PHYSICAL AND BIOGEOCHEMICAL PROCESSES IN ANTARCTIC LAKES
ANTARCTIC RESEARCH SERIES, VOLUME 59, PAGES 197-214

# THE RELATIONSHIP BETWEEN PHOSPHORUS LOAD AND EUTROPHICATION RESPONSE IN LAKE VANDA

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During the austral summer of 1980-1981, a study was undertaken on the applicability of the Vollenweider-Organization for Economic Cooperation and Development (OECD) phosphorus loading-eutrophication response relationships to Lake Vanda, a permanently ice-covered, meromictic lake located in the Wright Valley of Antarctica. The Vollenweider-OECD empirical relationships had been developed on the basis of load-response couplings for more than 300 lakes and reservoirs around the world that have a wide range of physical, chemical, and morphological characteristics. However, the Vollenweider-OECD empirical relationships had not been evaluated for their applicability to a body of water as oligotrophic as Lake Vanda or to one with its unusual physical and chemical characteristics. The Vollenweider-OECD phosphorus load-response models did indeed describe the relationships found for Lake Vanda when the model input was adjusted for the algal availability of the phosphorus load. Results of this study extend the range of conditions for types and trophic states of bodies of water for which the Vollenweider-OECD eutrophication models can be applied.

## INTRODUCTION

### *Scope of Study*

During the austral summer of 1980-1981, which is generally mid-November through January, we undertook a cooperative study with *Canfield and Green* [1985] to determine the relationships between nutrient load to Lake Vanda and the eutrophication-related water quality characteristics of that lake. The focus of this portion of the study was to evaluate the applicability of the empirical Vollenweider-Organization for Economic Cooperation and Development (OECD) phosphorus loading-eutrophication response relationships (models) (developed on the basis of several hundred waterbodies of diverse character around the world) to Lake Vanda, an ultraoligotrophic, permanently ice-covered lake that has unusual physical and chemical characteristics. To accomplish this study, the nutrient loadings to the lake and selected, associated eutrophication-related water quality response characteristics of the lake, as well as morphologic and hydrologic characteristics used in the normalization of the load, had to be determined and evaluated.

Even though data from a large number and a wide variety of bodies of water were used to develop these models, few oligotrophic bodies of water were evaluated in this framework for their phosphorus load-eutrophication response relationships. Since achievement and maintenance of low planktonic algal growth is a common water quality management goal, it is of interest to determine the applicability of these models to bodies of water with low algal biomass. This study presents a discussion of nutrient load-eutrophication response relationships for Lake Vanda in the light of the most recent updates of the Vollenweider-OECD eutrophication models. For convenience, we include in graphical and tabular forms certain relevant nutrient data developed for this study and previously published by *Canfield and Green* [1985]. We also include in graphical format the nutrient data of *Vincent et al.* [1981] and the hydrological data of *Chinn and Maze* [1983]. Readers are urged to refer to these works for methodological detail and commentary. The characteristics of "Vanda Bay" are presented here for the first time.

### *Nature of the Vollenweider-OECD Models*

During the mid-1970s, a cooperative study was conducted under the auspices of the Organization for Economic Cooperation and Development to examine and quantify relationships between the phosphorus loads to bodies of water and eutrophication-related water quality response of those bodies of water using the theoretical concepts for such relationships developed by *Vollenweider* [1968,1976]. A key component of the formulation of the basis for those relationships, developed by Vollenweider, was the normalization of the phosphorus load by the waterbody's mean depth, hydraulic residence time, and surface area.

The OECD eutrophication study included approximately 200 bodies of water (lakes and impound-

 

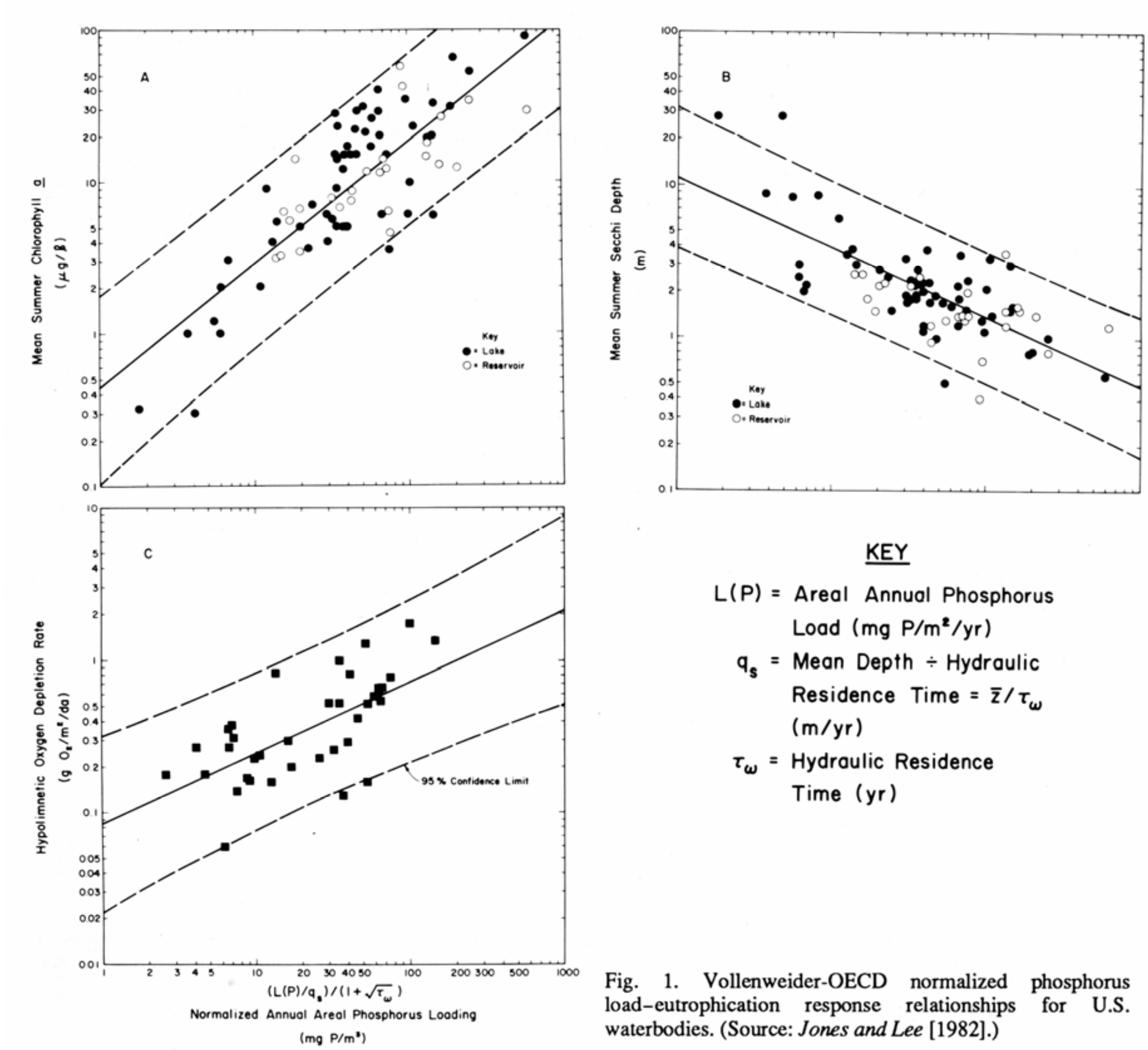


Fig. 1. Vollenweider-OECD normalized phosphorus load–eutrophication response relationships for U.S. waterbodies. (Source: *Jones and Lee* [1982].)

ments) in North America, Japan, Australia, and 14 countries in Western Europe. The U.S. portion of that study, which included more than 30 bodies of water or parts thereof, was completed in 1976; the relationships identified were published in a U.S. Environmental Protection Agency (EPA) report [*Rast and Lee*, 1978] and by *Lee et al.* [1978]. The remaining results were subsequently published by the *Organization for Economic Cooperation and Development* [1982].

