Information Needed to Apply the Vollenweider–OECD Eutrophication Study Results to Nutrient-Related Water Quality Evaluation in Domestic Water Supply Waterbodies

Anne Jones-Lee, PhD and G. Fred Lee, PhD, PE, BCEE
G. Fred Lee & Associates
El Macero, California
gfredlee@aol.com   www.gfredlee.com

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Introduction

The manifestations of beneficial-use impairments of the Sacramento San Joaquin Delta (the Delta) in the Central Valley of California, along with the ever increasing demands on that water source, have heightened awareness of the complexity of water quality management in the Delta. One aspect of the water quality challenges in the Delta is the quality of the water for domestic water supply. More than 23 million people in Northern and Southern California rely on the Delta for their drinking water. However, the quality of Delta water for this purpose is significantly adversely impacted, both directly and indirectly, by algae. Excessive algae in water supplies cause adverse tastes and odors, and shortened filter runs, and also may contribute trihalomethane precursors. Domestic water supply water quality problems caused by algae are widespread through the world with the excessive fertilization of water supply waterbodies being one of the most significant causes of domestic water treatment problems.

One of the most powerful and reliable tools available for assessing the impact of alterations in nutrient loading to algae-related water quality characteristics of waterbodies is the Vollenweider/OECD load-response models. Most of the literature discussion of this modeling approach, however, has focused on algae as they impact recreational and fisheries uses of the receiving water. This paper provides a review and update of information resources on algae-related water-supply water quality problems in the Delta, and the use of the OECD nutrient load-response modeling approach for water supply waterbodies, and describes information needed to apply the model to water supplies such as the Delta.

Nutrient-Related Water Quality Issues in the Delta

While aquatic plant nutrients, themselves, do not cause adverse impacts, they stimulate and support the growth of algae and other aquatic plants, which cause water quality problems; sufficient control of nutrients can effect the control of the growth of algae.

In March 2008, the California Water and Environment Modeling Forum sponsored the "Delta Nutrient Water Quality Modeling Workshop." The presentations made at that workshop provided a good overview of the nutrient-related water quality problems in the Delta and in downstream waterbodies that receive Delta water. The PowerPoint slides used by workshop speakers are available on the CWEMF website page, http://www.cwemf.org/workshops/NutrientLoadWrkshp.pdf. A synopsis of the presentations is available at:

Lee, G. F., and Jones-Lee, A., "Synopsis of CWEMF Delta Nutrient Water Quality Modeling Workshop – March 25, 2008, Sacramento, CA," Report of G. Fred Lee & Associates, El Macero, CA, May 15 (2008).
http://www.gfredlee.com/SJR-Delta/CWEMF_WS_synopsis.pdf

Lee and Jones-Lee (2008) provided additional discussion of nutrient-related waster quality problems in the Delta in:

Lee, G. F., and Jones-Lee, A., "Delta Nutrient-Related Water Quality Problems," PowerPoint Slides Presented at CALFED Science Conference, Sacramento, CA, October 24 (2008). http://www.gfredlee.com/SJR-Delta/CALFED_SciConf10-08.pdf

In response to mounting nutrient-related water quality concerns in Delta-derived domestic water supplies, the California Central Valley Regional Water Quality Control Board (CVRWQCB) is developing a "Drinking Water Policy," and the State Water Resources Control Board (SWRCB) is developing numeric criteria for aquatic plant nutrients (nitrogen and phosphorus compounds). Information on those programs is available at:
http://www.waterboards.ca.gov/centralvalley/water_issues/drinking_water_policy/.

The Policy and criteria are intended to regulate nutrient discharges to the Delta and its tributaries to reduce the algae that utilize the nutrients, and hence their impact on domestic water supply, as well as other beneficial uses of Delta waters.

In addition to causing water supply water quality problems, excessive growths of algae are also responsible for the low dissolved oxygen problem in the San Joaquin River (SJR) Deep Water Ship Channel (DWSC) and several other channels in the South Delta. The nutrients discharged to tributaries of the Delta support the growth of algae, which then die and decompose; the bacterial decomposition of the dead algae utilizes dissolved oxygen, leading to low dissolved oxygen problems in the SJR DWSC and in some Delta channels.

Nitrogen and phosphorus compounds also stimulate the growth of floating and rooted aquatic plants in the Delta. Of greatest concern are water hyacinth and egeria, which adversely impact recreation as well as aquatic life habitat in the Delta. These aquatic plant growth cause significant water quality problems to the beneficial uses of the Delta resources.

In order to develop a technically valid, cost-effective management program for nutrient-related water quality impacts, it is necessary to understand and quantify the sources of nutrients and determine the water quality improvements that could be achieved by altering the nutrient loads. Such assessments are made using models that describe the relationships between nutrient loading and water quality response.

This paper discusses the use of the Vollenweider-OECD Eutrophication Study results to describe/model the relationship between phosphorus loads to the water supply reservoirs that are filled by Delta water and the planktonic algae-related water quality problems that develop in those waterbodies. As discussed herein, that empirical load–response modeling approach has been found applicable to a wide variety of types of lakes and reservoirs world-wide; its predictive capability has been demonstrated by documenting changes in water quality characteristics following nutrient reductions to waterbodies. If demonstrated to be applicable to a waterbody, it provides a relatively simple, easily used approach to predict how the waterbody's domestic water supply nutrient related water quality will change with changes in phosphorus loads. Such findings are useful for guiding the development of management approaches to begin to manage the excessive fertilization of the waterbodies. Because of the widespread applicability and reliability of this modeling approach and its ease of use in assessing nutrient control strategies, it is of interest to assess its applicability to the Delta.

This paper presents an overview of the Vollenweider-OECD modeling approach – its development, evaluation, and use for the evaluation and management of excessive fertilization of waterbodies – through an annotated bibliography of the authors' and associates' key publications on those issues. That is followed by a discussion of the application of that modeling approach to water supply reservoirs that are filled with Delta water, as well as other waterbodies.

Background Information on OECD Eutrophication Modeling Approach

In the 1970s under the leadership of Dr. R. Vollenweider and through the Organization for Economic Cooperation and Development (OECD), 22 countries in Western Europe, North America, Japan, and Australia conducted a five-year study of the relationships between nutrient (nitrogen and phosphorus) loads to lakes and reservoirs, and planktonic algal biomass as measured by chlorophyll. In that approximately $50-million effort, approximately 200 waterbodies were studied. G. Fred Lee had the US EPA contract to develop a synthesis report covering the US part of that study; he also served as the US representative to the international OECD Eutrophication Study steering committee.

The US OECD Study synthesis report was published as,

> 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, OR (1978).

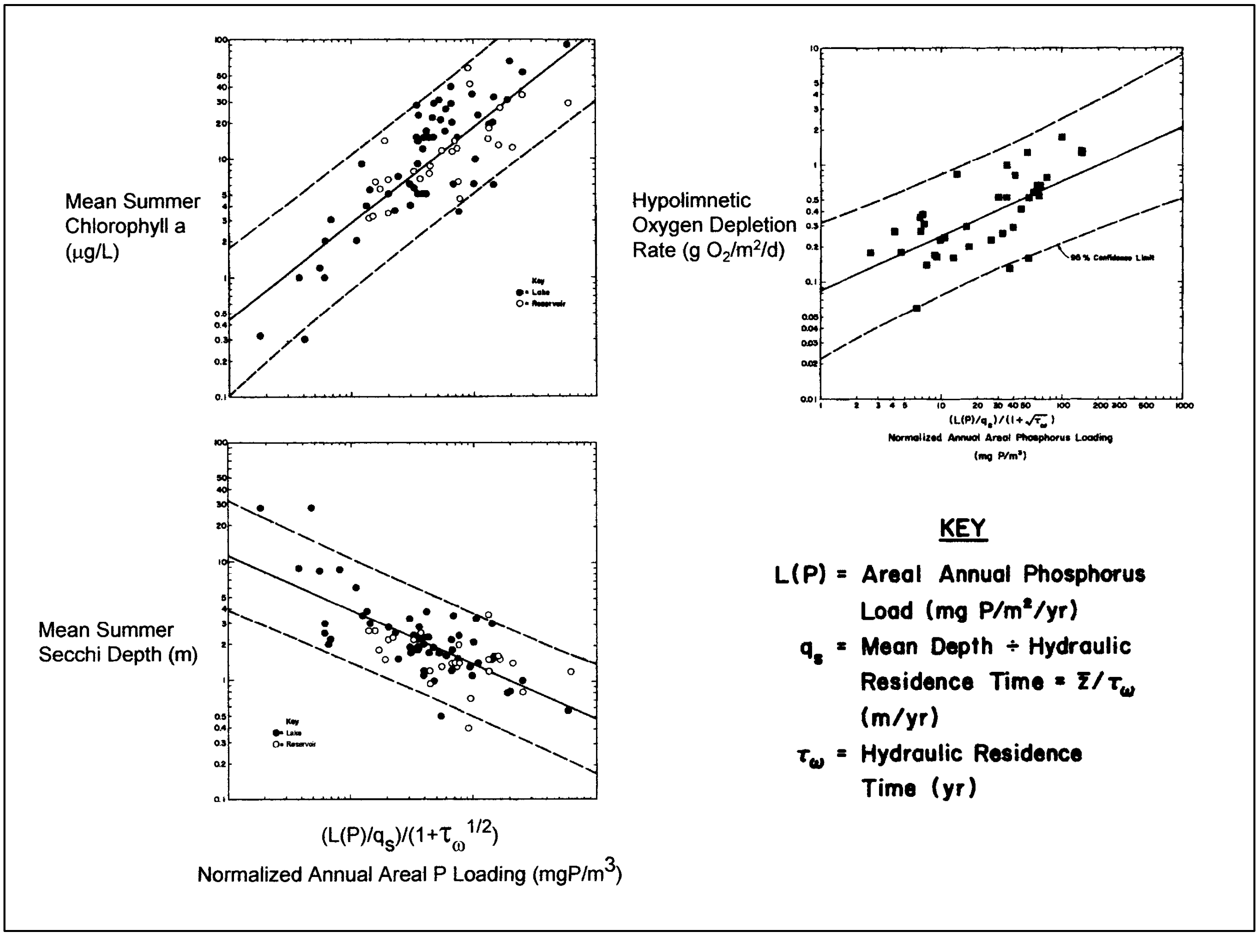
A summary of that report was published as,

> Lee, G. F., Rast, W., and Jones, R. A., "Eutrophication of Water Bodies: Insights for an Age-Old Problem," *Environ. Sci. & Technol.* 12:900-908 (1978).
> http://www.gfredlee.com/Nutrients/Eutrophication-EST.pdf

Using the US OECD database, Rast and Lee (1978) and Lee et al. (1978) showed that Vollenweider's empirical relationships between phosphorus load as normalized by waterbody mean depth and hydraulic residence time, and planktonic algal chlorophyll concentration described the couplings measured in waterbodies across the US. Lee et al. (1978) expanded Vollenweider's concepts to examine the relationship between normalized P load and other planktonic algae-related parameters of Secchi depth (water clarity) and hypolimnetic oxygen depletion rate. Figure 1 presents the lines of best fit and 95% confidence intervals between normalized nutrient load and the response parameters of mean summer planktonic algal chlorophyll, Secchi depth, and hypolimnetic oxygen depletion rate for the US OECD waterbodies. Each dot in the figure represents a waterbody in which the phosphorus load to the waterbody and the waterbody's summer planktonic algal chlorophyll had been measured for at least one year.

