrations in the July and October 2009 samples were below the target value; the TP concentrations measured at those times, however, were greater than the 81 µg P/L TP target.

Secchi Depth
Figure 19 presents the Secchi depth data for Lake Shaokatan for the period 1989 – 2009. The 2005 values are in the same range as those in other recent years. At times during each summer during the 2000s the Secchi depth has been below the TMDL water quality target of 0.7 m. It also appears, however, that there were more times in recent years when the Secchi depth was greater than 2.5 m (i.e., the lake was clearer) than there had been in the 1990s.

A comparison of the planktonic algal chlorophyll concentration in the lake with Secchi depth reveals that at times this lake has lower clarity (lower Secchi depth and greater turbidity) than would be expected based on the behavior of many lakes in the world, if the water clarity were controlled by planktonic algae. This is an indication that there is more particulate matter in the

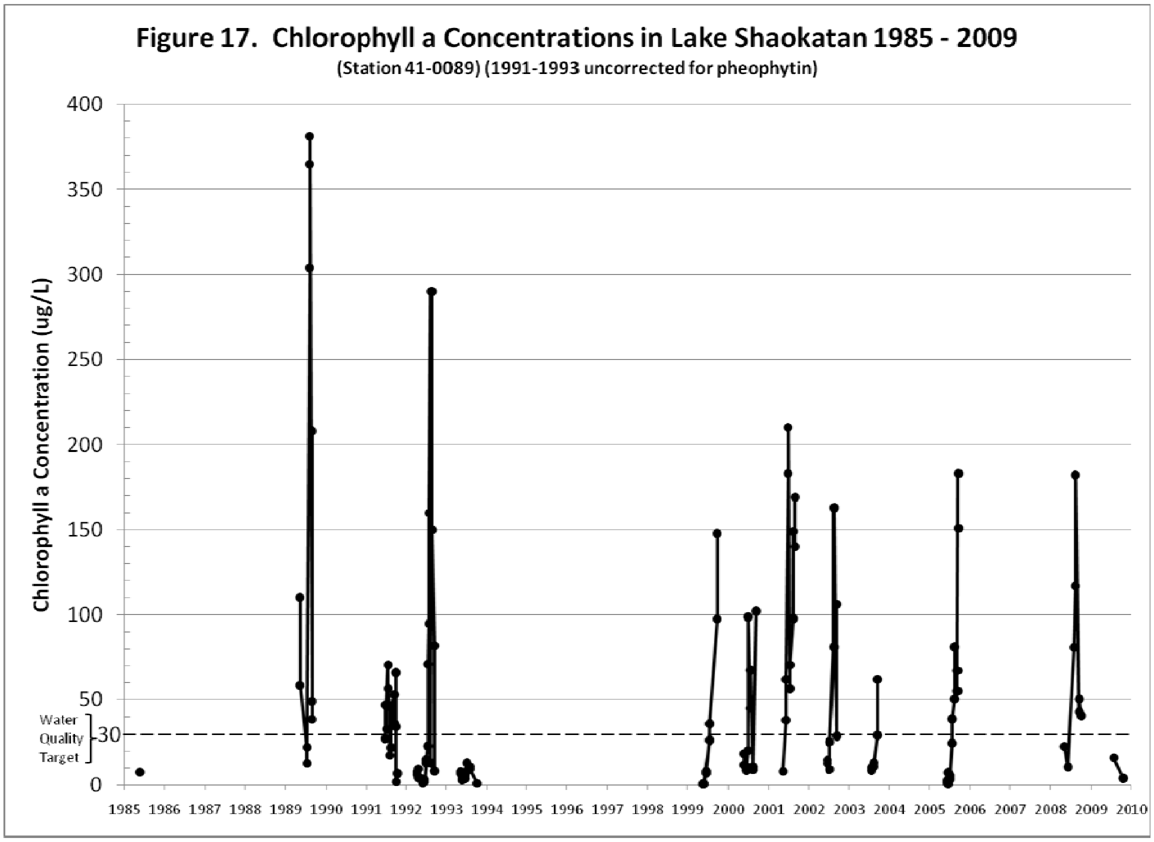


Figure 17. Chlorophyll a Concentrations in Lake Shaokatan 1985 - 2009
(Station 41-0089) (1991-1993 uncorrected for pheophytin)
Chlorophyll a Concentration (ug/L)
400
350
300
250
200
150
100
50
30
0
Water Quality Target
1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010