Through the U.S. OECD and overall OECD eutrophication studies and through Vollenweider's concepts, empirical models were developed that describe the relationships between phosphorus loading to bodies of water and their eutrophication-related water quality responses, as measured by several characteristics, including water greenness (chlorophyll concentration), water clarity (Secchi depth) for nonturbid to moderately turbid systems, and rates of oxygen depletion in the hypolimnia.

Figure 1 presents the Vollenweider-OECD normalized phosphorus load-eutrophication related water quality response relationships (models) that were developed on the basis of data from U.S. bodies of water. It shows the regression relationships between phosphorus load (normalized by mean depth, hydraulic residence time, and surface area) and the water quality response parameters of chlorophyll, Secchi depth and hypolimnetic oxygen depletion rate.

Subsequent to our work on U.S. OECD water-bodies, we continued to evaluate the relationships between nutrient load and eutrophication-related water quality response, using the Vollenweider-

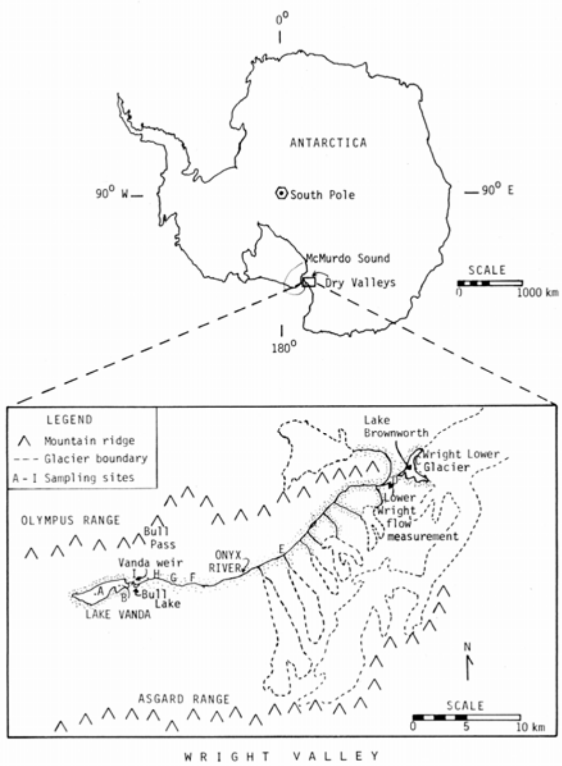


**Fig. 2. Location of Lake Vanda and the sampling sites for the cooperative study.**

OECD eutrophication modeling approach for other bodies of water in the United States and elsewhere. *Jones and Lee* [1982] presented an update and a review of the use and applicability of those models and updated the findings and the models again in 1986 to include data on other OECD bodies of water and on more than 100 other lakes and impoundments [*Jones and Lee*, 1986]. As discussed subsequently, the updating of the normalized phosphorus load-chlorophyll response relationship [*Jones and Lee*, 1986] revealed that the regression illustrated in Figure 1*a* remained unchanged. The bodies of water upon which the models were developed span a wide range of size and depth and of climatic, geologic, and trophic characteristics. The use and capability of these models to predict changes in eutrophication-related water quality characteristics after phosphorus load changes have been documented by *Rast el al.* [1983].

### *Review of Characteristics of Lake Vanda and the Onyx River*

Lake Vanda is situated in a closed bedrock basin in the western portion of the ice-free Wright Valley, Antarctica, about 35 km west of McMurdo Sound (Figure 2). The area is arid. There is no rainfall, and snowfall tends to sublime rather than to melt [*Chinn*, 1980], normally leaving the valley bare of snow. Lake Vanda is about 5.6 km long and 1.4 km wide, has a maximum depth of about 67 m at its "deep hole" [*Nelson and Wilson*, 1972], and is permanently covered with 3 to 4 m of ice. During the warmer austral summer months, the ice opens around the edges of the lake to form a "moat."

Lake Vanda is fed by the approximately 28-km-long Onyx River, which originates at the Wright Lower Glacier 17 km from the lake (Figure 2). In 1969, under the direction of the New Zealand Antarctic Division of the Department of Scientific and Industrial Research, a V-notch stream-gaging weir was constructed in the Onyx River 0.5 km upstream from Lake Vanda (Figure 2.). (The New Zealand Ministry of Works and Development publishes its records of the daily mean discharges of the Onyx River at the Vanda weir (see *Chinn*, this volume).) The record for the decade prior to our study is shown in Figure 3. The river flow typically begins in mid-December and continues into early February, with about three periods of peak discharge. Except for the unusually high flow found in the 1970-1971 season, maximum mean daily discharge tends to be about 1500 L $s^{-1}$ and total flows tend to range between $1\times10^6$ and $3\times10^6$ $m^3$ $yr^{-1}$. With no water outlet from the lake, the water balance of Lake Vanda is maintained by sublimation of ice from the lake surface caused by the strong katabatic winds from the plateau to the west [*Ragotzkie and Likens*, 1964]. During the decade prior to our study, the cumulative lake level remained rather constant [*Chinn and Maze*, 1983].

Lake Vanda is meromictic and is stratified into two major layers, with a transition zone between them (Figure 4). The waters in the upper, mixed layer, which extends approximately to the 45- to 50-m depth at the deep hole, are essentially fresh; those below have a maximum salinity about 2.6 times that of seawater. Figure 4 shows specific conductance and temperature profile information on the deep hole of Lake Vanda during the time of our study.

The dissolved oxygen profile at the deep hole during our study in the austral summer of 1980-1981, as reported by *Canfield and Green* [1985], showed concentrations in the upper, mixed zone to range from about 18 to 22 mg $L^{-1}$. Between the 50-m and 55-m depths, the dissolved oxygen concentration steadily increased from 18 to 22 mg $L^{-1}$. Beneath the 55-m depth, the dissolved oxygen concentration steadily decreased with depth until no measurable dissolved oxygen was found at 60 m. This pattern is