Rast and Lee published several papers on the results of the US part of the OECD Eutrophication Studies. Many of those papers are available as downloadable files from the Lee and Jones-Lee website, www.gfredlee.com, in the Nutrient/Excessive Fertilization section located at: http://www.gfredlee.com/pexfert2.htm and http://www.gfredlee.com/pdwswq2.htm.

Figure 1-US OECD Eutrophication Study Results (f*rom Rast and Lee, 1978).*



The analysis of the international OECD data set was not as expansive as that of the US OECD data set. However, when the international findings were published a decade later, it was revealed that the relationship between normalized P load and chlorophyll for the entire data set was essentially the same as that found for the US OECD waterbodies.

After completion of their work on the international OECD Eutrophication Studies in 1978, Lee and Jones continued to evaluate the applicability of the Vollenweider/US OECD eutrophication modeling approach to additional waterbodies throughout the world, and examined its applicability to other algal-related water quality characteristics. They published three review papers on this work:

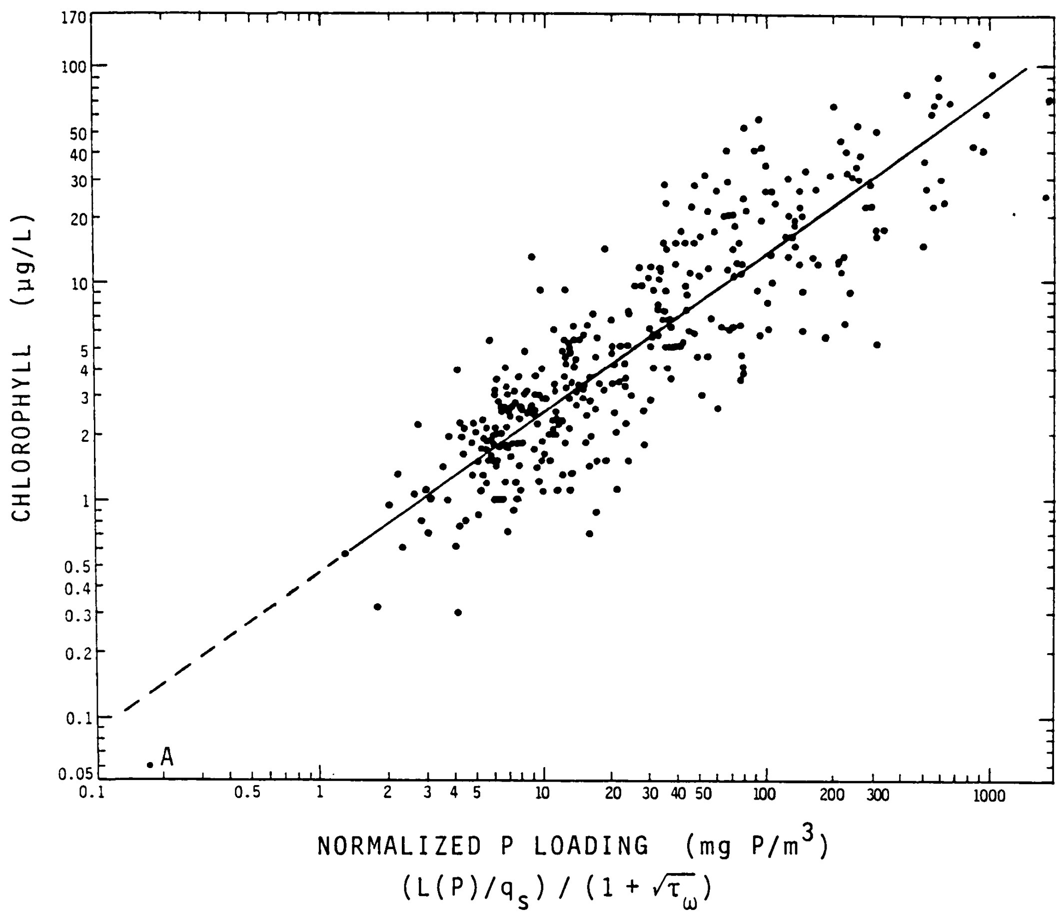
Jones, R. A., and Lee, G. F., "Recent Advances in Assessing the Impact of Phosphorus Loads on Eutrophication-Related Water Quality," Journ. *Water Research* **16**:503-515 (1982). http://www.gfredlee.com/Nutrients/RecentAdvWaterRes.pdf

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

Jones, R. A. and Lee, G. F., "Use of Vollenweider-OECD Modeling to Evaluate Aquatic Ecosystem Functioning," *Functional Testing of Aquatic Biota for Estimating Hazards of Chemicals*, ASTM STP 988, Amer. Soc. Test. & Mat., Philadelphia, pp. 17-27 (1988).
http://www.gfredlee.com/Nutrients/EcosystemFunctionOECD.pdf

Figure 2 shows the relationship between normalized P load and chlorophyll that was developed by Jones and Lee (1986) based on data from more than 750 waterbodies of diverse type around the world.

Figure 2-Updated Normalized Phosphorus Load-Planktonic Algal Chlorophyll Results (f*rom Jones and Lee, 1986).*



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unique aspect of the Vollenweider-OECD eutrophication modeling approach, as compared with many of the deterministic and other models, is its demonstrated reliability in estimating changes in planktonic algal-related response of a waterbody to quantified changes in phosphorus load to the waterbody. This model verification was conducted based on comparing predictions of changes with those measured in waterbodies to which phosphorus loads had been altered. The predictive capability of this modeling approach was discussed in:

> Rast, W., Jones, R. A. and Lee, G. F., "Predictive Capability of US OECD Phosphorus Loading-Eutrophication Response Models," Journ. Water Pollut. Control Fed. 55:990-1003 (1983). http://www.gfredlee.com/Nutrients/PredictiveCapabilityOECD.pdf

The review papers cited above discussed many aspects of the appropriate application of the OECD eutrophication modeling approach to waterbodies. As they discussed, while these models are applicable to most lakes and reservoirs as well as to some other types of waterbodies including such as estuaries and some riverine systems, there are some conditions in waterbodies which necessitate that the nutrient loads, waterbody characterization, and/or algal biomass response must be modified to make the application reliable. The need for such alteration is typically evident from the waterbody characteristics, and is not simply an exercise in forcing the model to fit. Some characteristics that may require site-specific modification of some model parameters or diminish the reliability of model predictions include the following.

Turbid Waterbodies. Highly turbid waterbodies may not fall within the body of data shown in Figures 1 and 2. Most of the waterbodies upon which the regressions were based had low to moderate turbidity. Excessive turbidity may cause sufficient light-limitation of algal growth to reduce the maximum planktonic algal biomass that develops in a waterbody. Typically waterbodies with Secchi depths of less than about 0.2 m tend to grow fewer algae than predicted based on the OECD study database. Excessive turbidity also skews the relationship between chlorophyll and Secchi depth.

Type of Aquatic Plant Growth. The OECD eutrophication modeling approach is also applicable only to waterbodies in which aquatic plant growth is dominated by phytoplankton. In its current development it cannot be used to reliably assess planktonic algal chlorophyll response to nutrient loading when there is substantial aquatic macrophyte or attached algae growth present. It is also not designed to assess the aquatic macrophyte or attached algal response to nutrient loading. As discussed by Newbry et al. (1979), however, it is likely possible to develop nutrient load-response relationships for macrophytes by assessing response in terms of the percent of the area of the waterbody with depth less than 2m that is covered by aquatic macrophytes and attached algae.

Short Hydraulic-Residence-Time Waterbodies. A general constraint on the application of the OECD eutrophication model is that the average hydraulic residence time (i.e., filling time as computed by dividing the annual water input by the waterbody volume) of the waterbody must be two weeks or more. Such a residence time gives algae time to grow in response to nutrient input. For waterbodies having a hydraulic residence time shorter than two weeks during the summer growing season, it may be possible to modify the model, as was done by Jones and Lee (1978a) for Lake Lillinonah, CT. For that waterbody, the summer average hydraulic residence time was used since each spring, the waterbody is essentially completely flushed.

Phosphorus Limitation. Previous discussions of constraints have suggested that the Vollenweider OECD modeling approach was best suited to waterbodies in which phytoplankton biomass was limited by available phosphorus, as it was on such waterbodies that the approach was originally formulated. The limiting nutrient in a waterbody or an area of a waterbody can be determined by measuring the concentrations of algal-available N (NO_3^- plus NH_3) and available P (soluble ortho P) during the period of maximum phytoplankton biomass. In general, if the available P concentration is a few µg P/L or less, phytoplankton growth at the time the samples were collected was most likely limited by P. If the available N concentrations are on the order of 30 to 50 µg/L or less, N is likely limiting phytoplankton production. If both nutrients are present in concentrations greater than those levels, some other factor is likely limiting maximum planktonic algal biomass. Although less reliable, the ratio of available N to available P is also used to suggest which nutrient may be depleted first (i.e., potentially limiting) in a water, based on the theoretical uptake ratio of these nutrients by algae of 7.5 N to 1 P on a mass/L basis.

Algal assays are also used to estimate the limiting nutrient by determining which nutrient, if added, would promote increased algal growth. Caution must be exercised in using the latter two approaches to determine the limiting nutrient; they must be performed near the time of maximum algal production since the results of such tests run at other times of the year will not necessarily give an accurate representation of the limiting nutrient during the period of water quality concern. Further, analyses for available N and P during peak biomass production should be conducted in conjunction with these procedures to verify that one of these nutrients is actually limiting the growth; while an N-to-P ratio may indicate a lesser relative abundance of one nutrient, some other factor such as light may in reality limit algal growth during the period of concern.