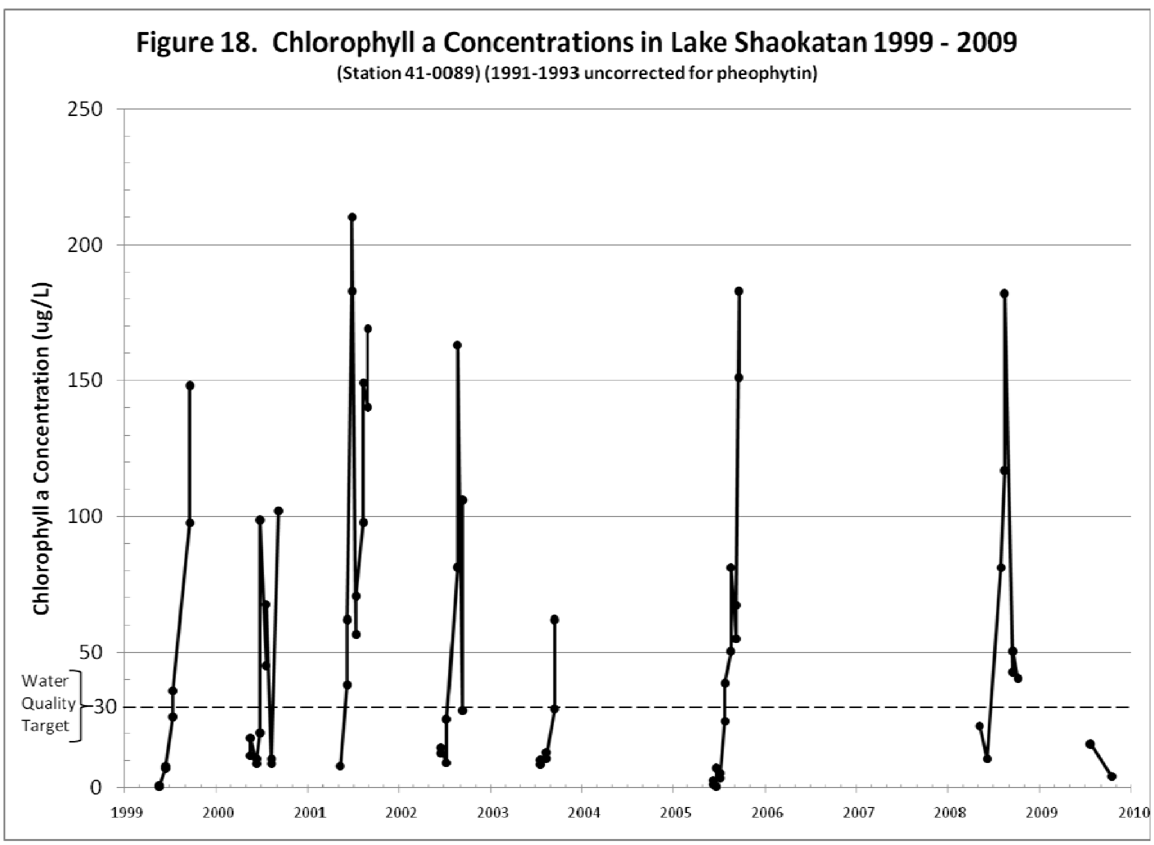
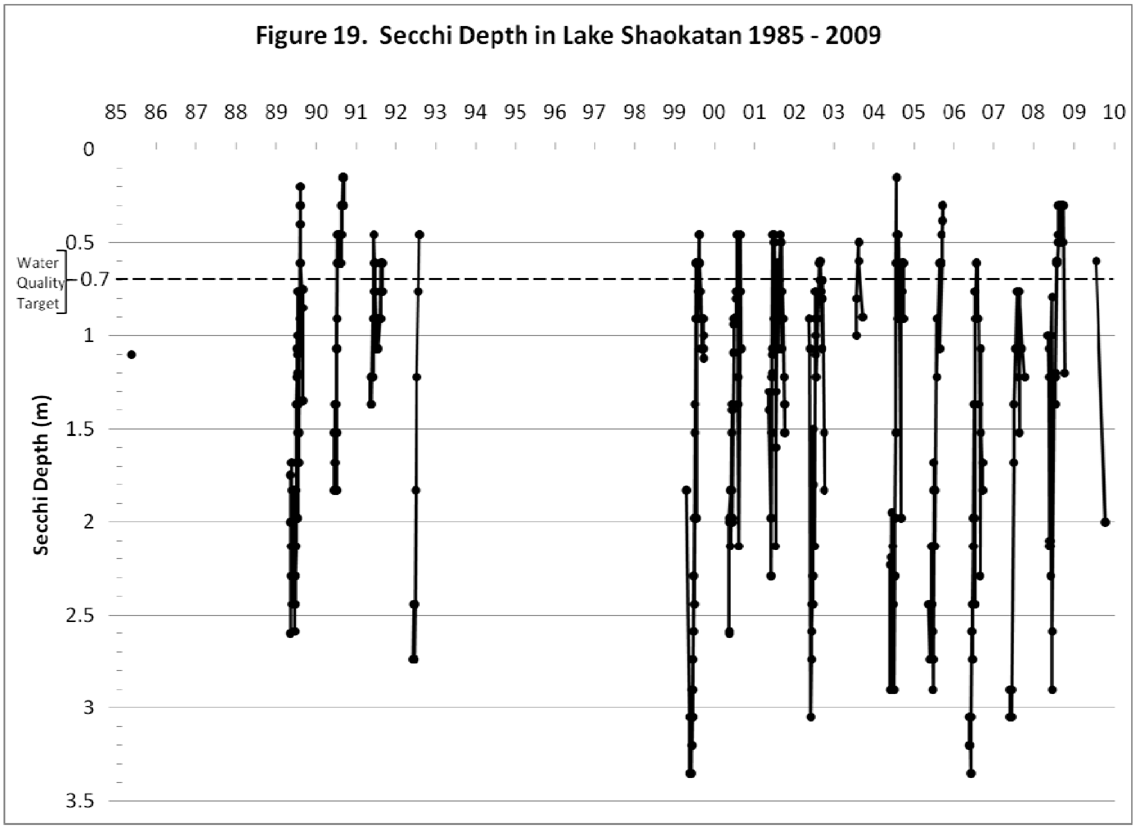


Figure 18. Chlorophyll a Concentrations in Lake Shaokatan 1999 - 2009
(Station 41-0089) (1991-1993 uncorrected for pheophytin)
Chlorophyll a Concentration (ug/L)
250
200
150
100
50
30
0
Water Quality Target
1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010



lake's water column than expected from algae; this reflects apparent stirring of the sediments into the water column via wind, boats, fish, etc. as previously discussed. This means that while Secchi depth (water clarity) is a reliable water quality parameter relevant to the public's beneficial uses of a waterbody, it is not a suitable nutrient-related TMDL target for Lake Shaokatan since it is influenced, and possibly controlled, by non-nutrient related factors that caused the lake's water column to be more turbid than normally occurs in lakes due to algae. This could lead to agricultural interests' spending large amounts of money trying to control nutrient inputs to the lake without the achievement of the Secchi depth TMDL target. In order for a TMDL target to be appropriate for a lake the target must be directly related to the nutrient inputs to the lake.

As part of developing the synthesis report for the US OECD eutrophication study, Lee and his colleagues defined the relationship between chlorophyll concentration and Secchi depth from data reported in the limnological literature. After screening out waterbodies reported to contain unusually high levels of inorganic turbidity and/or color, they plotted more than 200 couplings of Secchi depth as a function of chlorophyll. That work is described in:

> Rast, W. and Lee, G. F., "Summary Analysis of the North American (US Portion) OECD Eutrophication Project: Nutrient Loading-Lake Response Relationships and Trophic State Indices," EPA 600/3-78-008, US EPA-Corvallis (1978).

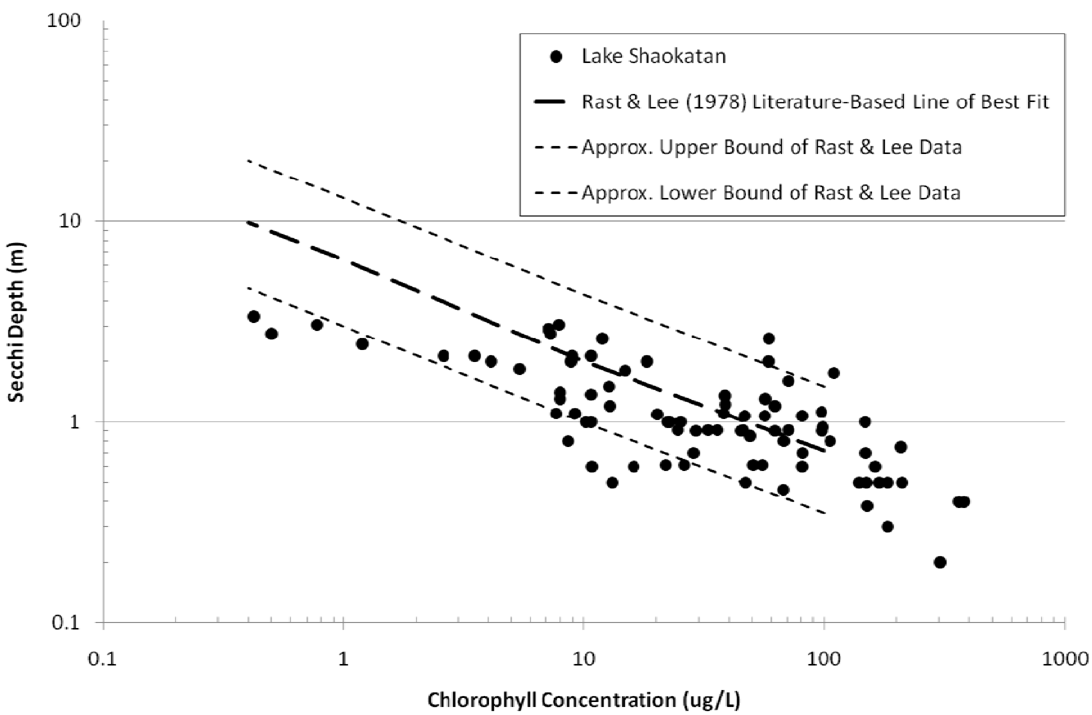
and

Lee, G. F Jones-Lee, A., and Rast, W., "Secchi Depth as a Water Quality Parameter" report of G. Fred Lee and Associates, El Macero, CA available as EF 012 from gfredlee@aol.com.