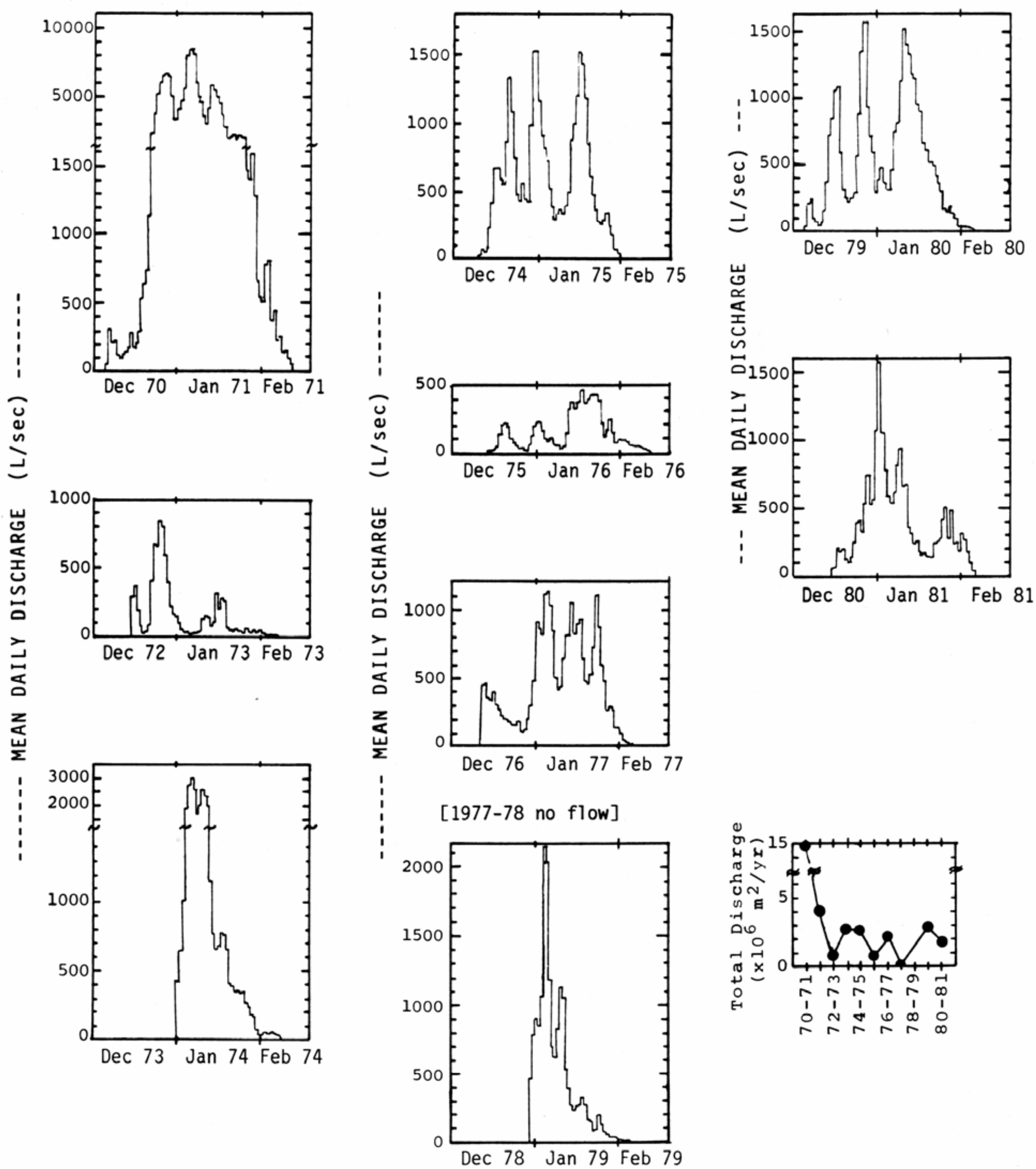


Fig. 3. Onyx River daily average discharge and total flow records. (Source of data: New Zealand Ministry of Works and Development annual reports on hydrology and glaciology, dry valleys, Antarctica.)

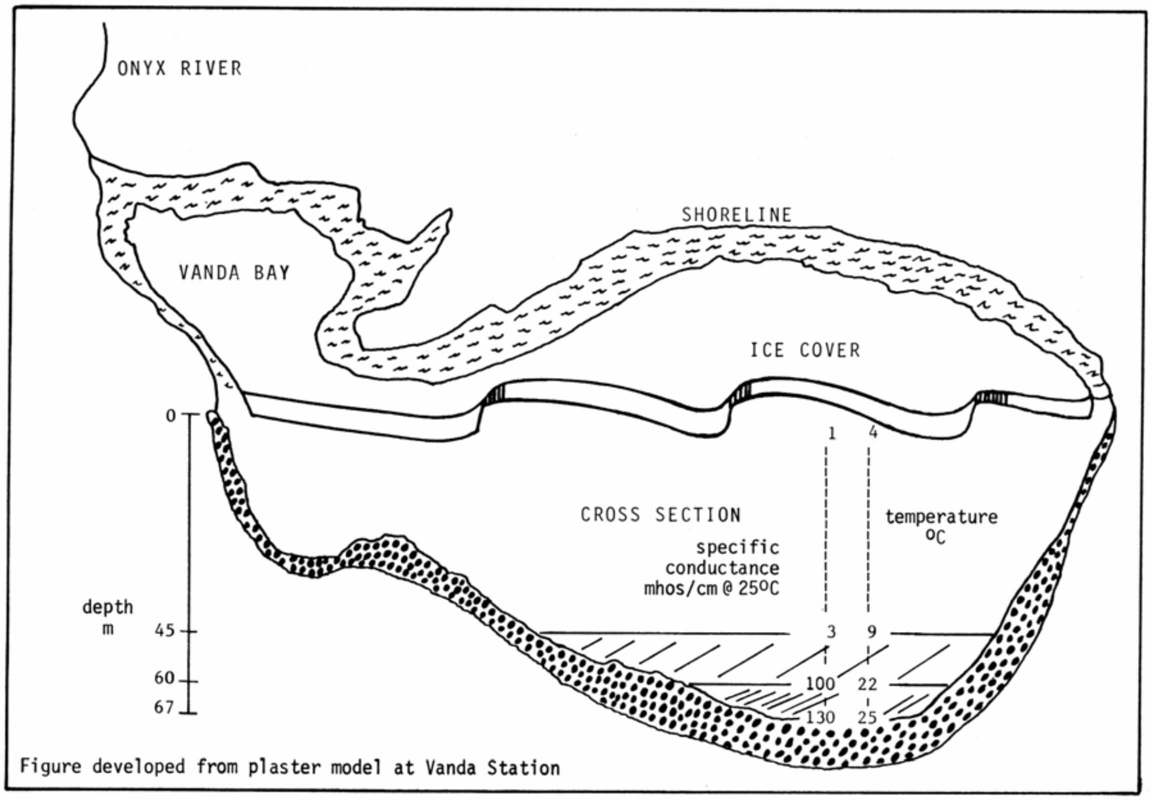


Fig. 4. Cross section view of Lake Vanda with temperature and specific conductance profiles for December 1980 (developed from a plaster model at Vanda Station). (Source of data: *Vincent et al.* [1981].)

consistent with that reported by *Parker et al*. [1982] for the austral summer of 1977-1978. The higher concentrations between the 50- and 55-m depths would be expected because of the planktonic algal layer just at the edge of the brine/freshwater interface. That increase in dissolved oxygen concentration represents an even greater increase in degree of dissolved oxygen super-saturation because of the warming of the water with depth. *Benoit et al*. [1971] attributed the presence of elevated dissolved oxygen concentrations in the water column to a combination of dissolved oxygen production from algal photosynthesis and the inability of dissolved oxygen to escape to the atmosphere through the ice cover. However, *Love et al*. [1983] reported that air exhausted by their scuba divers was observed to pass quickly through the ice cover. Elevated concentrations of sulfide and ammonia, which may result from the decomposition of sinking organic matter, have been measured in the saline bottom waters by *Benoit et al*. [1971] and *Canfield and Green* [1985].

*Goldman et al*. [1967] estimated from their February 1963 study that 1% of the incident unfiltered surface radiation reached a depth of more than 50 m in Lake Vanda. They reported depth-averaged carbon uptake rates attributed to photosynthesis of only 14 mg of C per square meter per day, which, on the basis of a 60-m euphotic zone, was equivalent to 0.24 mg of C per cubic meter per day. Those rates are higher than the areal production rates determined by *Parker et al*. [1982] in the austral summer of 1977-1978 of 1.9 mg of C per square meter per day; *Parker et al*. [1982] also reported that the light penetration was less than it had been in 1963 during Goldman et al.'s study. *Goldman et al*. [1967] indicated that the volume-based carbon fixation rate in Lake Vanda was at a maximum between the 55- and 60-m depths; there the rates were several times higher than they were in the upper waters. *Parker et al*. [1982] did not sample at the 57-to 60-m depth. The dramatically higher rate of photosynthesis in the warmer brine layer, where the temperature is as high as 25°C, led *Goldman et al*. [1967] to suggest that one of the primary limitations to organic production in Lake Vanda is temperature. However, *Vincent and Howard-Williams* [1985] reported that their more recent work did not support that suggestion.

The measurement of primary productivity estimates the rate at which algae grow. A key concern in the assessment and management of eutrophication-related water quality, however, is the algal biomass present; relationships between those two parameters are not well-defined. Previous assessments of algal biomass (chlorophyll) are limited and are discussed with the presentation of data for our study.

Until recently, nutrient limitation of algal growth in Lake Vanda had not been addressed in detail in the literature. *Goldman et al*. [1967] reported that Goldman's previous work showed that the addition of nitrate to samples of littoral waters of the lake caused considerable stimulation of carbon fixation, whereas addition of phosphorus did not. *Nakaya et al.* [1977] and *Torii and Yamagata* [1981] reported nitrogen and phosphorus concentrations in the Onyx River and Lake Vanda in the early 1970s, but the detection limits for the phosphorus determinations were not low enough to be used in nutrient limitation work. *Vincent et al*. [1981] and *Vincent and Vincent* [1982] made measurements of nitrogen and phosphorus in Lake Vanda during the austral summer of 1980-1981 and reported that there was a tendency for phosphorus limitation in Lake Vanda.