With increased experience in the use of the OECD eutrophication modeling approach, it has come to be understood that the approach can, in fact, be reliably used to evaluate and quantify improvement in planktonic algal-related water quality parameters that expected to result from alterations in nutrient loading, even when phosphorus concentrations in the waterbody are well-above the phosphorus-limiting concentrations and N to P ratios at peak biomass do not indicate P limitation. The authors discussed those findings in the following two papers:

> 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
>
> Lee, G. F., and Jones-Lee, A., "Synopsis of CWEMF Delta Nutrient Water Quality Modeling Workshop – March 25, 2008, Sacramento, CA," Report of G. Fred Lee & Associates, El Macero, CA, May 15 (2008).
> http://www.gfredlee.com/SJR-Delta/CWEMF_WS_synopsis.pdf

At the CWEMF Delta Nutrient Water Quality Modeling Workshop, Dr. Erwin Van Nieuwenhuyse, Fishery Biologist with the US Bureau of Reclamation Division of Environmental Affairs, Sacramento, CA (evannieuwenhuyse@mp.usbr.gov) discussed the impact of altering phosphorus loads to the Delta on phytoplankton biomass in his presentation entitled, "Impact of Sacramento River Input of Phosphate to the Delta on Algal Growth." His presentation is available at the CWEMF website, http://cwemf.org/Calendar/index.htm.

Van Nieuwenhuyse presented data describing the significant decrease in planktonic algal chlorophyll in the Rhine River in Europe resulting from decreased phosphorus concentrations. He also pointed out that those data suggested that phosphorus concentrations of about 400 ng/L appear to be an upper limit of the concentration range in which decreasing the P concentration effects a reduction in planktonic algal biomass.

Also at the CWEMF workshop, Dr. Lee mentioned the Rast et al. (1983) review of the literature to identify changes in planktonic algal chlorophyll concentrations that have been measured before and after quantified alterations in phosphorus loading (concentrations). Using that information Rast et al. (1983) were able to independently verify the ability of the Vollenweider-OECD eutrophication modeling approach to reliably predict changes in chlorophyll that would result from given alterations in nutrient load. Rast et al.'s findings also support the position that reduction in phosphorus load/concentration can be expected to result in reduction of planktonic algal chlorophyll levels, even in waterbodies containing phosphorus in excess of the typically reported half-saturation-constant of a few nanograms per liter, up to a few hundred nanograms P per liter.

Fisheries. It can be anticipated that the greater the levels of nutrients in a waterbody, the greater the amount of algae that can be grown, and hence the greater the fish biomass that may be supported. Using the Vollenweider-OECD modeling approach and measurements of fish yield, phosphorus load, and waterbody characteristics reported for waterbodies in the literature, Lee and Jones (1991) described an empirical relationship between normalized phosphorus load and a waterbody's fish yield. Figure 3 shows that relationship. In their paper:

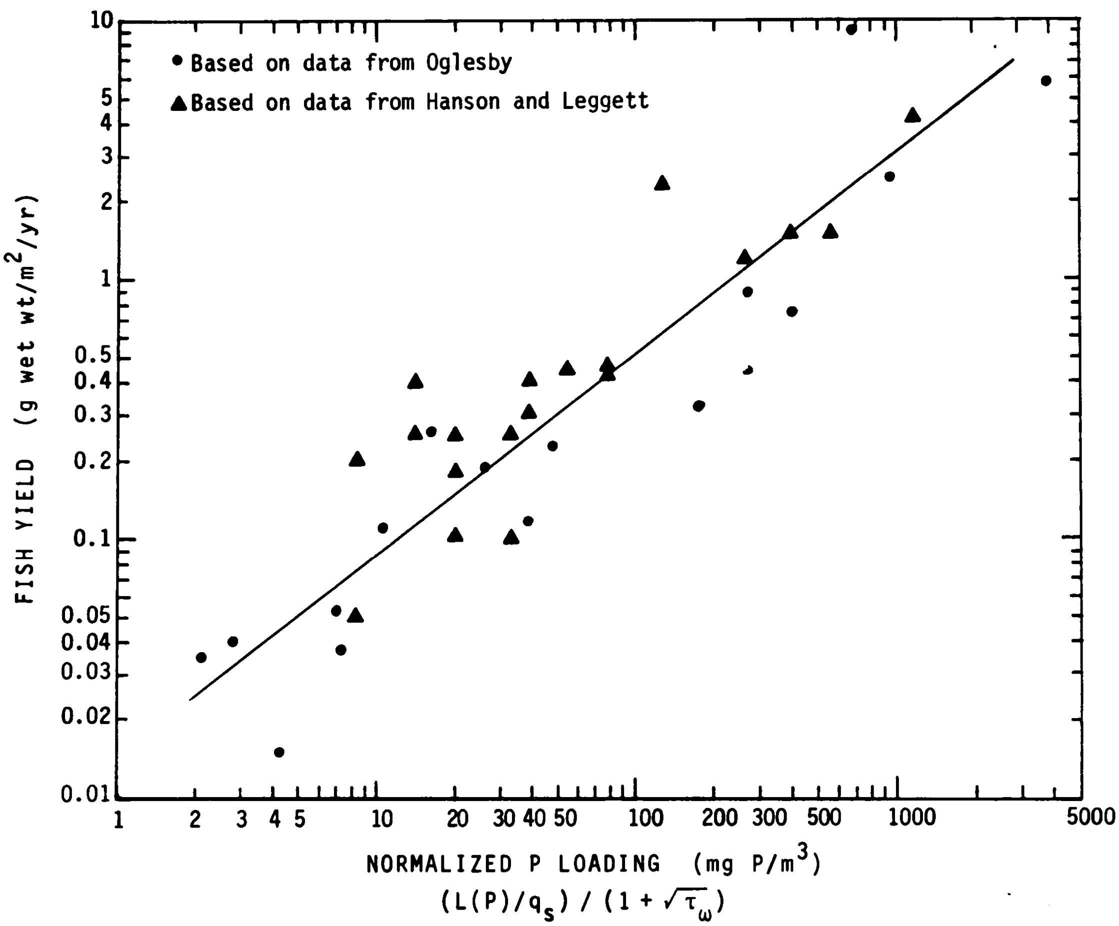
> Lee, G. F. and Jones, R. A., "Effects of Eutrophication on Fisheries," *Reviews in Aquatic Sciences*, **5**:287-305, CRC Press, Boca Raton, FL (1991).
> http://www.gfredlee.com/Nutrients/fisheu.html

the authors discussed the use of this relationship to estimate how changing the phosphorus loads to a waterbody impacts fish production. As they noted, changing the phosphorus load not only impacts overall fish production, but can also influence the types of fish that dominate. As waterbodies become more fertile they tend to lose cold water fisheries and develop more "rough" fish such as carp.

Application of OECD Eutrophication Modeling Approach to Water Supply Waterbodies

Domestic water supply is one of the key beneficial uses of waterbodies that can be significantly adversely impacted by planktonic algal growth, and hence by excessive nutrient inputs. Planktonic algae in a raw water supply can cause shortened filter runs in the treatment plant, as well as tastes and odors, and, under some conditions, increase trihalomethane (THM) precursors in the finished water. The planktonic algae can also adversely impact the dissolved oxygen resources of a lake and reservoir, through bacterial decomposition of dead algae, and thereby adversely impact the usability of the waterbody as a raw water supply source.

Figure 3 -Effect of Phosphorus Loads on Fish Production
(from Lee and Jones, 1991)



The senior author has been involved in the investigation of domestic water supply water quality and water treatment since the mid-1950s. A summary of his experience in that area is available as:

> Lee, G. F., "Synopsis of G. Fred Lee and Anne Jones-Lee's Work on Domestic Water Supply Water Quality, and TOC Issues in the Sacramento/San Joaquin River Delta," Report of G. Fred Lee & Associates, El Macero, CA (2004).
> http://www.gfredlee.com/SJR-Delta/GFL-DeltaTOCWork.pdf

During the late 1970s and early 1980s Dr. G. Fred Lee served as chairman of the American Water Works Association (AWWA) Quality Control in Reservoirs Committee. During that time Dr. Lee and his associates developed several committee reports and papers that discussed the application of the OECD eutrophication modeling approach to water supply reservoirs. The authors discussed the utility of chlorophyll as an indicating parameter in the evaluation of a water for raw water use, and provided guidance to water utilities on monitoring their water supply waterbodies for planktonic algal chlorophyll as part of managing algae-related raw water quality in:

Jones, R. A., and Lee, G. F., "Chlorophyll -- a Raw Water Quality Parameter," *Journ. AWWA* **74 (9)**:490-494 (1982).
http://www.gfredlee.com/WSWQ/ChlorophyllRawWater.pdf

They described the reliability and use of the Vollenweider-OECD modeling approach for predicting water quality in a proposed reservoir in:

Lee, G. F. and Jones, R. A., "Predicting Domestic Water Supply Raw Water Quality in Proposed Impoundments," IN: Proc. American Water Works Association 1984 Annual Conference Proceedings, pp 1611-1630 (1984).
http://www.gfredlee.com/WSWQ/RawWQProposedImp84.pdf

The importance of developing a domestic water supply intake structure that can take water at various depths in order to minimize algal related raw water quality problems is discussed in:

Lee, G. F. and Harlin, C. C., "Effect of Intake Location on Water Quality," Ind. Water Eng. 2:36-40 (1965). available from upon request as DW003 from gfredlee@aol.com

Additional Publications on the Use of Vollenweider-OECD Eutrophication Modeling Approach for Water Quality Evaluation

The authors (Lee and Jones, 1992) described a water quality monitoring program to develop the data needed for application of the model to a waterbody, and for evaluation of the impact of land use in a waterbody's watershed on the waterbody's nutrient related water quality.

Lee, G. F. and Jones, R. A., "Study Program for Development of Information for Use of Vollenweider-OECD Eutrophication Modeling in Water Quality Management for Lakes and Reservoirs," Report of G. Fred Lee & Associates, El Macero, CA, 22pp (1992). Available as EF007 upon request from gfredlee@aol.com.

More recently, they published the following discussion of the development of technically sound, site-specific nutrient criteria for managing excessive fertilization of waterbodies:

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

They contributed the following synthesis of their decades of experience in this area in the *Water Encyclopedia*:

Jones-Lee, A. and Lee, G. F., "Eutrophication (Excessive Fertilization)," *Water Encyclopedia: Surface and Agricultural Water*, Wiley, Hoboken, NJ pp 107-114 (2005).
http://www.gfredlee.com/Nutrients/WileyEutrophication.pdf

A reliable modeling approach for eutrophication-related water quality enables reasonable projections to be made of expected characteristics of reservoirs before they are constructed. When incorporated into the design stages of proposed reservoirs they can reveal potential impacts of certain hydrological and morphological options on the eutrophication-related water quality characteristics of the reservoir once built, and thus help in optimizing utility and character of the waterbody. The Vollenweider-OECD eutrophication modeling approach has been applied to several proposed reservoirs including the following:

Lee, G. F. and Jones, R. A., "Water Quality Monitoring Program for Water Quality Management for Madrigal Reservoir, Dominican Republic," Report submitted to Corporacion del Acueducto y Alcantarillado de Santo Domingo, Report of G. Fred Lee & Associates, El Macero, CA (1981).