That expansive relationship is useful for identifying waterbodies in which inorganic turbidity and/or color may be an important factor in controlling Secchi depth.

Figure 20 presents the chlorophyll–Secchi depth couplings for Lake Shaokatan from data available from 1985–2009, relative to the Rast and Lee literature-based line of best fit and range for that line described above. Overall, most of the couplings are within the body of data reported in the literature. The points that cluster below the lower-bound line at the lower chlorophyll levels are couplings from late May and June of 1999 and 2005. The points that cluster below the lower-bound line at the higher chlorophyll levels are couplings from July and August of several years. Couplings that plot below the lower-bound line are indicative of water that is more turbid than most lakes having similar chlorophyll levels. This indicates greater than commonly found levels of particulate matter in the water column. The points that cluster above the upper-bound line in Figure 20 are the couplings for three sets of data collected on one day in May 1989.

Figure 20. Secchi Depth as a Function of Chlorophyll Concentration in Lake Shaokatan 1985 - 2009



TP and Chlorophyll

One of the most comprehensive quantitative investigations of the cause-and-effect relationships between nutrient loading and planktonic algal growth in waterbodies was conducted in the 1970s through the OECD (Organization for Economic Cooperation and Development) eutrophication study and follow-on work conducted by G. Fred Lee and his associates. The Vollenweider–OECD model that has emerged from that work provides one of the few reliable quantitative tools for assessing and quantifying the expected change in planktonic algal-related water quality that can be achieved by a given reduction in P loading. (The papers cited below discuss foundation for, application of, and limitations to the application of this model.)

The OECD eutrophication study was a 5-year, $50-million investigation of about 200 waterbodies in North America, Western Europe, Japan, Australia, to evaluate the impacts of nutrient loads on the algae-related water quality of lakes and reservoirs. Through that study, R. Vollenweider developed an empirical relationship (model) between mean summer chlorophyll concentration and annual phosphorus load normalized by waterbody area, mean depth, and hydraulic residence time. That model demonstrated and quantified the importance of waterbody morphology and hydrology in controlling the use of P in the production of planktonic algal chlorophyll. The "normalized P loading term" defined by Vollenweider was theoretically, essentially equivalent to the mean in-lake P concentration.

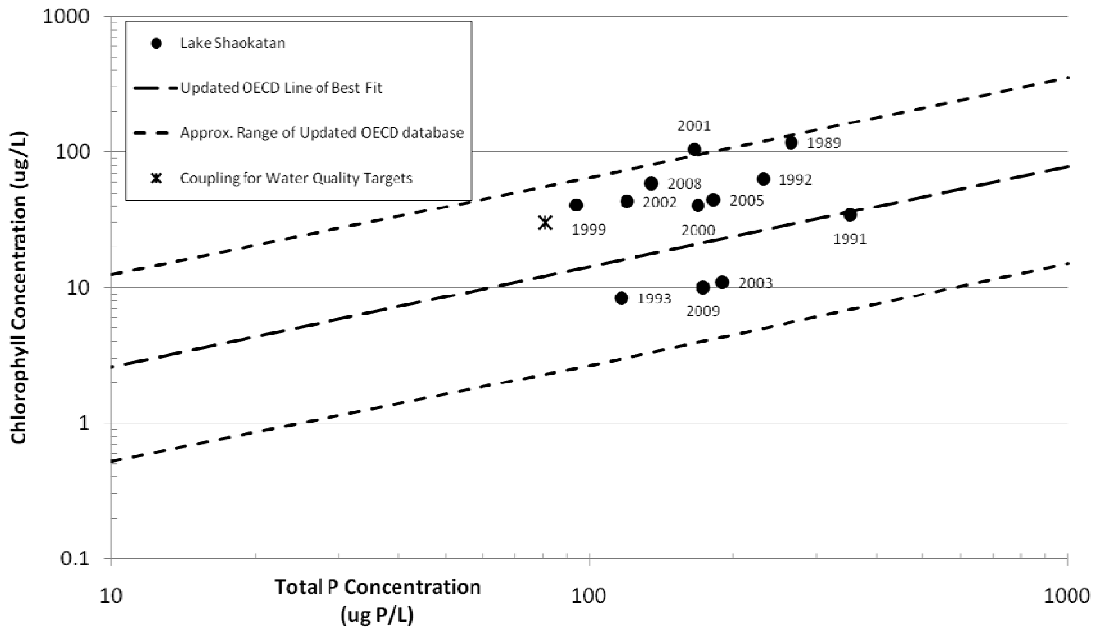
G. Fred Lee was selected by the US EPA to evaluate, and develop the synthesis report for, the US part of the OECD eutrophication study. Using Vollenweider's model, he and his colleagues described empirical relationships between normalized P load and eutrophication-related water quality characteristics for a diverse group of lakes and reservoirs across the US, relationships that were in keeping with those subsequently developed upon the entire OECD study database. Following the completion of their work on the US OECD database, Dr. Lee and colleagues continued the OECD-type eutrophication studies of waterbodies, beyond the OECD database, expanding the total database foundation of the model to more than 700 waterbodies of varied character located in areas covering most of the world. They also investigated and documented the predictive capability of the modeling approach and described the use of the model for water quality evaluation and management.

The line of best fit describing the expanded P loading–chlorophyll relationship, as well as the general upper and lower ranges of the database composing the model, are shown in Figure 21. (The P loading term that is conventionally plotted on the x-axis has been replaced with the "in-lake P concentration" as there were insufficient data available to reliably compute normalized P loading for Lake Shaokatan; in-lake P concentration was used as a surrogate as discussed subsequently.) Additional information on the development of the Vollenweider–OECD data base and the modeling approach is available in the following papers as well as in several other papers and reports on the Lee and Jones-Lee website [www.gfredlee.com] in the Excessive Fertilization section at [http://www.gfredlee.com/pexfert2.htm].