*Canfield and Green* [1985] reported the concentrations of nitrogen and phosphorus in the Onyx River and Lake Vanda in the austral summer of 1980-1981. While they computed ratios of average nitrate and phosphorus concentrations in the Onyx River and Lake Vanda, such ratios do not demonstrate which, if any, nutrient limits the growth of phytoplankton in the lake [see *Lee and Jones*, 1981, and *Rast et al*., 1983].

## METHODS

### Nutrient Loads

The primary source of nutrients to Lake Vanda is the Onyx River. The nutrient loads to the lake for the year of study were estimated by multiplying the concentrations of significant forms of nutrients in the river by the daily average flows of the river at the Vanda weir. The records of daily average discharge at that location for the study period were obtained from *Chinn and Maze* [1983]. We computed daily loads of total phosphorus, condensed phosphorus, soluble orthophosphate, and nitrate by multiplying measured concentrations by the daily mean discharges. For days on which concentrations were not measured, the average of the last measurement and the next measurement was used for all days in between. The daily loads were summed to yield the total loads for the year.

### In-Lake Characteristics

In order to estimate the average in-lake (mixed-layer) concentrations of nutrients, the average concentrations in 50 m of the water column were multiplied by the volume of the lake to that depth. The volume computations were based on the hypsometric characterization of the lake bed developed by *Nelson and Wilson* [1972], who determined the area of the lake at approximately 5- to 10-m depth intervals. G. Simmons and his colleagues from Virginia Polytechnic Institute and State University melted a circular diving hole through the permanent ice cover, and Secchi depth was measured by lowering a 20-cm black-and-white Secchi disk through the hole.

### Chemical Analytical Procedures

*Canfield and Green* [1985] described the procedures used for analysis of water samples for nitrogen compounds, total phosphorus, and soluble orthophosphate. Condensed phosphate measurements were made following the procedures of the *American Public Health Association (APHA) et al.* [1975], which involve mild acid hydrolysis of the samples. Ordinarily this procedure is used to measure the concentrations of pyrophosphates and tripolyphosphates that are incorporated, as builders, in detergent formulations. It would not be expected that there would be detergent phosphorus in the waters of Lake Vanda or the Onyx River because the introduction of wastewaters to the lake and river is strictly prohibited. The condensed phosphate analyses, as performed in this study, therefore, measure the sum of soluble orthophosphate, phosphorus that is easily leached from solids in the sample at pH 1, and the organic phosphorus that is easily hydrolyzed.

Concentrations of chlorophyll *a* and pheophytin were determined using the fluorometric method described by *APHA et al*. [1975]. Samples (200 mL each) were filtered through 0.45-µm pore size membrane filters that were then extracted with 90% acetone for 24 hours. Fluorescence was measured on a Turner fluorometer specifically equipped for determination of chlorophyll. Chlorophyll concentrations were corrected for pheophytin, as prescribed by *APHA et al.* [1975]. Specific conductance was measured with a Yellow Springs Instrument Co. model 33 SCT meter. Values were corrected mathematically to 25°C; laboratory determination of the change in conductance with temperature for these waters showed a 2.5% increase in conductance per Celsius degree increase.

TABLE 1. Concentrations of Nutrients in Onyx River at Lake Vanda (Austral Summer of 1980–1981)

| Date/Hour | Specific Conductance, µmho/cm* | Soluble Orthophoshpate,† µg P per liter | Total Phosphorus,† µg P per liter | Condensed Phosphorus, µg P per liter | Nitrate,† µg N per liter | Nitrite,† µg N per liter |
|---|---|---|---|---|---|---|
| December 1980 | | | | | | |
| 14/1500 | 442 | ... | 150 | ... | 359 | 6.5 |
| 15/0445 | ...‡ | ... | 9.4 | ... | 89 | 4.8 |
| 16/2200 | 132 | 0.8 | 10 | ... | 50 | 3.6 |
| 17/1205 | 129 | 2.0 | 13 | ... | 66 | 3.2 |
| 23/1400 | 112 | 1.3 | 6.8 | 1.8 | 10 | <0.4 |
| 23/2300 | 96 | ... | 7.7 | ... | 10 | ... |
| 24/0800 | ... | ... | 4.8 | 2.6 | 8.1 | <0.4 |
| 24/2100 | 102 | 1.0 | 7.2 | ... | ... | <0.4 |
| 25/1300 | 88 | 0.9 | ... | 2.8 | 6.6 | ... |
| 26/1000 | 105 | ... | 6.3 | 1.0 | 8.0 | <0.4 |
| 26/2300 | 104 | 1.8 | 6.2 | ... | 4.8 | <0.4 |
| 27/1000 | 112 | ... | ... | 1.1 | ... | ... |
| 28/0900 | 101 | ... | 7.3 | 1.1 | 8.4 | <0.4 |
| January 1981 | | | | | | |
| 6/1415 | ... | 0.8 | 4.4 | ... | 3.3 | <0.4 |
| 6/2200 | ... | ... | 5.2 | 1.0 | 4.5 | <0.4 |
| 8/0935 | ... | ... | ... | 2.3 | 4.3 | <0.4 |
| 8/2345 | 85 | 0.8 | ... | ... | 3.1 | ... |
| 17/2200 | 91 | ... | 5.9 | ... | ... | ... |
| 18/2200 | 90 | ... | 3.9 | ... | ... | <0.4 |

*At 25°C. Measured value was mathematically corrected from an estimated ambient temperature of 3°C.
†Source of graphically presented data: *Canfield and Green* [1985].
‡Dots indicate parameters not measured.

## RESULTS

### *Nitrogen and Phosphorus Loads*

*Chinn and Maze* [1983] reported the daily mean discharge for the Onyx River at the Vanda weir during the austral summer of 1980-1981. During that summer, the Onyx River flow reached the Vanda weir on December 14 (Figure 3), which according to *Chinn and Maze* [1983] is close to the average date for first flows to pass over that weir. The maximum daily discharge for the season occurred on January 1, when the discharge reached nearly 1600 L $s^{-1}$. The Onyx River continued to flow until about February 5, providing a total water input for 1980-1981 of $1.8\times10^6$ $m^3$ [*Chinn and Maze*, 1983], which is about average for the annual flows recorded (Figure 3). Discharge during the previous year (1979-1980) had been at the upper end of the range found in recent years [*Chinn and Oliver*, 1983].

Specific conductance and concentrations of nitrogen and phosphorus compounds were measured in samples collected in the Onyx River at the Vanda weir periodically between December 14, 1980, and January 18, 1981. These data are presented in Table 1. The first sample for nutrient analysis was collected 10 min after the first water passed over the weir. That sample contained disproportionately high concentrations a total phosphorus, nitrate, and nitrite, as well as specific conductance, compared to levels found in subsequent samples collected there. As illustrated in Figure 5, the first sample represents the flushing of the system of the previous year's accumulated materials. It was also suggested by *Vincent and Howard-Williams* [1985] that accumulations of windblown materials at the surface of the glaciers supplying the water contributed to the elevated initial concentrations of nutrients in the Onyx River. Concentrations in the river decreased steadily with time.

The total phosphorus concentration in the first sample collected at the Vanda weir was 150 µg P per liter; it decreased over the monthlong sampling period to about 4 µg P per liter. The daily total phosphorus loads, plotted in Figure 6, show that while the water flowing over the weir initially contained a relatively high concentration of total phosphorus, flushing contributed only a small portion of that year’s total phosphorus load to the lake. The greatest portion of the 10.5 kg total phosphorus load