That work in the pre-development evaluation of a proposed impoundment in the Dominican Republic showed that if the reservoir were developed as proposed the algal growth that would develop in the reservoir would be sufficient to require a different approach for treating the raw water for a domestic water supply source.

As discussed by Lee and Jones (1980), the application of the Vollenweider-OECD eutrophication modeling approach to a proposed cooling reservoir, for which the only source of water would only have been treated domestic wastewater from the city of Fort Collins, CO, correctly predicted the algae-related water quality in the reservoir.

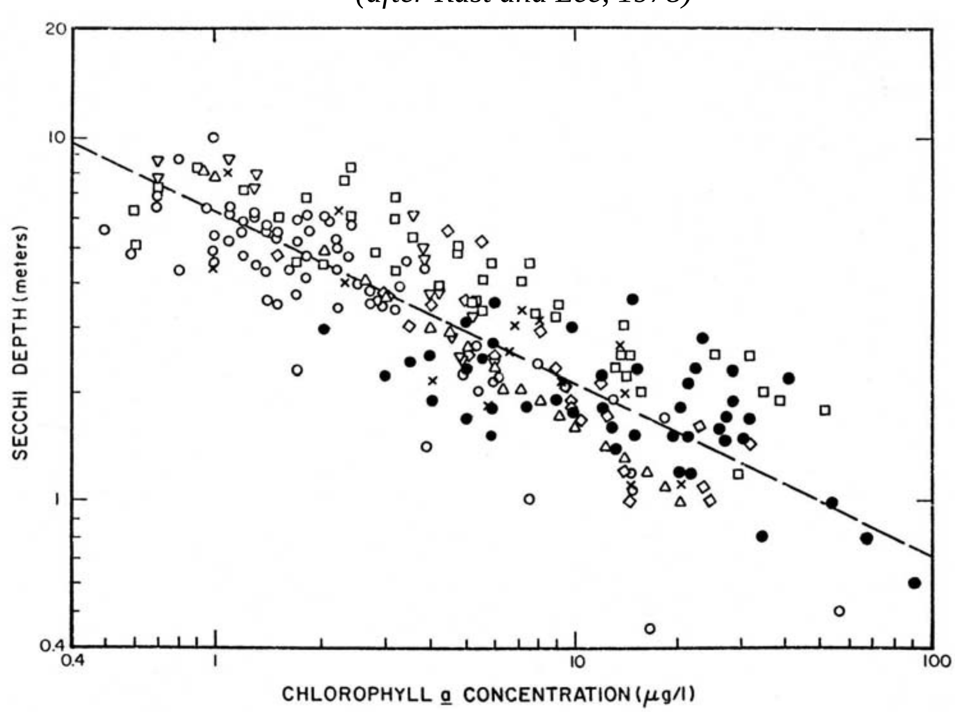
Lee, G. F. and Jones, R. A., "Water Quality Management Program for Rawhide Electric Generating Station Cooling Impoundment," Report to Platte River Power Authority, Report of G. Fred Lee & Associates, El Macero, CA September (1980). NTIS PB 82-111980.

Impact of Planktonic Algae on Secchi Depth (Water Clarity)

Secchi depth is a simple measure of water clarity (depth of light penetration). In waterbodies whose clarity is not controlled by inorganic turbidity or color, Secchi depth is related to the depth of the photic zone in which algal photosynthesis can occur, and is controlled by concentrations of planktonic algae. Figure 4 shows the relationship between Secchi depth and chlorophyll concentration developed by Rast and Lee (1978) from the body of data they found in the literature.

Figure 4. Relationship between Secchi Depth and Chlorophyll Concentration

(after Rast and Lee, 1978)



Building on the relationship between Secchi depth and chlorophyll concentration, the lower-left graph in Figure 1 showed the Vollenweider-OECD model of Secchi depth as a function of normalized P load to lakes and reservoirs. Since inorganic turbidity can be an important factor in influencing planktonic algal growth through light limitation, it is important to examine whether the inorganic turbidity in a waterbody is an important factor in controlling planktonic algal biomass in a waterbody. Variations in amounts of inorganic turbidity in waterbodies no-doubt contributed to the variability about the Secchi depth lines of best fit. If a waterbody's planktonic algal chlorophyll is low relative to the line of best fit in Figure 4, it is likely that the waterbody's growth of planktonic algae is more severely light limited than most waterbodies.

Lee et al. (1995) discussed how Secchi depth can be employed as a water quality parameter, using the Vollenweider-OECD eutrophication modeling approach.

> Lee, G. F., Jones-Lee, A., and Rast, W., "Secchi Depth as a Water Quality Parameter," Report of G. Fred Lee & Associates, El Macero, CA (1995). Available from gfredlee@aol.com as EF012.

Lee and Archibald (1981) discussed how land use in the watershed impacted domestic water supply-related water quality in Lake Ray Hubbard, a domestic water supply reservoir for the city of Dallas, TX.

> Archibald, E. M. and Lee, G. F., "Application of the OECD Eutrophication Modeling Approach to Lake Ray Hubbard, Texas," *Journ. AWWA* **73**:590-599 (1981). http://www.gfredlee.com/Nutrients/OECDLakeRayHub.pdf

That paper described how changes in the phosphorus loads to various parts of Lake Ray Hubbard would impact planktonic algal chlorophyll in the reservoir, using the Vollenweider-OECD eutrophication modeling approach as illustrated in Figure 5. The letter designations in that figure refer to different phosphorus loading or flow scenarios evaluated for the lake proper, as well as for one of its arms, Rowlette Arm, and the associated mean chlorophyll concentrations. Points "A" and "L" represent the conditions that were found during the 1976-77 study period. The position of point A shows that this waterbody fits the line of best fit for the Jones-Lee and Lee expanded OECD Eutrophication Study results. Point L shows that the Rowlette Arm phosphorus load chlorophyll relationship produces less chlorophyll than expected based on its normalized phosphorus load. This is attributed to the large amounts of inorganic turbidity in the water due to stirring of the shallow water sediments in this arm. This turbidity causes reduced light penetration and reduced algal growth. See the Archibald and Lee paper for details.

Rate of Recovery. One of the issues of concern is how rapidly a waterbody will respond in chlorophyll levels to changes in phosphorus loads to the waterbody. Sonzogni et al published,

> Sonzogni, W. C., Uttormark, P. C., and Lee, G. F., "A Phosphorus Residence Time Model: Theory and Application," *Journ. Water Res*. **10**:429-435 (1976). http://www.gfredlee.com/Nutrients/P-ResidenceTime.pdf

which demonstrate that the rate of water quality response of a waterbody to changes in phosphorus loads is related to the phosphorus residence time in the waterbody. The phosphorus residence of a waterbody is equal to the total mass of phosphorus in a waterbody divided by its annual input load. Basically, the rate of response is about equal to three times the phosphorus

Figure 5 Application of OECD Eutrophication Study Results to Lake Ray Hubbard Dallas, Texas

(from Archibald and Lee, 1981)

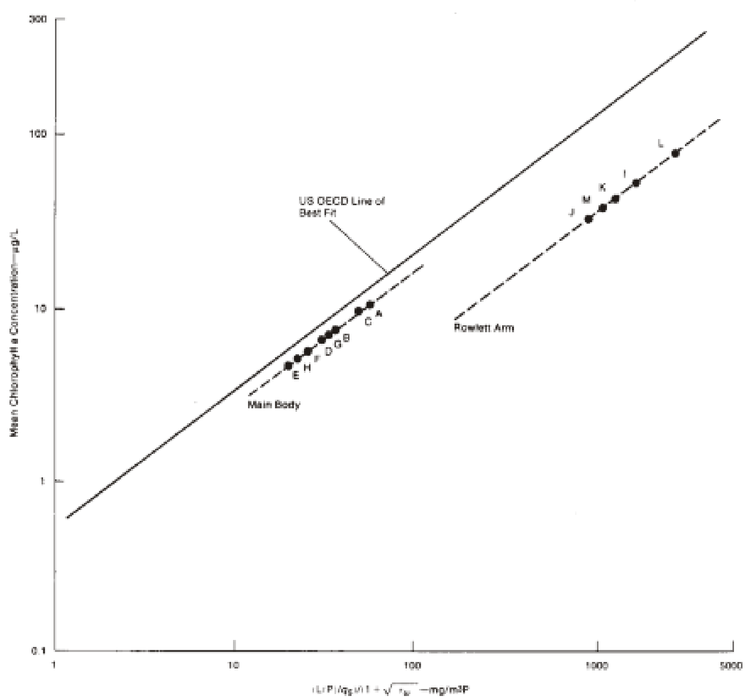


Figure 13. Relationship between phosphorus loading and chlorophyll a in the Main Body and Rowlett Arm of Lake Ray Hubbard

residence in the waterbody. Typically the phosphorus residence time in lakes and reservoirs in about one year.

As part of investigating the impact of detergent phosphate bans on a waterbodies water quality it was found that at least a 20% change in the phosphorus load to a waterbody was needed to develop a perceptible change in planktonic algal populations biomass. Figure 6 shows this relationship as applied to the impact of removal of detergent phosphorus on a waterbodies nutrient related water quality. This was published as,

> Lee, G. F. and Jones, R. A., "Detergent Phosphate Bans and Eutrophication," *Environ. Sci. Technol.* 20(4):330-331 (1986).
> http://www.gfredlee.com/Nutrients/DetergentPBan.pdf

The results of this figure apply to any waterbody in which there is a change in phosphorus load relative to the total phosphorus load to the waterbody.

Another outgrowth of the Rast and Lee OECD eutrophication studies is the developing national nutrient export coefficients. They published,

> Rast, W., and Lee, G. F., "Nutrient Loading Estimates for Lakes," *Journ. Environ. Engr*. 109(2):502-518 (1983). See also closure discussion, "Nutrient Estimates for Lakes," *Journ. Environ. Engrg*. **110**:722-724 (1984).
> http://www.gfredlee.com/Nutrients/NutrientLoadingEstRast.pdf

For many waterbodies an estimate of the nutrient load to a waterbody can be made based on land use in the waterbodies watershed. The Tetra Tech report,

> Sujoy Roy, Katherine Heidel, Clayton Creager, Chih-Fang Chung, and Tom Grieb "Conceptual Models for Constituents of Drinking Water Concern in the Central Valley and Delta: Organic Carbon, Nutrients and Pathogens," Tetra Tech, Inc. Lafayette, CA. (2006) http://rd.tetratech.com/drinkingwater

presents information on the development of nutrient export coefficients for the Central Valley of California. In general these results that the irrigated agriculture land use in the Central Valley has nutrient export coefficients similar to those developed by Rast and Lee (1983).