> Lee, G. F. and Jones-Lee, A., "Developing Nutrient Criteria/TMDLs to Manage Excessive Fertilization of Waterbodies," Proceedings Water Environment Federation, TMDL 2002 Conference, Phoenix, AZ, November (2002). http://www.gfredlee.com/Nutrients/WEFN-Criteria.pdf

Jones, R. A. and Lee, G. F., "Eutrophication Modeling for Water Quality Management: An Update of the Vollenweider-OECD Model," World Health Organization's Water Quality Bulletin 11:67-174, 118 (1986).
http://www.gfredlee.com/Nutrients/voll_oecd.html

Figure 21. Mean Summer Chlorophyll Concentrations in Lake Shaokatan as a Function of Average Total P Concentration 1989 - 2009



*Vollenweider-OECD model and lines of best fit apply to couplings of mean summer chlorophyll and annual P load normalized by morphology & hydrology. The normalized P loading term is theoretically equivalent to average in-lake P concentration. Annual loading and hydrologic information were not available, so the in-lake P concentrations that were available were averaged and used as the abscissa value.

The data available for Lake Shaokatan were inadequate for definitive modeling with the Vollenweider–OECD approach; most significantly, sufficient reliable information on hydraulic residence time and P loading was lacking. However, the position of this lake within the Vollenweider–OECD model can be estimated by using the in-lake P concentrations as a surrogate for the normalized P loading term. The positions of Lake Shaokatan in the years for which P concentration and chlorophyll data were available are shown in Figure 21. This lake plots well-within the range found for waterbodies around the world, which indicates that this lake behaves as would be expected in its use of its P load in the production of planktonic algae.

Use of Model for Evaluating Impacts of P Load Reductions

For a given waterbody with sufficient necessary data, the position on this model tracks parallel to the Vollenweider–OECD line of best fit once the waterbody has come into new equilibrium with a substantial P load alteration, or alteration in mean depth or hydraulic residence time. Thus one can compute the alteration in mean summer chlorophyll concentration that can be expected from a given alteration in P load, mean depth, or hydraulic residence time. The variability in year-to-year position of Lake Shaokatan in the model (Figure 21) is reflective of an apparent variability in P loading from sediments, potentially significant growths of rooted aquatic plants, and lack of water outflow from the lake, in addition to the data insufficiency and questionable quality. It is clear that a better quantitative understanding of these characteristics is needed before reasonable predictions can be made of improvements in eutrophication-related water quality that could be achieved from reductions in P loads. That notwithstanding, the fact that Lake Shaokatan plots within the Vollenweider–OECD model indicates that such quantitative predictions could be made once reliable data are obtained for the internal P load, groundwater P load, and hydraulic residence time, as well as associated annual external P load and mean summer chlorophyll concentrations.

In the following paper, Lee and Jones-Lee discussed how to assess, and what one can expect in improvements in eutrophication-related water quality from reductions in P loads.

> Lee, G. F., and Jones-Lee, A., "Eutrophication, Detergent Phosphate" a summary of Lee, G. F. and Jones, R. A., "Detergent Phosphate Bans and Eutrophication," Environ. Sci. Technol. 20(4):330-331 (1986) (updated) IN: SCOPE Newsletter, No. 67, pp 5-6, February 2007 CEEP of Cefic Bruxelles - Belgium. www.ceep-phosphates.org (2007). http://www.gfredlee.com/Nutrients/ScopeDetergentPBan.pdf

Based on their OECD-follow-on work specifically addressing impacts of P load reductions, they found that on the order of at least 20 to 25% change in available P load to a lake must occur before a discernable change in planktonic algal chlorophyll occurs. This amount is independent of the trophic state of the waterbody. While there are some who claim that "every little bit of P control helps improve water quality," that position is in keeping with what the data reveal, as discussed in the above-cited paper. This finding has important implementations for the amount of P load change that must be achieved in Lake Shaokatan before the public will be able to perceive and improvement in planktonic algal chlorophyll.

Land Use in Lake's Watershed

Figure 22 is a Goggle-Earth map of Lake Shaokatan and its watershed imaged in June of 2003. According to T. Dritz, since 2003 the following changes have taken place in the lake's watershed land use since 2003.

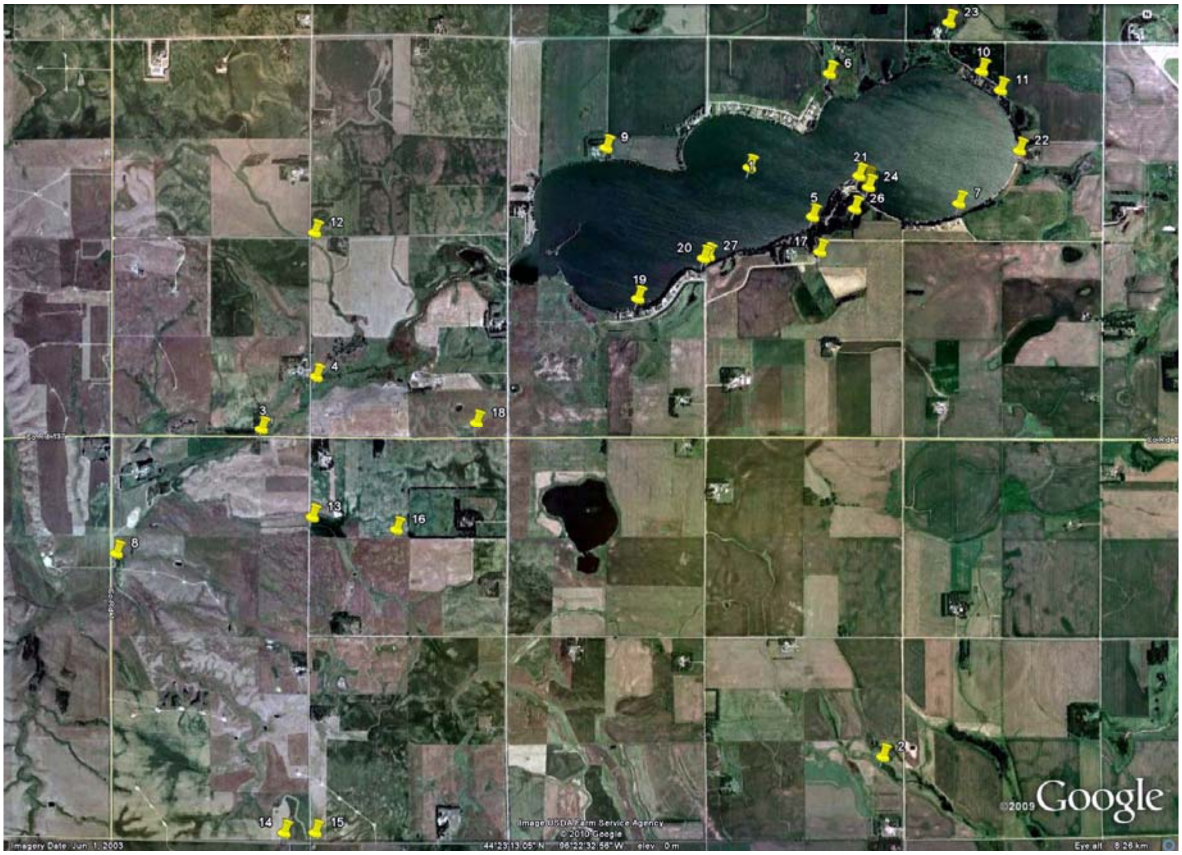
"*Biggest change was a tile placed between pins 17 and 26, diverting the water into an improved wetland between pins 26 and 24. New housing development running about 1/8 mile north of pin 22 to 1/8 mile south of pin 22. One or more tile intakes replaced with french drain intakes at the following pins, 9, 10, 11, 17,and 27, and I believe some on pin 19. I think at lease some of the water flowing to pin 27 gets diverted thought a wetland just east of the pin. Pin 2 flows South into Lake Benton."*