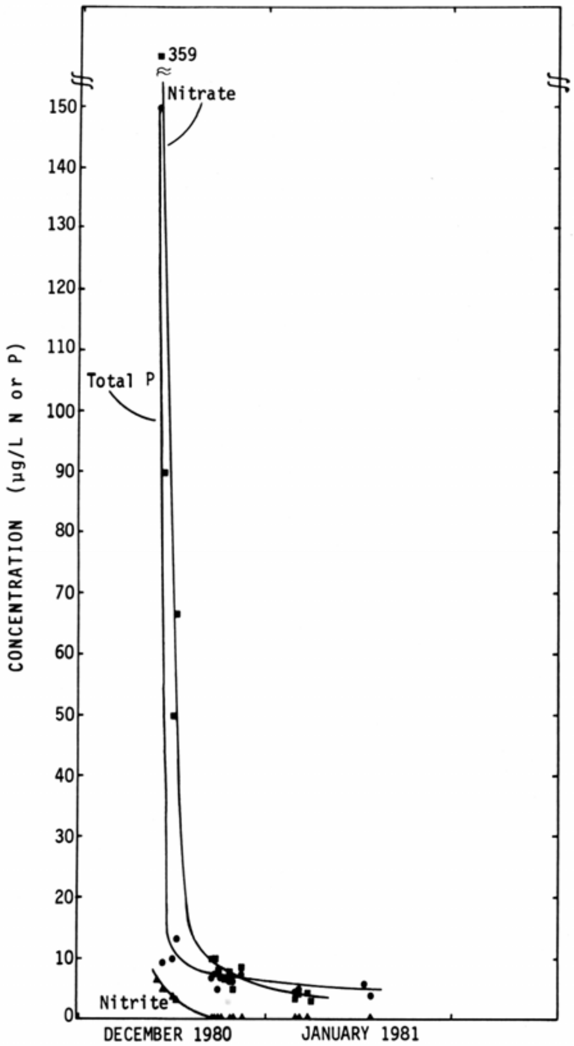


Fig. 5. Concentrations of nitrogen and phosphorus at Vanda weir, austral summer of 1980–1981.

for the 1980-1981 season was contributed during the high flows between late December and early January.

Soluble orthophosphate, the form of phosphorus that is readily available to support planktonic algal growth, was measured on eight samples of the Onyx River water collected at the Vanda weir [*Canfield and Green*, 1985]. As shown in Table 1, the soluble orthophosphate concentrations ranged from 0.8 to 2 µg P per liter. The estimated daily loads of soluble orthophosphate to Lake Vanda are presented in Figure 6. Soluble orthophosphate represented about 18% of the total phosphorus load for the year of study.

The concentrations of condensed phosphate in the 8 Onyx River samples collected at the Vanda weir during the study (Table 1) ranged from 1 to 2.8 mg P per liter. The condensed phosphate load for 1980-1981 is estimated to have been 3.1 kg, about 30% of the total phosphorus load to the lake. It has been found [*Lee et al.*, 1980] that generally only part of the phosphorus measured after the mild acid treatment of the condensed phosphate test would likely become available to support algal growth. It is highly unlikely that any of the phosphorus not measured by this technique would be converted to a form that would support algal growth. These results indicate that a substantial part of the total phosphorus measured in the Onyx River water at the weir, about 70%, is not likely to be available to support algal growth in Lake Vanda. This is an unusually high proportion of the total phosphorus load that is unavailable, compared with that found for many other lakes.

Nitrate, nitrite, and ammonia are the forms of nitrogen that are readily available for algal growth. Examinations of Table 1 and Figure 5 show that the concentration of nitrate in the Onyx River at the Vanda weir decreased steadily during the first week of flow and by the second week in January was on the order of 3 to 5 µg $L^{-1}$ N. That pattern also appears to have been related to a flushing from the river system of nitrate that had accumulated the previous year. Similarly, the nitrite concentrations decreased from about 6.5 µg N per liter on December 14 to levels below detection (<0.4 µg N per liter) during the remainder of the sampling period beginning on December 23. Ammonia was measured in samples collected December 24 and January 18 and was found to have been below the lower detection limit of 2 µg N per liter. The daily loadings of nitrate, which would be expected to be approximately equal to the loadings of total nitrogen, are plotted in Figure 7. Most of the nitrogen appears to have entered the lake in mid- to late December. The total loading of nitrate for the year of the study was estimated to be 13.4 kg N per year.

### *Characteristics of Lake Vanda*

The waters of Lake Vanda were characterized at the deep hole in the main body of the lake at the site labeled A in Figure 2. In addition, a profile characterization was made of “Vanda Bay," at the site labeled B in Figure 2. W. Vincent and associates were studying Lake Vanda and the Onyx River at the time that our study was being conducted. Their results, which were from the same sampling locations, have augmented and supported the data collected here. At the time of sampling for our study, the water appeared to be mixed down to about 45 m, on the basis of specific conductance and temperature profiles developed by *Vincent et al*. [1981].

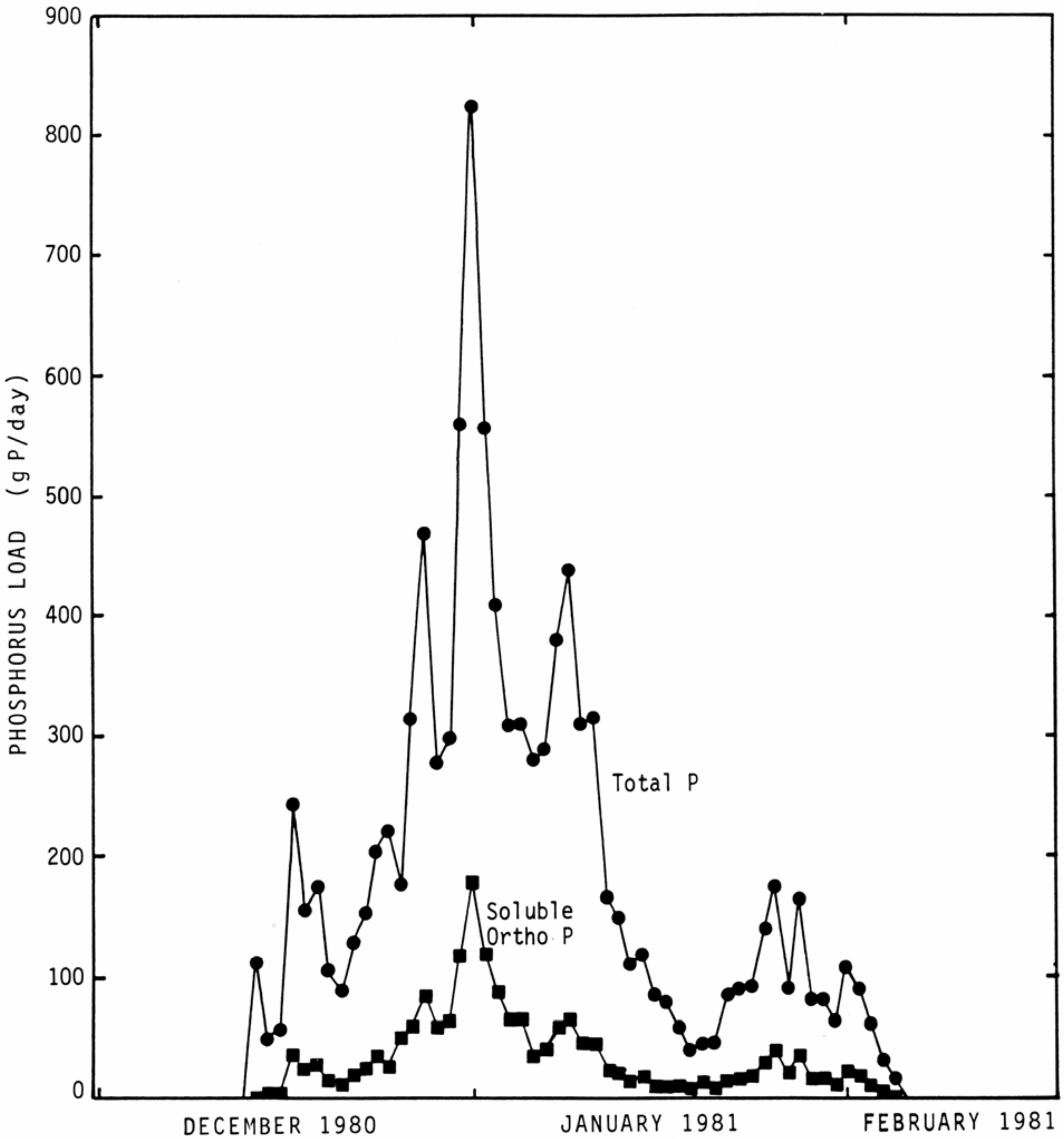


Fig. 6. Daily phosphorus loading to Lake Vanda from Onyx River, austral summer of 1980–1981.