Figure 6-Impact of Altering Phosphorus Load on Eutrophication Response
(from Lee and Jones, 1986)

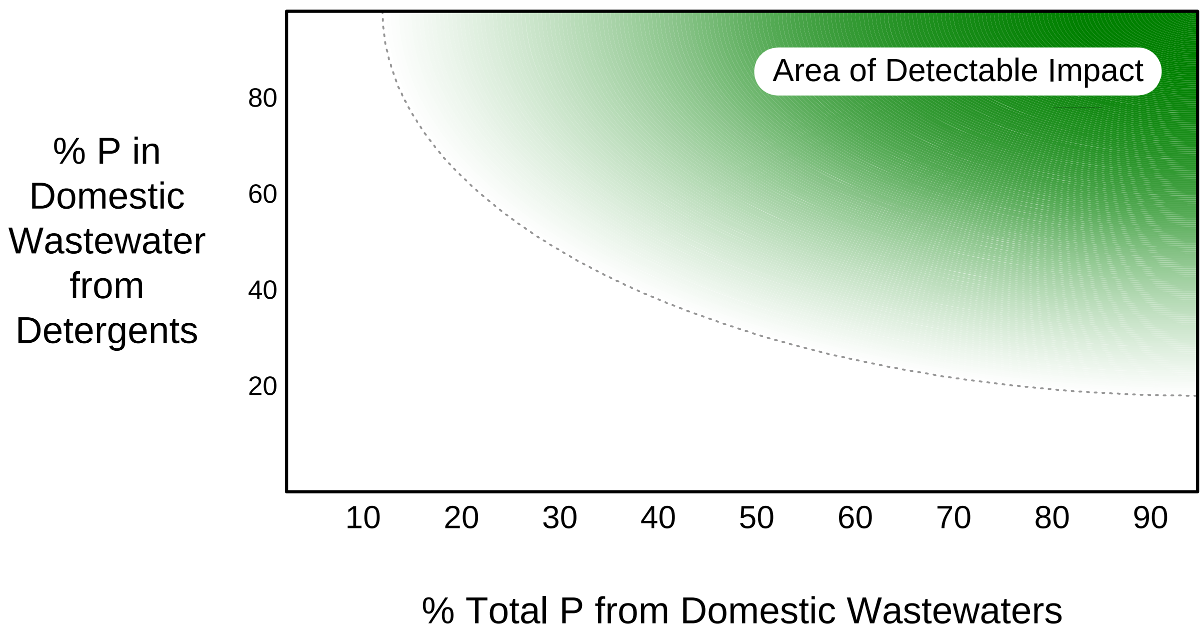


Table 1 presents the results of the Rast and Lee national land use nutrient export coefficients.

Table I. Watershed Nutrient Export Coefficients

Land Use	*Export Coefficients ($g/m^2/y$)*		
	Total Phosphorus	*Total Nitrogen*	
Urban	0.1	0.5	0.25[a]
Rural/Agriculture	0.05	0.5	0.2[a]
Forest	0.01	0.3	0.1[a]
Other:			
Rainfall	0.02	0.8	
Dry Fallout	0.08	1.6	

[a] Export Coefficients Used in Calculating Nitrogen Loadings for Waterbodies in Western US.
From Rast and Lee (1983).

According to Rast and Lee (1983) the typical municipal domestic wastewater contribution of nutrients from conventionally secondarily treated domestic wastewater is 1.1 kg P/person/yr and 2.2 kg N/person/yr. Sujoy et al. (2006) has reported similar values.

It is estimated that the majority of the data presented in Figures 1 and 2 for the normalized P load is based on essentially all of the phosphorus added to a waterbody is algal available. For this reason total P is used in determining the normalized P load.

Impact of Wetlands. Lee et al found that the drainage wetlands to produce agricultural lands results in

> Lee, G. F., Bentley, E. and Amundson, R., "Effect of Marshes on Water Quality," In: Ecological Studies 10, Coupling of Land and Water Systems, Springer-Verlag, New York, pp 105-127 (1975). Available from Gfredlee@aol.com upon request.

Available Phosphorus. During the 1960s/70s there was considerable work done on determining the amounts of algal available P. An invited review paper,

> Lee, G. F.; Jones, R. A. and Rast, W., "Availability of Phosphorus to Phytoplankton and its Implications for Phosphorus Management Strategies," IN: Phosphorus Management Strategies for Lakes, Ann Arbor Science Publishers, Inc., Ann Arbor, MI (1980). http://www.gfredlee.com/Nutrients/Avail-P.pdf

discussed the findings of Lee and his associates and well as others in that the algal available P is approximately equal to the sum of the sol OP plus about 20% of the inorganic particulate P. It has been found that waterbodies with large amounts of erosional particulate P must correct the phosphorus loads to a calculated algal available P to correctly relate phosphorus loads to planktonic algal chlorophyll.

For waterbody tributaries in which there is a large amounts of planktonic algae added to the waterbody, the particulate phosphorus in the algal cells will likely become available to support additional algal growth in the waterbody through mineralization of the tributary algal cells when they die in the waterbody.

It has been found that impoundments typically remove about 75% of the phosphorus load added to it. This phosphorus removal is the result of algal growth in the impoundment which results in the phosphorus becoming incorporated into the impoundments sediments. For waterbodies in which the tributary has an impoundment on it that has a hydraulic residence time of about two weeks or more then the phosphorus load to the impoundment should be adjusted to about 25% of this load as the contribution to the tributary downstream of the impoundment.

Impact of Nutrients/Algae on THM Formation

There is interest in assessing the role of nutrients that develop into algae on the development of trihalomethane (THM) precursors such as TOC and DOC. Lee and Jones published,

> Lee, G. F., "Synopsis of G. Fred Lee and Anne Jones-Lee's Work on Domestic Water Supply Water Quality, and TOC Issues in the Sacramento/San Joaquin River Delta," Report of G. Fred Lee & Associates, El Macero, CA (2004). http://www.gfredlee.com/SJR-Delta/GFL-DeltaTOCWork.pdf
>
> Lee, G. F. and Jones-Lee, A., "Issues that Need to Be Considered in Evaluating the Sources and Potential Control of TOC that Leads to THMs for Water Utilities that Use Delta Water as a Water Supply Source," Report of G. Fred Lee & Associates, El Macero, CA, May (2003). http://www.gfredlee.com/SJR-Delta/TOC_update.pdf
>
> > Lee, G. F. and Jones, R. A., "Impact of the Current California Drought on Source Water Supply Water Quality," Presented at CA/NV AWWA Fall Conference, Anaheim, CA, 30pp, October (1991). Available upon request as DW001 from gfredlee@aol.com.
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> > Lee, G. F. and Jones, R. A., "Regulating Drinking Water Quality at the Source," Proc. University of California Water Resources Center Conference: Protecting Water Supply Water Quality at the Source, Sacramento, CA, 39pp, April (1991). http://www.gfredlee.com/WSWQ/wswqsour.htm

reviewed this issue as it relates to the use of Delta water as a domestic water supply raw water source. They concluded that the chlorination of a water that has algae in it can lead to increased THM formation. The magnitude of this problem is dependent on the water treatment plant approach for treating the water with particular reference to where in the treatment process the chlorination occurs and the type of chlorine used. They also found that the development of algae in a water supply reservoir leads to a temporary increase in TOC and DOC. In general the algae will be mineralized with the result that the overall TOC/DOC in a waterbody is not increased by increasing the trophic state of the waterbody.

Impact of Nutrients on the Growth of Hyacinth and Egeria

Some waterbodies including parts of the Delta develop floating and attached water weeds such as hyacinth and egeria. The nutrients added to those waterbodies typically do not use the nitrogen and phosphorus added to the waterbody to develop planktonic algae. The growth of hyacinth is dependent on the nutrient concentrations in the water column. Egeria growth is dependent on nutrients present in the sediments. Thus far the OECD Eutrophication modeling approach has not been applied to hyacinth growth although it is likely that it will likely be adopted to relate phosphorus loads to those parts of the waterbody where hyacinth growths dominate aquatic plant growth. The amount of hyacinth produced can be measured by the aerial extend of waterbody surface covered by hyacinth. Lee et al. addressed the modeling of the impact of nutrients on waterbodies where floating macrophytes and attached algae are developed as.

> Newbry, B. W., Jones, R. A. and Lee, G. F., "Application of the OECD Eutrophication Modeling Approach to Cherokee Reservoir and Other TRS Impoundments," Report to Tennessee Valley Authority, Chattanooga, TN, September (1979).

Wilson et al. have been investigating the factors that influence the growth of hyacinth in South African waterbodies. They have published,

> Wilson, J., Holst, N., Rees, M., "Determinants and Patterns of Population Growth in Water Hyacinth," Aquatic Botany 81:51-67 (2005).

They have developed logistic modeling approach for modeling the relationship between hyacinth and phosphorus concentrations in a waterbody.

Thomas and his associates in Brazil have conducted a number of studies on the factors influencing egeria growth including,

> Thomaz, S., Chambers, P., Pierini, S., and Pereira, G., "Effects of Phosphorus and Nitrogen Amendments on the Growth of *Egeria najas*," Aquatic Botany 86(2**)**:191-196 February (2007).

They have shown that it is the nutrient content of the sediments that determines the growth of egeria. Studies by G. F. Lee and his associates such as

> Bortleson, G. C., and Lee, G. F., "Recent Sedimentary History of Lake Mendota, Wisconsin," *Environ. Sci. & Technol*. 6:799-808 (1972).
> http://www.gfredlee.com/Nutrients/BortlesonSedHistMendota.pdf

and

> Delfino, J., Bortleson, G., and Lee, G. F., "Distribution of Mn, Fe, P, Mg, K, Na, and Ca in the Surface Sediments of Lake Mendota, Wisconsin," *Environ. Sci, & Technol.* 3(11**)**:1189-1192 (1969).
> http://www.gfredlee.com/SurfaceWQ/DelfinoDistributionMn.pdf

have shown that there are a number of factors that influence the concentration of phosphorus in aquatic sediments including the phosphorus load to the waterbody and the non phosphorus associated sediment load to the waterbody.