MPCA 2009 Summary of Lake Condition

"*The lake modeling analysis indicates that Lake Shaokatan has received annual loads of phosphorus ranging from 577 to 4,300 kilograms. A total phosphorus load of 1,537 kilograms per year would be required to reach the water quality goal of 81 µg/L; the goal includes a 10 percent margin of safety. For some years, a reduction from watershed sources of up to about 2,800 kg/yr or 65 percent would be required to meet this goal.*"

There are several key issues that are important to address and define before TMDL target goals are finalized. First, it needs to be determined if achieving the target loads can, in fact, be

Figure 22. Google-Earth Satellite View of Lake Shaokatan & Watershed
(Imaged June 2003)



expected to result in the target water quality characteristics in the lake. The target levels appear to have been established without the recognition of factors other than external total P input that control the extent to which P is used in the production of planktonic algal chlorophyll. One key factor that has not been addressed is the influence of hydraulic residence time.

Second, if achieving the target load is determined to be able to effect the desired water quality characteristics, attention needs to be given to whether or not that target P load can be achieved. That assessment will require a reliable quantification of the amounts of P contributed by each source, and the amount by which that loading can be reduced without exacting unacceptable consequences for the sources. It is of concern that the internal loading of P, which appears likely to be responsible for a sizable portion of the P input that controls eutrophication-related water quality characteristics of the lake, has not been well-defined. Further, the role of groundwater transport of phosphorus from septic tanks in the immediate vicinity of Lake Shaokatan in contributing to the near shore eutrophication-related water quality problems in the lake has also not been adequately addressed. It could be found that external P loads could be significantly reduced without causing an acceptable water quality improvement owing to the lack of control of the internal loading. In addition, the role of aquatic macrophytes in contributing to P cycling with the lake and in contributing to perceived water quality degradation in the lake has not been quantified.

Thus, it will be very important to define, before the TMDL P load is adopted, the amount of the load reduction that agricultural entities in the watershed will be expected to achieve. It could happen that it is not possible to achieve the target P loads and maintain viable agriculture in the Lake Shaokatan watershed. This is especially of concern if the needed reductions in internal P load have to be met by additional reductions in external loads from agricultural lands.

In 2003 the authors developed a report for the California Central Valley Regional Water Quality Control Board that discussed the potential to control nutrients derived from irrigated agriculture in the San Joaquin River watershed:

> Lee. G. F., and Jones-Lee, A., "Synthesis and Discussion of Findings on the Causes and Factors Influencing Low DO in the San Joaquin River Deep Water Ship Channel near Stockton, CA: Including 2002 Data," Report Submitted to SJR DO TMDL Steering Committee/Technical Advisory Committee and CALFED Bay-Delta Program, G. Fred Lee & Associates, El Macero, CA, March (2003). http://www.gfredlee.com/SJR-Delta/SynthesisRpt3-21-03.pdf

In that report they stated,
"*It should be understood, as discussed by Lee (2001b), that controlling algal nutrients (nitrogen and phosphorus) from agricultural activities will be difficult and could be quite expensive compared to the profit margins that many parts of agriculture are experiencing today. Lee and Jones-Lee (2002a,b; 2003b) reviewed the literature summarizing the experience of nutrient control programs from agricultural sources in other parts of the country, such as in the Great Lakes region and in the Chesapeake Bay watershed. Sharpley (2000) and Logan (2000) have summarized the experience of attempting to control algal nutrients in agricultural runoff in the Chesapeake Bay and the Lake Erie watersheds. As summarized by Lee (2001b), the nutrient control programs that have been conducted over the past 15 to 20 years in these areas have thus far failed to be highly effective in controlling nitrogen and phosphorus inputs to these waterbodies. It has been reported by Sprague, et al. (2000) that the major ag-derived nutrient reductions that have occurred in the Chesapeake Bay watershed are associated with the cessation of agricultural activities in parts of the watershed.*"

Overall Findings Regarding Nutrient TMDL for Lake Shaokatan
Because of the complexity of the Lake Shaokatan watershed and the reportedly significant in-lake contributions of phosphorus, and the variety of factors that influence how phosphorus from a source impacts the lake's water quality characteristics/beneficial uses, a TMDL P load allocation should be incorporated as part of the P TMDL for Lake Shaokatan. Because of these unusual conditions, it is only with a proposed TMDL P load allocation that the public and affected parties can have confidence that the impact of all significant P sources have been properly considered, that all of the factors that impact how P from the sources have been properly considered, and that the achievability and consequences of the proposed TMDL P load and water quality target goals have been determined. Of particular concern is the reputedly large contribution of P to Lake Shaokatan from internal sources that has arisen from the construction

of the dam. That dam increases the lake elevation sufficiently to impede the normal processes of lake flushing, and prevents flow out of the lake for years at a time.

From the studies on lakes around the world conducted by us and others, it has been well-established that the external P load to a lake is commonly the primary factor controlling development of planktonic algal chlorophyll; the sediments also contribute P to the watercolumn. Even with some sediment contribution of P, it has been well-established that significant reductions in the external P load to a waterbody lead to predictable and rapid reductions in planktonic algal chlorophyll. However, Lake Shaokatan is, in a number of key ways, not like many other waterbodies. Unlike most lakes, Lake Shaokatan experiences long periods of time with no flushing owing to the elevation of the dam. This lack of flushing results in the accumulation of a massive reservoir of recyclable P in the sediment that, through a variety of mechanisms including pumping of the P by aquatic plants, is recycled each year into the watercolumn where it is available for algal growth. Schuler suggested that approximately 50% of the total annual load is from the sediment. Because of this unusually large internal P loading, the responsiveness of Lake Shaokatan to reductions in external P load alone, is not predictable with the information available. Therefore, in order for a meaningful P TMDL to be developed, a reliable quantification is needed for the external, as well as the internal, P loads to the lake. In addition, a reliable quantitative assessment must be made of the effect of load reductions from the external and internal sources on planktonic algal chlorophyll, the target water quality parameter, as well as an assessment of the degree to which those loads can be reduced and the implications of those load reduction requirements. Thus, these elements of a TMDL P load allocation need to be included in the TMDL.

Absent an in-lake allocation component of the TMDL, agricultural interests would be placed in the position of having to control their respective loads sufficiently to account for not only their own inputs to the lake, but also the lake sediment's contribution. Since the Schuler report stated that the sediments contribute 50% of the load, the agricultural interests would have to basically double an otherwise justified P load reduction in order to make up for the sediment load. Whether agricultural interests could reduce their contributions sufficiently to achieve that total load reduction while maintaining financial viability, or whether even the absence of farming in the watershed could achieve this total load reduction, has not been addressed by the TMDL because it did not address the input of P from the sediment or reliably quantify the P loads. In any event, it would be an undue burden on agricultural interests to be required to make up for the internal P load apparently brought about by the damming of the lake.