Table 2 presents the characteristics of Lake Vanda measured for our study. Figure 8 gives the concentrations of total phosphorus and soluble orthophosphate measured by *Vincent et al.* [1981] and those concentrations reported by *Canfield and Green* [1985] in samples collected for our study in December 1980 from the deep hole of Lake Vanda. The concentrations reported by *Vincent et al.* [1981] for soluble orthophosphate in the water column (determined after filtration with a glass fiber filter rather than a membrane filter) were similar to those found in our study at the same location 1.5 to 2.5 weeks earlier. Soluble orthophosphate concentrations ranged from 0.4 to about 0.9 µg P per liter in the uppermost 45 m, the mixed layer. After reaching a minimum concentration at about 50 m, the concentra-

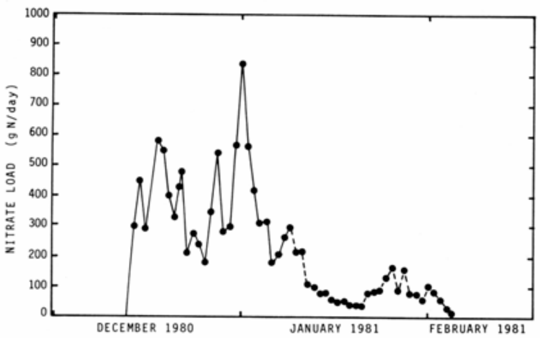


Fig. 7. Daily nitrate loading to Lake Vanda from Onyx River, austral summer of 1980–1981.

tions increased markedly at the 55-m depth and below, to 100 µg P per liter at 65 m. The minima found at the 50-m depth are consistent with the findings of elevated planktonic algal production at that depth. The concentrations of algal-available phosphorus in the mixed layer were sufficiently low to limit the production of planktonic algae.

Total phosphorus concentrations ranged from about 7 to 12 µg $L^{-1}$ in the uppermost 50 m, below which they increased with depth to 215 µg $L^{-1}$ at 65 m. The pattern of increasing phosphorus concentrations in the bottom waters of Lake Vanda is consistent with the fact that below about 60 m the waters are anoxic, a condition that would promote the release of iron-associated phosphorus from sediments. Because of the salt barrier to the mixing of the surface and bottom waters, the elevated concentrations of phosphorus remain trapped below the halocline.

Figure 9 presents the concentrations of nitrate, nitrite, and ammonia measured in the deep hole of Lake Vanda on December 11, 1980, for our study by *Canfield and Green* [1985], as well as those concentrations reported by *Vincent et al.* [1981] for samples collected at the same location 1.5 and 2.5 weeks later. In general, the concentrations of nitrite and ammonia reported for both studies were about the same; the patterns of concentration of both parameters with depth were also the same. Concentrations of each decreased with depth to about 35 m; beneath they increased substantially, to about 0.01 to 0.03 mg N per liter (nitrite) and 2 to 3 mg $L^{-1}$ N (ammonia) at the 45-to 55-m depth. Beneath 55 m, the concentrations of nitrite decreased to below detectable levels, whereas ammonia increased to about 7 mg N per liter during this study period and to 24 mg $L^{-1}$ N, as reported by *Vincent et al.* [1981]. The nitrate concentrations measured in the two studies were measurably different in the upper, mixed layer, although the patterns of concentration with depth were about the same. Nitrate concentrations decreased with depth to 25 to 35 m, beneath which they increased substantially (Figure 9).

From their work on microbial activity, *Vincent et al.* [1981] found that the rate of nitrification was greatest at about 55 m, whereas the rate of denitrification was greatest at about 62 m. This is consistent with the concentration patterns shown in Figure 9. The concentrations of algal-available nitrogen (nitrate, nitrite, and ammonia) in the mixed layer during the study were 0.03 to 0.1 mg N per liter. These levels are above those which would be expected to limit the growth of algae.

During the austral summer of 1980-1981, *Vincent and Vincent* [1982] measured the chlorophyll concentrations at the deep hole of Lake Vanda. Their data and ours are presented in Figure 10; ours are

TABLE 2. Characteristics of Lake Vanda, Deep Hole, December 11, 1980

| Depth, m | Total Phosphorus,* µg P per liter | Soluble Orthophosphate,* µg P per liter | Chlorophyll *a*,† µg $L^{-1}$ | Pheophytin, µg $L^{-1}$ |
|---|---|---|---|---|
| 5 | 11.0 | 0.60 | 0.079 | <0.005 |
| 15 | 9.9 | 0.78 | 0.022 | 0.074 |
| 25 | 7.3 | 0.87 | 0.045 | 0.014 |
| 35 | 7.0 | 0.73 | 0.13 | <0.005 |
| 45 | 7.0 | 0.40 | 0.051 | <0.005 |
| 48 | 12.5 | 0.40 | 0.045 | <0.005 |
| 51 | 7.4 | <0.01 | 0.090 | <0.005 |
| 54 | 15.8 | 0.66 | 0.017 | 0.012 |
| 57 | 22.4 | 13 | 0.96 | <0.005 |
| 60 | 87 | 20.4 | 0.52 | 0.013 |
| 65 | 215 | 100 | 0.60 | 0.022 |

*Data from *Canfield and Green* [1985, Table 2].
†Values corrected for pheophytin.

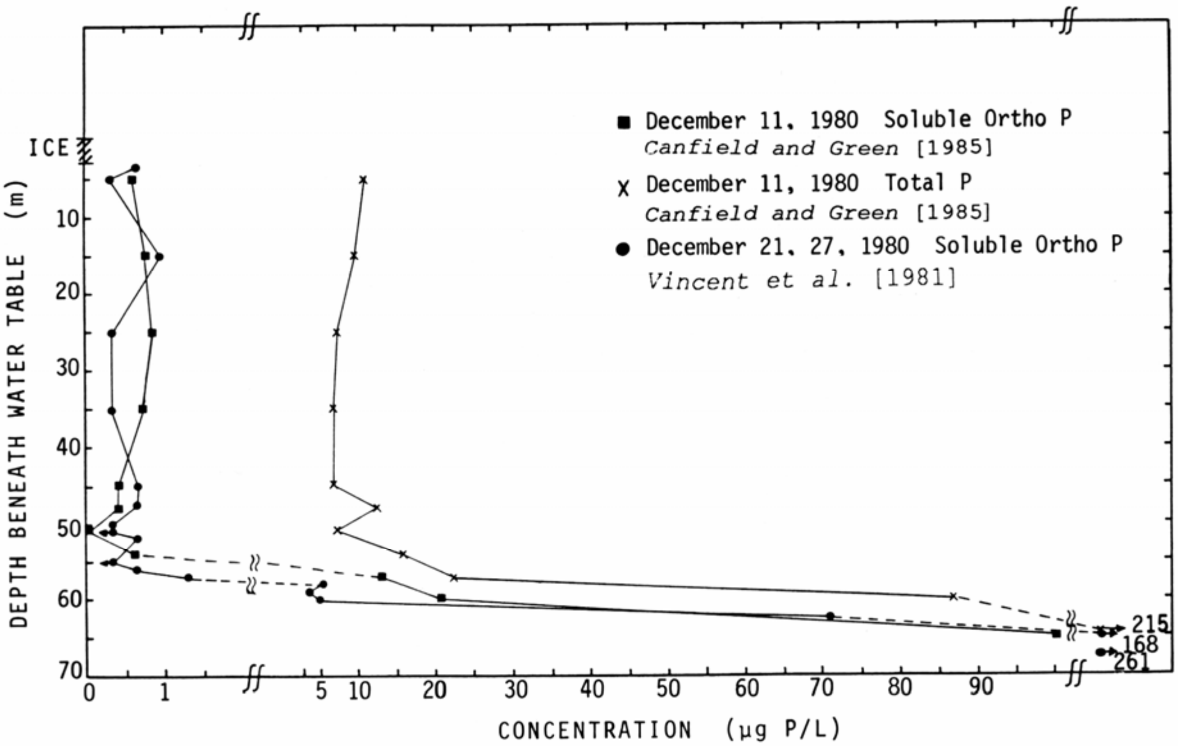


Fig. 8. Total phosphorus and soluble orthophosphate concentration profiles of Lake Vanda, austral summer of 1980–1981.

also given in Table 2. *Vincent and Vincent* [1982] used glass fiber filtration and boiling methanol extraction rather than the acetone extraction procedure we used. The method used by *Vincent and Vincent* [1982] tends to have greater extraction efficiency but less recovery, owing to the pore sizes in the glass fiber filter. The data of *Vincent and Vincent* [1982] were also not corrected for pheophytin. Nonetheless, as shown in Figure 10, the chlorophyll concentrations determined by *Vincent and Vincent* [1982] on December 13 and January 11 were consistent with those that we measured on samples collected on December 11. In the upper 45 m of the water column, concentrations ranged from about 0.025 to 0.13 µg $L^{-1}$. The average mixed-layer chlorophyll concentration we found was 0.06 µg $L^{-1}$, which was the same as the average found by *Vincent and Vincent* [1982].