Impact of Nutrient/Algal on Dissolved Oxygen Resources of Waterbodies

Nutrients that develop into algae that subsequently die and decompose can have a variety of impacts on the dissolved oxygen (DO) resources of waterbodies. The range of impacts can be as great as occurs in the San Joaquin River (SJR) Deep Water Ship Channel (DWSC),

> 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

Lee, G. F. and Jones-Lee, A., "Supplement to Synthesis Report on the Low-DO Problem in the SJR DWSC," Report of G. Fred Lee & Associates, El Macero, CA, June (2004). http://www.gfredlee.com/SJR-Delta/SynthRptSupp.pdf

Lee, G. F. and Jones-Lee, A., "San Joaquin River Deep Water Ship Channel Low DO Problem and Its Control," PowerPoint slides presented at SETAC World Congress Portland, OR, November 2004. Updated December (2004).
http://www.gfredlee.com/SJR-Delta/LowDOSummaryDec2004.pdf

where the oxygen demand of algae that develop upstream of the SJR DWSC, die and decompose and deplete the DO in a 35 foot deep unstratified ship channel. This situation is unusual since normally DO depletion due to algal decomposition occurs in the hypolimnion of lakes and reservoirs. The surface water of most waterbodies shows the typical diurnal (night/day) DO and pH changes associated with algal photosynthesis and algal and bacterial respiration. These DO and pH changes can be sufficient to cause violation of DO and pH water quality standards.

The DO depletion of the hypolimnion of waterbodies was modeled by Rast and Lee (1978) and Lee et al. (1978) as part of the US OECD Eutrophication Studies. Figure 1 upper right figure shows the relationship that they developed for the impact of the normalized phosphorus load to a waterbody to the rate of DO depletion in the hypolimnion. This relationship has been used to estimate the impact of a proposed impoundment watershed and its associated phosphorus loads on whether the impoundment will develop an anoxic hypolimnion. Lee and Jones have developed,

Lee, G. F., and Jones-Lee, A., "Mechanisms of the Deoxygenation of the Hypolimnia of Lakes," Report of G. Fred Lee & Associates, El Macero, CA (1999). Available upon request as EF10 from gfredlee@aol.com.

Recently, Lee and Jones-Lee have developed several reports on the impacts of nutrient/algae impacts on the DO resources of waterbodies through the accumulation of oxygen demand in a waterbodies sediments. These reports,

Lee, G. F. and Jones-Lee, A., "Role of Aquatic Plant Nutrients in Causing Sediment Oxygen Demand Part I – Origin of Rapid Sediment Oxygen Demand," Report of G. Fred Lee & Associates, El Macero, CA, May (2007).
http://www.gfredlee.com/Sediment/NutrientSOD1RapidOD.pdf

Lee, G. F., and Jones-Lee, A., "Role of Aquatic Plant Nutrients in Causing Sediment Oxygen Demand Part II – Sediment Oxygen Demand," Report of G. Fred Lee & Associates, El Macero, CA, June (2007).
http://www.gfredlee.com/Sediment/NutrientSOD2SOD.pdf

Lee, G. F., and Jones-Lee, A., "Role of Aquatic Plant Nutrients in Causing Sediment Oxygen Demand Part III – Sediment Toxicity," Report of G. Fred Lee & Associates, El Macero, CA, June (2007). http://www.gfredlee.com/Sediment/NutrientSOD3Tox.pdf present information on how nutrients that develop into algae that die, settle and decompose in the sediments can adversely impact a waterbodies water quality. In addition to the types of situations discussed above the decomposition of algae in sediments leads to sediment toxicity to aquatic life due to low DO and the formation of ammonia and hydrogen sulfide. It has been found that low DO and associated ammonia and hydrogen sulfide is one of the most common causes of sediment toxicity. However, typically regulatory agencies ignore this situation and focus on heavy metals and organics as a cause of sediment toxicity. This is an example of the unreliable approach that is typically being followed in evaluating sediment quality.

Lee and Jones-Lee have also discussed in Part I of their series referenced above that one of the consequences of nutrient/algae low DO situations is that the depletion of DO in sediments leads to the accumulation of ferrous iron and hydrogen sulfide. Both of these can exert a very rapid inorganic oxygen demand in the water column when the sediment are mixed into it. This type of situation leads to short term episodic DO depletion that can have dramatic impact of aquatic life population in the sediments an water column including fish kills.

Overall nutrients can have a variety adverse impacts on a waterbodies that are typically not considered and addressed in water quality evaluation and management programs.

Information Needed to Apply the OECD Eutrophication Study Results to Waterbodies

The information needed to evaluate whether the OECD Eutrophication Studies results as expanded by Jones and Lee are applicable to a particular waterbody and therefore can be used to evaluate how altering the phosphorus load to a waterbody would affect eutrophication related water quality is summarized below.

Application of the OECD Eutrophication Study Results Delta Water Supply Reservoirs

In the simplest situation of a bowl shaped waterbody with essentially constant water level and a hydraulic residence time (filling time) of more than one year and approximately even monthly nutrient loads that does not have large amounts of inorganic particulate phosphorus load an evaluation of the application of the OECD eutrohication study results can be made by determining the normalized phosphorus load in mg P/m^2/year, summer average planktonic algae chlorophyll in µg/L, and the waterbodies mean depth (volume/area) and hydraulic residence in years. This information is applied to Figure 2 to determine whether the result plots near the line of line of best fit in this figure. If the result is located within the family of points on Figure 2 then this waterbody uses it phosphorus loads to develop planktonic algal chlorophyll as do waterbodies through the world.

If the waterbody computed result falls within the typical range of waterbodies shown in Figure 2 then it is possible to estimate how the planktonic algal chlorophyll will change upon changing the P load to the waterbody. This approach is presented in,

> Rast, W., Jones, A., and Lee, G. F., "Predictive Capability of US OECD Phosphorus Loading-Eutrophication Response Models," *Journ. Water Pollut. Control Fed.* 55(7):990-1003 (1983).
> http://www.gfredlee.com/Nutrients/PredictiveCapabilityOECD.pdf

Presented below is a listing of the types of data that are useful in applying the OECD Eutrophication Study results to waterbodies that have characteristics somewhat different from the "simplest" waterbody discussed above. Also the information needed to relate the results of the application of the results to manage a domestic water supply lake or reservoir source is presented.

The first step in evaluating whether the simplest approach for applying the OECD Eutrophication Study results is collect the information on the waterbody characteristics, such as waterbodies mean depth and hydraulic residence time as well as the normalized phosphorus load to the waterbody. This result is then applied to Figure 2 to determine if the resultant value falls within the family of points showed in this figure.

If the result of the simplest application fails to fit the results shown in Figure 2 then the following information should be collected. This information can normally be used adjust the waterbodies characteristics to enable the use of the OECD Eutrophication Study results to a waterbody.

Following on the publication of the paper,

> van Nieuwenhuyse, E., "Response of Summer Chlorophyll Concentration to Reduced Total Phosphorus Concentration in the Rhine River (Netherlands) and the Sacramento–San Joaquin Delta (California, USA)," Can. J. Fish, Aquat. Sci. **64**:1529-1542 (2007).

which presents data on phosphorus and planktonic algal chlorophyll concentrations in the Sacramento River near Hood and Central Delta a comparison was made between the measured concentrations and those that would be predicted based on the OECD Eutrophication Study results. In making that comparison, the in-waterbody P concentration was presumed to be equivalent to the normalized P load to the waterbody. It was found that the planktonic algal chlorophyll in the Sacramento River near Hood, which is downstream of the Sacramento Regional County Sanitation District's discharge of wastewater to the river, is considerably lower than what would be expected if the P had been used to develop algae to the extent that normally occurs in waterbodies. This is to be expected since a major source of P upstream of Hood has not had time to be used by the planktonic algae. A similar comparison for the average of several Central Delta channel monitoring locations showed that the planktonic algal chlorophyll was somewhat less than what would be expected based on the OECD eutrophication study results. The monitoring stations used for this evaluation are typically dominated by Sacramento River water during the summer. This could also be due to inadequate time between a major P load addition and monitoring point for the algae to use the P.

Another factor that could be causing a low planktonic algal chlorophyll level compared with that expected based on the P concentration is the presence of large numbers of clams on the bottom of the Delta channels; the clams in Delta channels are known to be harvesting large amounts of phytoplankton from the watercolumn.

Waterbody Morphology

> Surface Area at full pool and normal pool at start of the season when nutrient related water quality problems such as tastes and odors tend to occur.

What are the depths of the waterbody at the deepest location during full pool, beginning of summer, at end of the summer?

Is the waterbody bowl shape or long and thin with or without side arms where the amounts of summer planktonic algal chlorophyll is different from the main waterbody

How well do water inputs from tributaries mix into the waterbody, i.e., within a few days, weeks, or months?

Volume of waterbody at full pool and at start of the season when nutrient related water quality problems such as tastes and odors tend to occur.

Whether the waterbody thermally stratifies during the summer or temporarily stratifies for a few days/weeks or so and then loses stratification associated with strong wind or other events. Please provide typical mid waterbody deep area temperature profiles.

At what depth does the domestic water supply intake occur?

Water Quality Characteristics

When do the nutrient related water quality problems typically occur, spring, summer, fall or winter. What are the nutrient related water quality problems of greatest concern?

Average weekly/monthly summer planktonic algal total chlorophyll, chlorophyll a, pheophytin a

What are the dominant types of planktonic algae when water supply water quality problems occur? Do bluegreen algal scum develop?

Secchi depth each week during the spring, summer, fall. Does the waterbody become turbid due to inorganic turbidity?

Is the waterbody colored due to organics?

Percent of the waterbody area that is covered with attached or floating water weeds such as hyacinth, cattails attached algae etc.

Weekly concentrations of total P, sol OP, nitrate, ammonia, electrical conductivity or total dissolved solids

Does the hypolimnion become anoxic during the summer?

Hydrology

What is the typical annual and monthly inflows of water to the waterbody?

What is the estimated hydraulic residence time (filling time)?

Do any of the major water inputs to the waterbody short circuit between the inlet and any outlet?

Do the major inflows to the waterbody form density currents and therefore not readily mix with the surface waters in the waterbody?

Nutrient Loads

What is the monthly normal total P, sol O P, nitrate, ammonia and organic N, planktonic algal chlorophyll loads (grams/day) to the waterbody overall and to each major part of the waterbody if the input from an area does not rapidly mix with the bulk of the water in the waterbody?

What are the major sources of nutrient compounds from the waterbodies watershed?

Amount of watershed nutrients derived from domestic wastewaters, industrial wastewaters, urban stormwater runoff, agricultural land runoff, forested areas, range land, other?

How many people discharge wastewaters to the waterbody and or to its tributaries?

Is the watershed rapidly urbanizing?