Additional References Cited

Lee, G. F., "Potential Impact of Phosphorus Control on Low DO in the SJR DWSC," report to the SJR DO TMDL Steering Committee Technical Advisory Committee, G. Fred Lee & Associates, El Macero, CA, May (2001b).

Lee, G. F. and Jones-Lee, A., "Developing Nutrient Criteria/TMDLs to Manage Excessive Fertilization of Waterbodies," Proceedings Water Environment Federation TMDL 2002 Conference, Phoenix, AZ, November (2002a).

Lee, G. F. and Jones-Lee, A., “Assessing the Water Quality Impacts of Phosphorus in Runoff from Agricultural Lands,” Proc. of American Chemical Society Agro Division August 2001 Symposium, “Environmental Impact of Fertilizer Products in Soil, Air and Water,” Chicago, IL (2003b).

Logan, T., “Nonpoint Sources of Pollutants to the Great Lakes: 20 Years Post PLUARG,” IN: Nonpoint Sources of Pollution to the Great Lakes Basin, Great Lakes Science Advisory Board, International Joint Commission Workshop Proceedings, February (2000).

Sharpley, A. N., editor, Agriculture and Phosphorus Management, the Chesapeake Bay, CRC Press, Boca Raton, FL (2000).

Summary
Comparison of the 2005 TMDL Study Year to other Years and other Lakes
March 8, 2010

This section summarizes preliminary findings concerning the representativeness of the 2005 TMDL study year relative to other years for which data were available, and how the relationship between P load and planktonic algal chlorophyll in Lake Shaokatan compares with the relationships in other lakes.

Rainfall
The total rainfall in 2005 was somewhat above that of other years in the 2000s, making 2005 wetter-than-normal for the decade, especially in September. The 2.05-in rainfall event that occurred on September 13th seems to be correlated with a major increase in the lake's TP and chlorophyll. The greater rainfall could have caused greater runoff from the watershed, which increased the TP load; the increased precipitation on the lake's surface would also likely have increased the lake's TP load. The storm-induced turbulence in the lake would, at that time of the year, have lead to an increase in the internal P load. While the TMDL report stated that runoff from the lake's watershed was less in 2005 compared with other years, no data were presented to support that claim.

Lake Elevation-Flushing
From the data available it appears that over the past decade, lake water never reached the top of the dam and discharge water out of the lake. A statement was made in the TMDL report that the lake would be expected to "flush" in those years when there is flow over the dam and thus produce less planktonic algal chlorophyll. The hydraulic residence time of a waterbody exerts significant control over the production of planktonic algal chlorophyll in response to nutrient loading. With no flow out of the Lake, nutrients would tend to accumulate in the lake and enable greater production of planktonic algal chlorophyll. From preliminary evidence it appears that the hydraulic residence time of this lake can range from less than one year when it "flushes," to several years when there is no flow over the dam. The TMDL report indicated that in 2005, the hydraulic residence time was 2.2 years.

External P Load to the Lake
The surfacial external P load to the lake was quantified for only part of 2005. The accuracy of that quantification could not be evaluated as details of the use of flow and concentration data in the computation of the load were not made available. Based on the characteristics of the lake's flushing, there was additional P load to the lake that was not measured in 2004-2005 but that could have influenced the TP and planktonic algal chlorophyll in the lake in the summer of 2005. There is evidence in reports on Lake Shaokatan that local groundwaters contribute noteworthy amounts of P to the lake, apparently from septic tanks near the lake.

Total P in the Lake
The total P concentration in the lake during the 2000s was consistently greater than the TMDL water quality target of 81 µg P/L, especially in late summer. The TP in the lake tended to be below the target concentration in early summer, followed by ever-increasing concentrations over the summer. That pattern may reflect the pumping of P from the sediments into the water

column by aquatic macrophytes (weeds). That phenomenon appears to have led to the TMDL report's statement that about 50% of the total P load is derived from the internal P load. The major peak in the TP concentration in 2005 reflects the greater external and internal P loads, especially associated with the September precipitation event.

There has been a dramatic decrease in TP and soluble P in the lake since the P input reduction implemented by the agricultural interests in the late 1980s.

In the 2000s data indicate that only a small part of the reported TP concentration in the lake was in the soluble P form. This indicates that the phosphorus present is primarily in particulate forms, only some portion of which is likely available to support planktonic algal growth.

Secchi Depth

At times during each summer during the 2000s the Secchi depth has been below the TMDL water quality target of 0.7 m. In general, based on the relationship between chlorophyll and Secchi depth in waterbodies around the world, the water clarity in this lake is about as would be expected based on the planktonic algal chlorophyll concentration; the water clarity appears largely controlled by planktonic algae. There are also times when there is more particulate matter in the lake's water column than expected from algae; this would be expected when there is stirring of the sediments into the water column via wind, boats, fish, etc.

Secchi depth (water clarity) can be a reliable water quality parameter of concern to the public's beneficial uses of a waterbody in waterbodies in which water quality problems are associated with planktonic algal chlorophyll. However, it may not be a suitable parameter for nutrient TMDL target goals for Lake Shaokatan since it is influenced/possibly controlled by non-nutrient related factors that cause the lake's water column to be more turbid than normally occurs in lakes. This could lead to agricultural interests' spending large amounts of money trying to control nutrient inputs to the lake without achieving the Secchi depth TMDL target owing to inorganic and non algal turbidity in the water. Furthermore, to the extent that water quality problems in Lake Shaokatan are due to growths of aquatic weeds, Secchi depth would not be an appropriate water quality indicator. In order for a TMDL target to be appropriate for a lake the target must be directly related to the nutrient inputs to the lake that are causing water quality problems.

Comparison of Lake Shaokatan to Other Lakes

Based on the large, world-wide database developed in the international OECD eutrophication study and our follow-on work, and the limited data for Lake Shaokatan, the relationship between P load and planktonic algal chlorophyll in this lake is, in general, within the range commonly found.

Reliability of the TMDL Water Quality Targets

The Minnesota regulation, Section 3.1, states, "*Applicable Minnesota Water Quality Standards Minnesota's standards for lakes limit the quantity of nutrients, which may enter waters. Minnesota's standards at the time of listing (Minnesota Rules 7050.0150(3)) stated that in all Class 2 waters of the State (i.e., "…waters…which do or may support fish, other aquatic life,* *bathing, boating, or other recreational purposes…") "…there shall be no material increase in undesirable slime growths or aquatic plants including algae…"*

The MPCA nutrient TMDL targets for TP, Secchi depth, and chlorophyll were based on a limnological approach that does not necessarily have its basis in a requisite cause-and-effect relationship between nutrient input and resultant water quality/beneficial uses of the lake. TP is not a proper nutrient-related "water quality" impact; phosphorus, itself, does not adversely affect water quality. The water quality problems of concern are due to excessive levels of algae and/or aquatic plants (macrophytes), not the presence of phosphorus; phosphorus is only a problem to the extent that it stimulates growth of nuisance levels of algae and/or aquatic plants. The extent to which a given load of total phosphorus supports algae/aquatic plant growth depends largely on its "availability" (i.e., forms) and the morphology and hydrology of the waterbody. Thus, the proper nutrient-related impact for this lake is planktonic algal chlorophyll level and the areal extent and density of aquatic macrophytes growth, especially near shore.