As shown in Figure 10, as the lower boundary of the mixed layer was approached from above, the chlorophyll concentrations increased markedly to nearly 1 µg $L^{-1}$ at about 57 m. That pattern was found by *Vincent and Vincent* [1982] and by us. It is also consistent with the photosynthetic rate characteristics determined by *Vincent et al.* [1981] for the same period. They found the maximum $CO_2$ fixation rate, about 1.6 mg of C per square meter per day, to occur at the 57-m depth. This is also what *Goldman et al*. [1967] reported at that depth in their investigation in the early 1960s. The increased algal biomass and growth rate in the deeper waters can be attributed to a combination of factors, such as increased temperature and diffusion of nutrients from the brine layer to the overlying waters. *Green and Canfield* [1984] showed that the concentrations of salts in the water above the brine layer are diffusion-controlled. The water column profiles during the 1980-1981 study showed that algal growth was beginning its increase at the 50-m depth, at the bottom of the mixed layer, where it appeared to have depleted the concentration of soluble orthophosphate to <0.01 µg P per liter (<0.04 µg $L^{-1}$ reported by *Vincent and Vincent* [1982] (Figure 8)). Beneath that depth, additional algal growth was promoted by the diffusion of available phosphorus from the brine layer, as shown by the concentration profile in Figure 8.

It is important to evaluate whether there is adequate light reaching the 50- to 55-m depth to allow the algae, as measured by chlorophyll, to be actively photosynthesizing. The compensation depth of lakes is typically equal to about 2.5 to 3 times the Secchi depth. Secchi depth, measured through the diving hole near the deep hole of Lake Venda during our

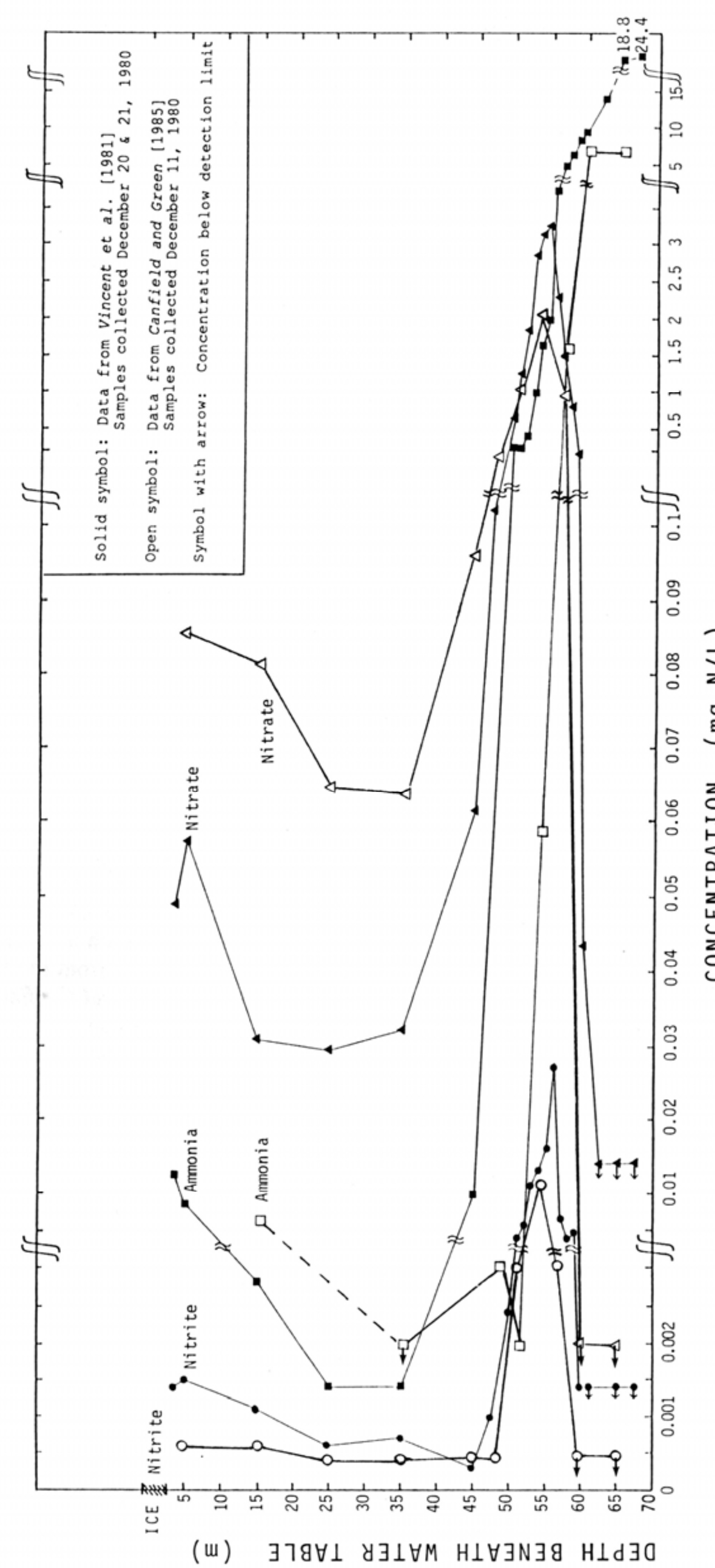


Fig. 9. Nitrogen concentration profiles of Lake Vanda, austral summer of 1980–1981.