How much nutrients are discharged to tributaries of the waterbody from dairies, feedlots, other animal husbandry activities?

What is the area of the waterbodies watershed that is devoted to agriculture, forest, urban area?

What is the area of wetlands in the waterbody watershed. When does the managed wetlands release water to tributaries of the waterbody? What is the composition of the released waters?

Costs of Treating to Control Nutrient Related Water Quality Problems

How much activated carbon is used for taste and odor control

Is there a relationship between activated carbon used and planktonic algal chlorophyll?

Are shortened filter runs a problem due to planktonic algae? How much additional backwashing of filters occurs during algal blooms?

What other costs are associated with treating the raw water due to planktonic algae?

Is there an increase in TOC, THMs during major algae blooms in the waterbody?

Is the waterbody treated with copper sulfate or other chemicals to control algae? What is the cost of treatment?

For rivers can a plug flow model be used to relate phosphorus concentrations to planktonic algal chlorophyll?

Questions about how to apply the OECD Eutrophication Study results to a particular waterbody can be directed to Dr. G. Fred Lee at gfredlee@aol.com.

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http://www.gfredlee.com/Nutrients/NitrogenFixationTorrey.pdf

Expertise and Experience of Drs. G. Fred Lee and Anne Jones-Lee in Evaluation and Management of Excessive Fertilization of Waterbodies

A substantial portion of Drs. Lee and Jones-Lee's professional work continues to be in the area of evaluation and management of the impacts of aquatic plant nutrients (nitrogen and phosphorus) on water quality/beneficial uses of waterbodies, including lakes, reservoirs, coastal marine waters, as well as riverine systems. Excessive fertilization (eutrophication) causes adverse impacts on recreational uses and aesthetics, raw water supply water quality (tastes & odors and THM formation), and fisheries resources through, among other things, oxygen depletion associated with algal decomposition. As discussed below, their work focuses on the causes, manifestation, and control of the wide range of excessive fertilization problems.

Dr. Lee's work in eutrophication evaluation and management began in the 1960s when he established, developed, and directed the Water Chemistry Program in the Department of Civil and Environmental Engineering at the University of Wisconsin, Madison. During the 13 years under his direction, that program was highly involved in lake and reservoir water quality investigation and management; approximately 100 of his graduate students did their Masters theses or Ph.D. dissertations on various aspects of lake and reservoir water quality. One of the principal focal points of that work was excessive fertilization issues. Dr. Lee pioneered in the development of approaches for evaluating the impact of a various sources of nutrients, including activities and conditions in a waterbody's watershed, on waterbodies' water quality.

In 1960, Dr. Lee was appointed vice-chair of the Lake Mendota Water Quality Management Committee. Lake Mendota is one of the most intensively studied waterbodies in the world due to the long history of limnological research conducted by the University of Wisconsin, Madison, faculty and students. From 1960 through the early 1970s many of the water chemistry studies conducted on Lake Mendota were under the direction of Dr. Lee. During that time Dr. Lee was also involved in Great Lakes water quality issues, and served as an advisor to the International Joint Commission for the Great Lakes and the US EPA on excessive fertilization issues. Over the years he has been an investigator or advisor on eutrophication-related water quality issues in many areas of the US as well as in the Netherlands, Norway, Italy, Spain, Israel, Jordan, Japan, the USSR, Dominican Republic, South Africa, Argentina, and Antarctica.

On behalf of the Water Resources Center at the University of Wisconsin, Madison, Dr. Lee developed the first comprehensive overview of the causes, processes, implications, and management of the eutrophication of waterbodies in the paper:

> Lee, G.F., "Eutrophication," University of Wisconsin Eutrophication Information Program Occasional Paper no. 2, 32 pp (1970) [also published in Transactions of the Northeast Fish and Wildlife conference, pp 39-60 (1973), and available upon request from gfredlee@aol.com as EF014]

More recently, he and Dr. Jones-Lee were asked to contribute the following review of eutrophication:

> Jones-Lee, A. and Lee, G. F., "Eutrophication (Excessive Fertilization)," In: Water Encyclopedia: Surface and Agricultural Water, Wiley, Hoboken, NJ, pp 107-214 (2005).
> [available at: http://www.gfredlee.com/Nutrients/WileyEutrophication.pdf]

Those reviews discuss the roles of nitrogen, phosphorus and other constituents in causing excessive fertilization-related water quality problems, as well as, and most importantly, approaches that can be used to manage excessive fertilization and evaluate the effectiveness of management strategies. Those two writings remain the most comprehensive reviews of eutrophication and its management.

Dr. Lee was also involved in the lake and reservoir management studies conducted by the state of Wisconsin in the late 1960s to early 1970s. As part of that program, whole-lake experimental approaches were used to assess the efficacy of a variety of strategies for evaluating and managing water quality in excessively fertile lakes; strategies evaluated included adding alum to the lake to remove phosphorus, aeration of the lake to mix the hypolimnion and epilimnion, hypolimnetic aeration, aquatic plant harvesting, among others. Dr. Lee was involved in a number of additional projects in the state of Wisconsin in which alum was used to treat whole lakes for phosphorus removal; he supervised the master thesis work of one of his students on this topic. Dr. Lee has developed specific guidance for discerning situations in which alum treatment for phosphorus removal can be effective, and where it should not be used. Critical to this assessment is the relative role of phosphorus in controlling excessive fertilization in the waterbody.

For a number of years beginning in the 1970s, Dr. Lee was a member of the American Water Works Association's national ‘Quality Control in Reservoirs’ Committee. During that time, the committee specifically addressed the value of mixing of lakes, either by aeration or pumping, for the purpose of managing eutrophication-related water quality problems. It was the committee's conclusion, supported by the fundamental chemistry of nutrients, that aeration of a whole waterbody could be significantly adverse to improving eutrophication-related water quality characteristics. Oxygenation of the hypolimnion, however, could be effective in maintaining cold-water fisheries and improving water supply water quality by reducing nutrient transport from the hypolimnion to the epilimnion. In 1965 Dr. Lee published a paper,

> Lee, G.F. and Harlin, C.C., "Effect of Intake Location on Water Quality," *Industrial Water Engineering* 2:36-40 (1965). [available upon request to gfredlee@aol.com as publication DW003].

which specifically addressed the importance of evaluating domestic water supply water quality as a function of depth, and how, through selective withdrawal, water utilities can optimize their water quality in a thermally stratified waterbody.

While working with the state of Wisconsin Department of Conservation, Dr. Lee studied the impact of aeration of Comstock Reservoir on water quality. He examined the impact of aeration not only on chemical and biological characteristics of the reservoir, but also on the fisheries of the waterbody. Dr. Lee has had extensive experience in the evaluation of the impacts of various types of chemicals used to control algae and other aquatic weeds, including copper and diquat, on a waterbody's water quality and fisheries. Further, he is familiar with regulatory issues associated with the use of chemicals for aquatic plant control and their impact on non-target aquatic life. More recently, in support of the DeltaKeeper and the California State Water Resources Control Board, Dr. Lee developed guidance for evaluating the water quality impact of herbicides used to control excessive growths of aquatic weeds, on non-target organisms:

Lee, G. F., “Developing a Reliable Program to Monitor Water Quality Impacts of Aquatic Pesticides,” Report of G. Fred Lee & Associates, El Macero, CA (2004). [available at: http://www.gfredlee.com/Nutrients/Aq-Pest-MonPgm.pdf]

Dr. Lee has had extensive experience in assessing and managing the couplings among eutrophication, eutrophication control, and fish and other aquatic organisms. He and Dr. Jones-Lee published what has become recognized as one of the most comprehensive reviews of the impacts of eutrophication and water quality management on fish populations:

Lee, G.F. and Jones R.A., "Effects of Eutrophication of Fisheries," Reviews in Aquatic Sciences, 5:287-305, CRC Press, Boca Raton, FL (1991), [http://www.gfredlee.com/Nutrients/fisheu.html]

That paper reviews how managing algae-related water quality in a reservoir can influence the fisheries of the waterbody.

During the 1970s, Dr. Lee was awarded the US EPA contract to develop a synthesis report for the US part of the Organization for Economic Cooperation and Development (OECD) eutrophication studies. The approximately $50-million OECD eutrophication studies examined the nutrient load—eutrophication-related water quality response relationships in about 200 waterbodies located in 22 countries (in western Europe, North America, Japan, and Australia) over a five-year period. Dr. Lee served as an advisor to the overall international studies, as well as developed the US OECD report synthesizing the data on about 40 US waterbodies. Dr. Lee's primary contribution to this effort was in the development, evaluation, and application of empirical nutrient load—eutrophication-response relationships that can be used by water utilities and others to examine how land use in a waterbody's watershed influences nutrient transport to the waterbody from the watershed and then, the waterbody's water quality. Drs. Lee and Jones-Lee and their associates have published extensively on this topic including several comprehensive reviews such as,

Lee, G. F., Rast, W. and Jones, R. A., "Eutrophication of water bodies: Insights for an age-old problem," Environmental Science & Technology 12:900-908 (1978). http://www.gfredlee.com/Nutrients/Eutrophication-EST.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(2):67-74, 118 (1986). http://www.gfredlee.com/Nutrients/voll_oecd.html.

Jones, R. A. and Lee, G. F., "Chlorophyll-A Raw Water Quality Parameter," Journal American Water Works Association 74:490-494 (1982). [http://www.gfredlee.com/WSWQ/ChlorophyllRawWater.pdf].

Key to the development and evaluation of effective nutrient/eutrophication control strategies is the ability to reliably assess the improvement in water quality that can result, or has resulted, from various control strategies. One of the important results of their work with the Vollenweider-OECD eutrophication modeling approach was their demonstration of the predictive capability and reliability of the models using data collected before and after nutrient load alterations. That work was discussed in:

Rast, W., Jones, R. A. and Lee, G. F., "Predictive Capability of US OECD Phosphorus Loading-Eutrophication Response Models," *Journ. Water Pollut. Control Fed.* **55**:990-1003 (1983).
[http://www.gfredlee.com/Nutrients/PredictiveCapabilityOECD.pdf]

While serving as chairman of the AWWA national Quality Control in Reservoirs Committee, Drs. Lee and Jones-Lee developed several committee reports that were designed to assist water utilities in managing their raw water quality:

Lee, G. F. and Jones, R. A., "Study Program for Development of Information For Use of Vollenweider-OECD Eutrophication Modeling in Water Quality Management for Lakes and Reservoirs," G. Fred Lee & Associates, El Macero, CA (1992). [available as EF007 upon request from gfredlee@aol.com].