It was speculated by MPCA that as the external P load is reduced, the summer planktonic algal chlorophyll level would decrease while the aquatic weed growth could increase. This could result in greater internal P loads, which would, in turn, be expected to promote greater algae and aquatic plant growth. Thus, the substantial expense for reducing external P load from agricultural interests may well-be perceived by the public not only as not having improved water quality/beneficial uses but also as having worsened it.

Based on the TMDL report key issues were not addressed in the development of the TMDL, including: the hydrology of the waterbody; the quantification of the cause-and-effect relationship between nutrient load and water quality problems in the lake; the sources, availability, and controllability of all nutrient inputs to the lake; and the issues associated with aquatic macrophytes in the lake. Establishing TMDL goals without addressing these issues could be expected to result in the expenditure of large amounts of money on nutrient control measures, and potentially curtail or eliminate agriculture in the watershed of Lake Shaokatan without achieving the desired water quality characteristics.

Overall

The 2005 TMDL study year does not provide an adequate database for the quantification of nutrient loads, lake response to the loads, or factors influencing lake response upon which to develop a reliable TMDL that could be implemented into allowable external P load alterations that would result in an improvement in the lake's overall water quality/beneficial uses to the public. While the draft 2005 TMDL report apparently covers the MPCA TMDL Protocol "check list" to some extent, the items on the check list were not covered adequately to form a technically sound foundation for establishment of a reliable TMDL. The external and internal P loads, and the hydrologic characteristics of the lake need to be properly studied over a several-year period before a reliable TMDL can be developed and implemented to achieve external P load allocations that can be expected to control water quality/beneficial uses of Lake Shaokatan. Also, the MPCA needs to eliminate the TMDL water quality goals of Secchi depth and TP and develop a new water quality goal for area and density of aquatic macrophytes.

Appendix A
Plots of Selected Lake Shaokatan Watershed TMDL Report
Reported Flow, TP, & Rainfall

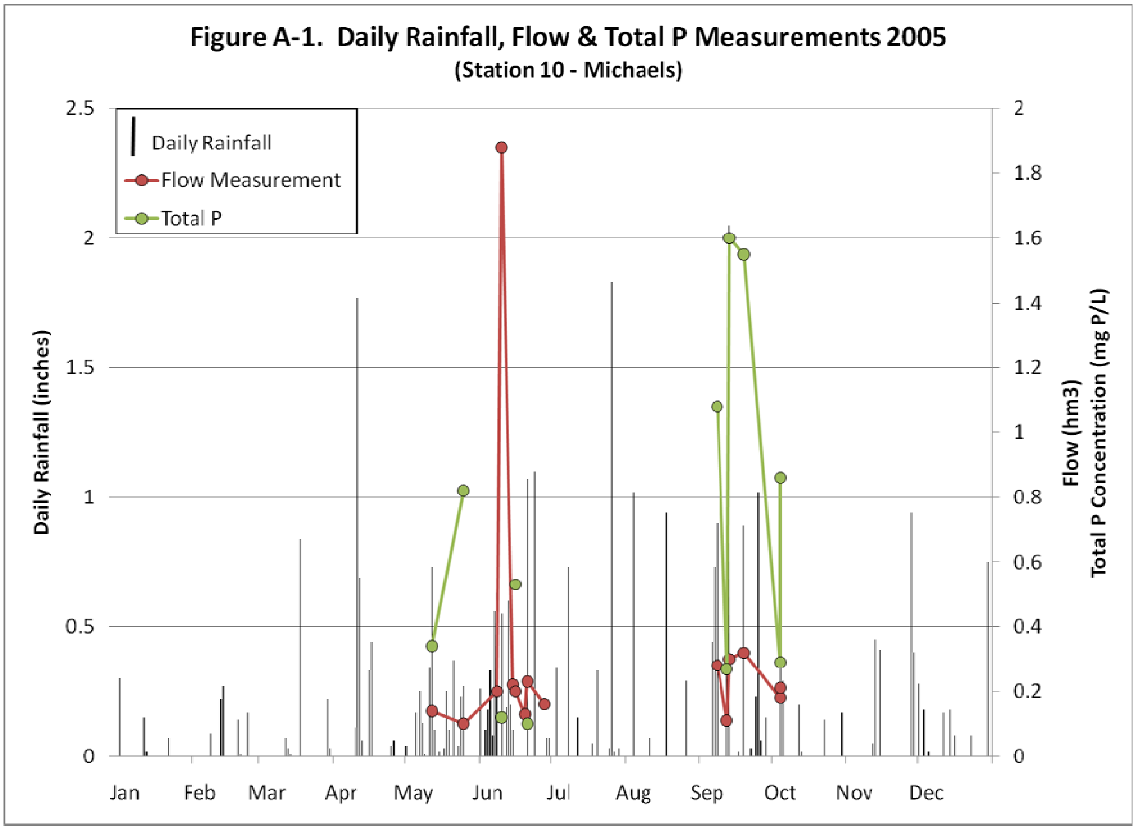


Figure A-2. Daily Rainfall, Flow & Total P Measurements 2005
(Station 8 - Highway 1 Bridge)