Dr. Lee was asked by the organizers of a University of California Water Resources Center conference devoted to water supply source water quality issues, to develop a review of water quality issues in the Sacramento/San Joaquin Delta in the Central Valley of CA. This resulted in Drs. Lee and Jones-Lee's publication of a paper and report:

Lee, G. F. and Jones, R. A., "Managing Delta Algal-Related Drinking Water Quality: Tastes and Odors and THM Precursors," Published in "Protecting Drinking Water Quality at the Source," proceedings of a Conference, Univ. of California Water Resources Center, Report no. 76, October (1991).

Lee, G. F. and Jones, R. A., "Regulating Drinking Water Quality at the Source," Presented at Univ. of California Water Resources Center Conference, "Protecting Drinking Water Quality at the Source," Sacramento, CA, April 3-4 (1991). http://www.gfredlee.com/WSWQ/wswqsour.htm

Those publications specifically discuss issues of how land use within and upstream of the Delta influences the quality of the domestic water supply derived from the Delta. Further, as part of the CA/NV AWWA Section Source Water Quality Committee, Dr. Lee developed a review for the committee on the impact of the drought in the late 1980s - early 1990s on domestic water supply water quality:

Lee, G. F. and Jones, R. A., "Impact of the Current California Drought on Source Water Supply Water Quality," Presented at CA/NV AWWA Fall conference, Anaheim, CA, 30pp, October (1991). [available upon request from gfredlee@aol.com].

That paper reviewed how the algae-related quality of the water derived from the Delta adversely impacts domestic water supply water quality through taste and odors and THMs.

Much of Dr. Lee's work on excessive fertilization of waterbodies has focused on eutrophic/hypertrophic waterbodies in which blue-green algae dominate the flora. Blue-green algae can be a significant source of tastes and odors in domestic water supplies. A number of Dr. Lee's graduate students did their Ph.D. dissertations on water quality issues associated with blue-green algae; topics investigated included nitrogen fixation by blue-green algae, the role of thermocline migration and erosion in the transference of hypolimnetic nutrients to surface waters where they stimulate blue-green algal blooms, and the role of sediments and other sources of nitrogen and phosphorus compounds in controlling blue-green algae dominance in waterbodies.

Dr. Lee has been involved in several major projects on behalf of water utilities specifically designed to examine how land use in a water supply reservoir's watershed influences raw water quality. In what is believed to be one of the most comprehensive studies of this type ever undertaken, Dr. Lee conducted a multi-year, several hundred-thousand-dollar project on behalf of the city of Dallas, Texas, water utility. That study specifically addressed the issues of how changes in land use in the watershed of Lake Ray Hubbard, one of the primary water supply reservoirs for the city of Dallas, influenced taste- and odor-related water quality. The study considered not only algae but also actinomycetes as sources of taste and odors. Dr. Lee and one of his graduate students published a paper on the results of that investigation:

> Archibald, E. M. and Lee, G. F., "Application of the OECD Eutrophication Modeling Approach to Lake Ray Hubbard, Texas," Journal American Water Works Association, 73:590-599 (1981).
> http://www.gfredlee.com/Nutrients/OECDLakeRayHub.pdf

Dr. Lee conducted a similar study for the Olathe, Kansas, water utility, in which he examined the relationship between land-use practices in Lake Olathe's watershed and the waterbody's raw water quality.

Dr. Lee also conducted a study on behalf of the Lubbock, Texas, water utility related to controlling THMs in its finished water by controlling the sources of organic carbon in its raw water derived from Lake Meredith. That was an unusual situation in that a freshwater sponge was growing in the raw water transmission line between the reservoir and the water utility; it developed to a thickness of a foot or more inside the pipe. The sponge was obtaining its nutrients from organics derived from in-line open reservoirs along the transmission line.

One of the areas that Dr. Lee has pioneered is the development of guidance to water utilities and others on how to design a water supply reservoir to minimize raw water quality problems. He presented a paper on this topic:

> Lee, G. F. and Jones, R. A., "Predicting Domestic Water Supply Raw Water Quality in Proposed Impoundments," IN: Proc. American Water Works Association 1984 Annual Conference Proceedings, pp 1611-1630 (1984).
> http://www.gfredlee.com/WSWQ/RawWQProposedImp84.pdf

Drs. Lee and Jones-Lee assisted the Municipal Water Supply Authority for Santo Domingo in the Dominican Republic to evaluate the adequacy of a proposed water treatment plant for treating the waters derived from a yet-to-be-developed water supply reservoir on a river. They were able to develop predictions of the raw water quality in the proposed reservoir based on land use in the reservoir's watershed. From that prediction, they concluded that the proposed water treatment plant would not be able to produce high-quality water, and recommended changes in the design of the treatment plant to more appropriately address the water quality characteristics that would be expected based on the proposed reservoir's watershed.

Dr. Lee has been active for many years in work on the impacts of releases from reservoirs on downstream water quality. For example he served as an advisor to the Tennessee Valley Authority and other agencies on the impact of reservoir releases on downstream water quality and co-authored a review on this topic:

> Krenkel, P. A., Lee, G. F. and Jones, R. A., "Effects of TVA Impoundments on Downstream Water Quality and Biota," IN: The Ecology of Regulated Streams, Plenum Press, New York, pp 289-306 (1979). [available upon request from gfredlee@aol.com.]

Another major concern about the impact of excessive fertilization on water quality is the utilization of dissolved oxygen in the bacterial decomposition of algae, which can lead to low dissolved oxygen or anoxic conditions in waterbodies. Drs. Lee and Jones-Lee served as the coordinating principal investigators for a $2-million CALFED project devoted to evaluating the cause and developing control programs, for the low dissolved oxygen problem in the San Joaquin River (SJR) Deep Water Ship Channel (DWSC) near the Port of Stockton. One of the primary causes of the dissolved oxygen depletion there is the oxygen utilization in the decomposition of algae that had developed upstream in the SJR. Upon entering the DWSC the algae settle, die and decompose; the decomposition depletes the oxygen resources of the channel. They developed a comprehensive synthesis report and supplementary discussion on that situation:

> 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 and CALFED Bay-Delta Program, G. Fred Lee & Associates, El Macero, CA, March (2003).
> http://www.gfredlee.com/SJR-Delta/SynthesisRpt3-21-03.pdf
>
> Lee, G. F. and Jones-Lee, A., "Supplement to Synthesis Report on the Low-DO Problem in the SJR DWSC," Report of G. Fred Lee & Associates, El Macero, CA, June (2004). http://www.gfredlee.com/SJR-Delta/SynthRptSupp.pdf

They have become involved in the issues of the development of appropriate approaches for controlling phosphorus from agricultural land runoff to improve those conditions, focusing in part on the comparative effects of controlling total phosphorus versus algal-available P in runoff waters. Dr. Lee's reviews,

> Lee, G. F., "A Proposal for Assessing Algal-Available Phosphorus Loads in Runoff from Irrigated Agriculture in the Central Valley of California," Report of G. Fred Lee & Associates, El Macero, CA, November (2006).
> http://www.gfredlee.com/Nutrients/AlgalAssayAvailP.pdf
>
> Lee, G. F., "Assessing Algal Available Phosphorus," Proceedings of US EPA Science Symposium: Sources, Transport, and Fate of Nutrients in the Mississippi River and Atchafalaya River Basins, Minneapolis, MN, November 7-9 (2006). http://www.gfredlee.com/Nutrients/AvailPEPASymp06.pdf

address those issues.

Drs. Lee and Jones-Lee are serving as advisors on the excessive fertilization of the Upper Mississippi River, examining the relative roles of agricultural land runoff and domestic wastewater sources in contributing to the problems. They are also working with the California Central Valley Regional Water Quality Control Board on the development of guidance for evaluating the water quality impact nitrogen and phosphorus in agricultural runoff/discharge and presented their findings in,

> Lee, G. F. and Jones-Lee, A., "Assessing the Water Quality Significance of N & P Compound Concentrations in Agricultural Runoff," Invited presentation to the Agrochemical Division, American Chemical Society national meeting, San Francisco, CA, September (2006). http://www.gfredlee.com/Nutrients/N-PRunoffACS.pdf
>
> Lee, G. F., and Jones-Lee, A., "Assessing Water Quality Significance of N & P Compound Concentrations in Agricultural Runoff," PowerPoint Slides for Invited Paper Presented at Agrochemical Division, American Chemical Society National Meeting, San Francisco, CA, September (2006).
> http://www.gfredlee.com/Nutrients/N-PSlidesACS.pdf

With support of the California State Resources Board they developed,

> Lee, G. F., and Jones-Lee, A., "Managing Nutrient (N & P) Water Quality Impacts in the Central Valley, CA," [Excerpts from: Lee, G. F. and Jones-Lee, A., "Review of Management Practices for Controlling the Water Quality Impacts of Potential Pollutants in Irrigated Agriculture Stormwater Runoff and Tailwater Discharges," California Water Institute Report TP 02-05 to California Water Resources Control Board/Central Valley Regional Water Quality Control Board, 128 pp, California State University Fresno, Fresno, CA, December (2002)], Report of G. Fred Lee & Associates, El Macero, CA (2002). http://www.gfredlee.com/SJR-Delta/CentralValleyNutrientMgt.pdf

That report presents a comprehensive review of nutrient evaluation/management issues.
More recently, Drs. Lee and Jones-Lee worked with the California Water Environmental Modeling Forum to develop a workshop devoted to Delta Nutrient Water Quality Issues. Information on that workshop is available in,

> Lee, G. F., and Jones-Lee, A., "Delta Nutrient Water Quality Modeling Workshop — Background Information," Report of G. Fred Lee & Associates, El Macero, CA, September (2007).
> [available at: http://www.gfredlee.com/Nutrients/NutrWorkshopRev4.pdf]

The workshop was held on March 25, 2008 in Sacramento, California. The workshop speakers PowerPoint slides are available on the CWEMF website page at:
http://www.cwemf.org/workshops/NutrientLoadWrkshp.pdf. A synopsis of the presentations made at this workshop are available at:

> Lee, G. F., and Jones-Lee, A., "Synopsis of CWEMF Delta Nutrient Water Quality Modeling Workshop – March 25, 2008, Sacramento, CA," Report of G. Fred Lee & Associates, El Macero, CA, May 15 (2008).
> http://www.gfredlee.com/SJR-Delta/CWEMF_WS_synopsis.pdf

These presentations provide a good overview of the nutrient related water quality problems in the Delta and in downstream waterbodies that receive Delta water.

Information on other of their nutrient-related activities is available on their website at http://www.gfredlee.com/pexfert2.htm.

Additional information on Dr. Lee and Dr. Jones-Lee's expertise in the evaluation and management of water supply water quality is available upon request from Dr. Lee.