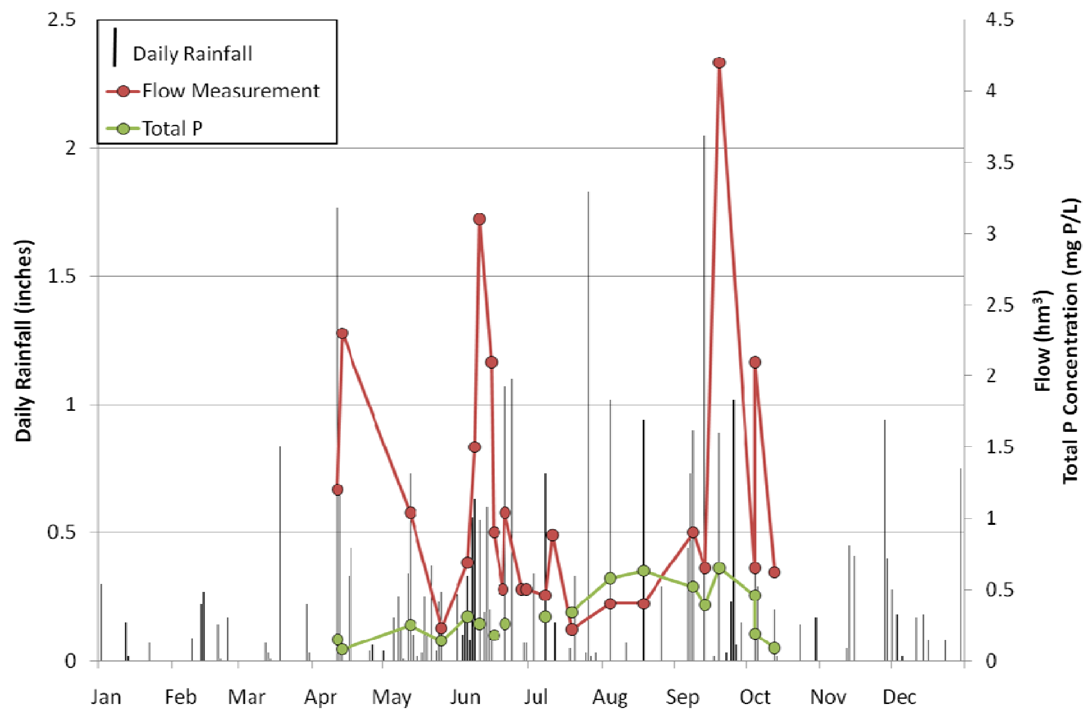
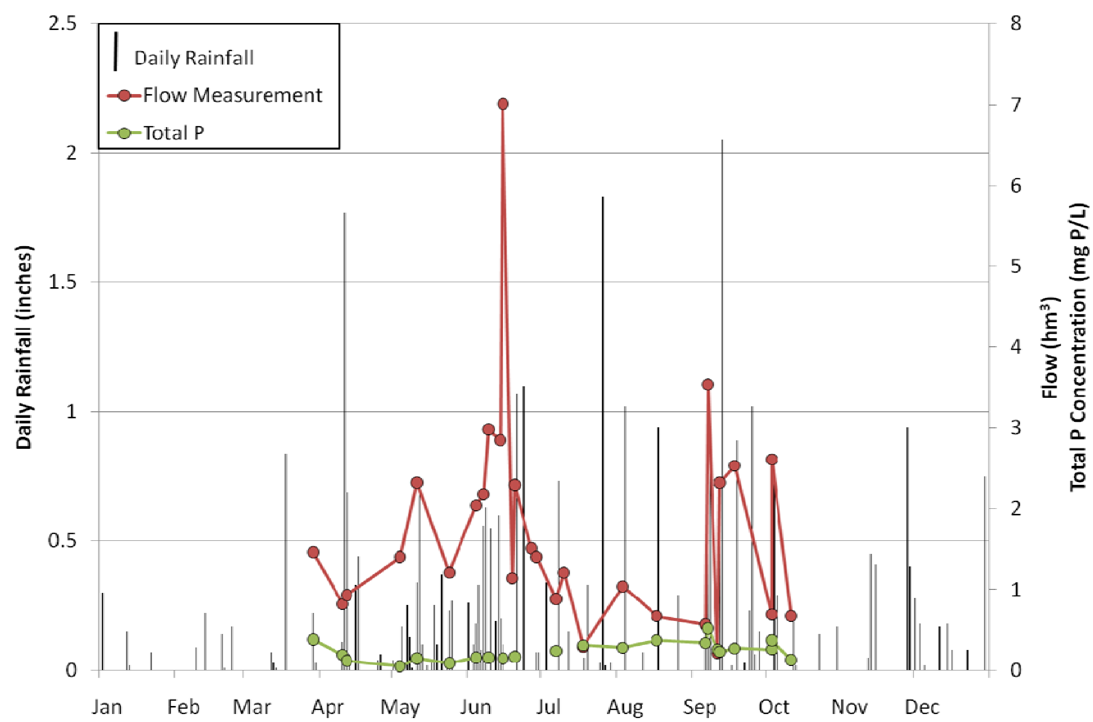


Figure A-3. Daily Rainfall, Flow & Total P Measurements 2005
(Station 1 - Co. Road 15)



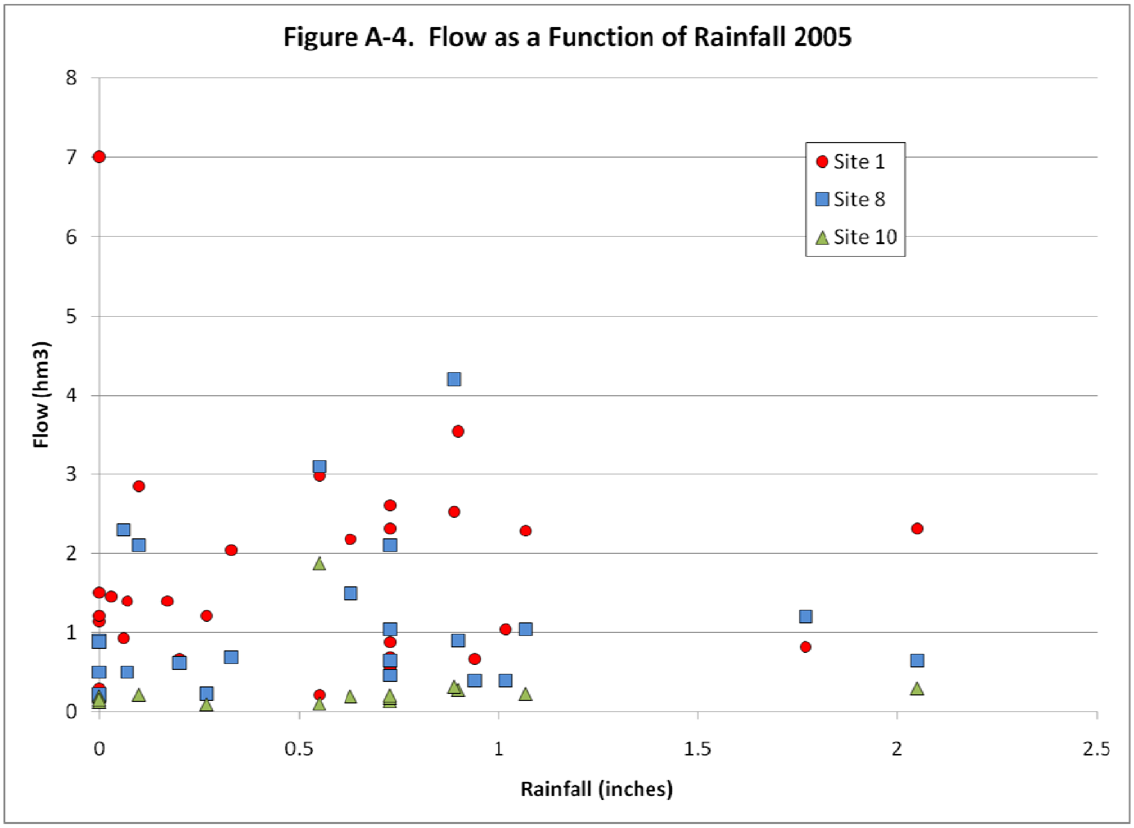


Figure A-4. Flow as a Function of Rainfall 2005
Flow (hm3)
Rainfall (inches)
Site 1
Site 8
Site 10
0
1
2
3
4
5
6
7
8
0
0.5
1
1.5
2
2.5