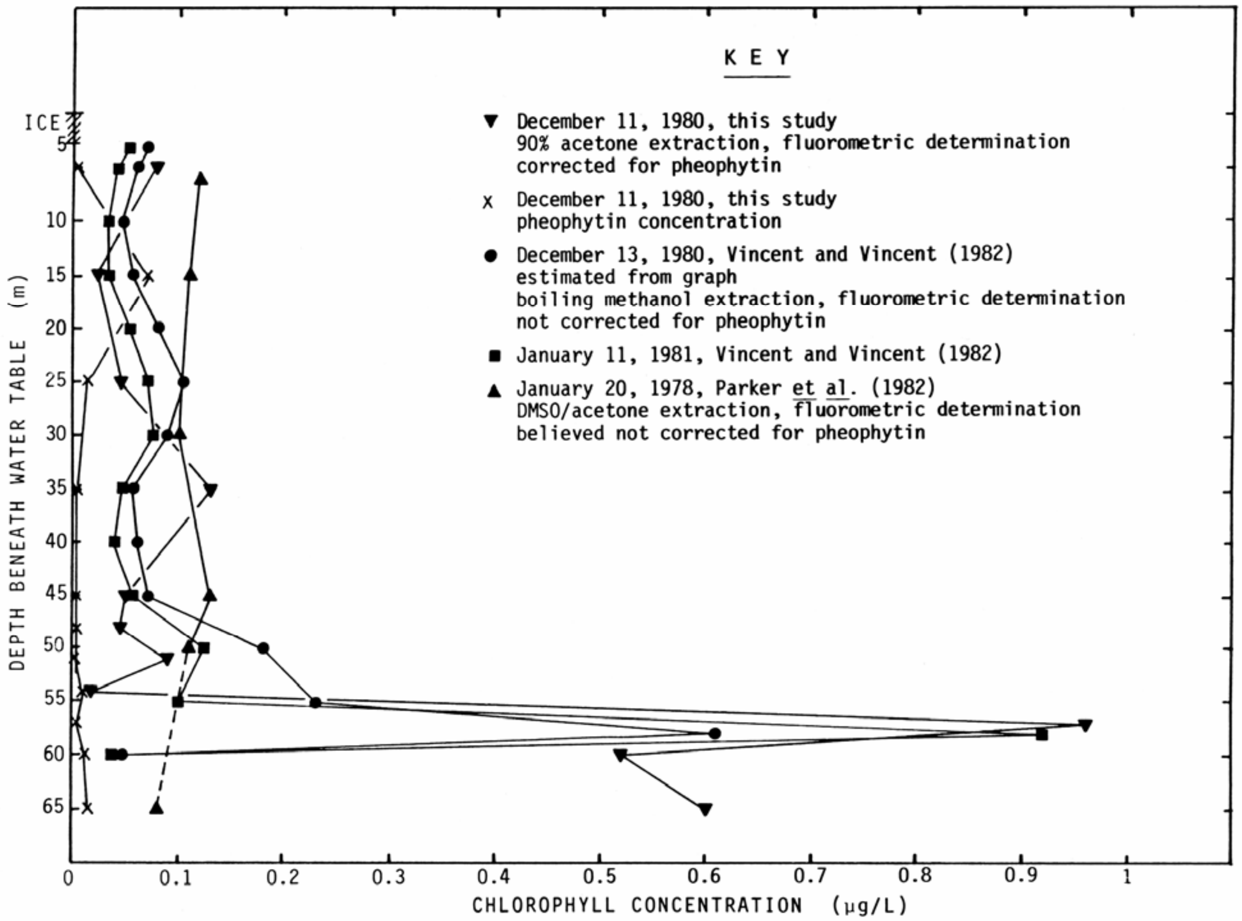


**Fig. 10.** Chlorophyll concentration profiles of Lake Vanda.

study, was 22 m. It is not known whether sediment was stirred into the water column during prior diving activity and decreased the clarity of the water in the region of the hole where the Secchi depth measurements were made. It has been reported that the algal mat at the bottom of the lake can be sloughed by turbulence [*Love et al.*, 1983]. Thus increased turbidity may have occurred because of diving, which may have resulted in a somewhat lower Secchi depth value than is characteristic for the lake. The compensation depth estimated from Secchi depth (55 to 66 m) indicates that there might be adequate light down in the brine layer to allow substantial algal photosynthesis there, although the ice cover might cause the depth of actual light penetration to be less than that estimated. This estimation is in keeping with the notation made by *Goldman et al.* [1967] that the compensation depth for the lake was below the 50-m depth. Furthermore, primary productivity data of *Vincent and Vincent* [1982] from 24-hour *in situ* incubations during the austral summer of 1980-1981 showed that the greatest rate of primary production occurred at about the 58-m depth, indicating that algae were actively photosynthesizing at that depth.

*Parker et al.* [1982] measured chlorophyll concentration with depth in Lake Vanda on January 20, 1978. They used dimethyl sulfoxide/acetone extraction to effect greater chlorophyll extraction. The concentrations *Parker et al.* [1982] measured in the mixed layer were consistently somewhat greater than those found by *Vincent and Vincent* [1982] and by us during 1980-1981, although the concentrations were of the same order (average: 0.12 μg $L^{-1}$). *Parker et al.* [1982] did not identify the layer of elevated chlorophyll at 57 m, and they did not analyze samples from that region.

### *Characteristics of "Vanda Bay"*

Table 3 presents the profiles of temperature, dissolved oxygen, specific conductance, and chlorophyll concentration in "Vanda Bay" (see B in Figure 2) on December 16, 1980. The temperature of the water beneath the ice cover increased somewhat

TABLE 3. Characteristics of "Vanda Bay," December 16, 1980

| Depth,* m | Temperature, °C | Dissolved Oxygen, mg $L^{-1}$ | Specific Conductance, µmho/cm† | Chlorophyll, µg $L^{-1}$ | Pheophytin, µg $L^{-1}$ |
|---|---|---|---|---|---|
| 0.3 | 0.1 | ...‡ | 583 | ... | ... |
| 1 | 0.2 | ... | 585 | ... | ... |
| 2 | 0.2 | ... | 588 | ... | ... |
| 2.5 | 0.2 | 10.4 | ... | ... | ... |
| (Bottom of ice) | | | | | |
| 3 | 0.3 | 11.2 | 588 | ... | ... |
| 3.5 | 4.5 | ... | 1066 | ... | ... |
| 4 | 4.5 | 22 | 1066 | 0.047 | <0.005 |
| 5 | 4.9 | 22.4 | 1058 | ... | ... |
| 6 | 4.9 | 22.4 | 1058 | ... | ... |
| 7 | 5.0 | 22.6 | 1056 | ... | ... |
| 8 | 5.0 | 22.6 | 1067 | 0.038 | <0.005 |
| 9 | 5.0 | 22.6 | 1067 | ... | ... |
| 10 | 5.0 | 22.6 | 1062 | ... | ... |
| 11 | 5.0 | 22.6 | 1062 | ... | ... |
| 12 | 5.6 | 24.6 | 1165 | 0.05 | <0.005 |
| 13 | 5.8 | 25.8 | 1161 | ... | ... |
| 13.5 (Bottom) | | | | | |

* Depth below water surface in sampling hole.
†At 25°C.
‡Dots indicate parameters not measured.

the

with depth, as did the dissolved oxygen concentration; the bottom waters were supersaturated with oxygen. The specific conductance above the 3-m depth was influenced by the melting of ice in the sampling hole. Beneath the ice, the specific conductance was constant to the bottom; the values were about the same as those found in the upper waters of the main body of the lake. Chlorophyll concentrations in the 3 samples analyzed were about 0.04 to 0.05 µg $L^{-1}$, a level which was similar to that of the main body of the lake.

## APPLICATION OF THE VOLLENWEIDER-OECD EUTROPHICATION MODELING APPROACH

### *Main Body of Lake Vanda*

The Vollenweider-OECD eutrophication models require the normalization of the phosphorus load by the area, mean depth, and hydraulic residence time of a body of water. Because of the likelihood of restricted mixing between the main body of the lake and "Vanda Bay," the morphological characteristics of the main body should be used for normalizing the phosphorus load in applying the model to the main body of the lake. Although the surface area of the entire lake has been estimated to be 5.44 $km^2$, the surface area of the water beneath the ice of the main body of the lake is approximately 4 $km^2$. The volume of water in the lake, which is needed to compute both hydraulic residence time and the mean depth, was assumed to be the volume of the mixed layer above the brine layer, i.e., above about 45 m, of the main body of the lake. That volume, rather than the volume of the entire body of water, should be used because the brine layer is not mixed with the overlying waters; the volume of the mixed layer was computed to be $13.5 \times 10^7$ $m^3$. The mean depth was thus calculated to be 33.8 m and the hydraulic residence time about 75 years. These and other characteristics used in the modeling are summarized in Table 4.

The total phosphorus load to Lake Vanda was computed to be 10.5 kg P per year. Although the Vollenweider-OECD modeling approach uses the total phosphorus load and accounts internally for a portion of the load's being unavailable for algal growth and for the fact that some phosphorus is internally recycled from the sediments, the phosphorus loadings for those waterbodies that form the models were in large part (more than about 75%) available. It was noted previously that more than 70% of the total phosphorus load to Lake Vanda was made up of forms unavailable to support algal growth. Thus the use of the total phosphorus load for Lake Vanda would not be technically appropriate in applying the model.

*Lee et al*. [1980] reported that for watersheds in the Great Lakes region, the amount of phosphorus in a tributary that would be expected to become available in those lakes could be estimated to be the sum of the

TABLE 4. Summary of Characteristics of Lake Vanda and "Vanda Bay"

| Parameter | Lake Vanda | Vanda Bay |
|---|---|---|
| Surface area ($km^2$) | 4 | 1 |
| Volume ($\times 10^6$ $m^3$) | 135 | 9 |
| Mean depth (m) | 33.8 | 9 |
| Hydraulic residence time (years) | 75 | 5 |
| Total phosphorus load (kg P per year) | 10.5 | 10.5 |
| Soluble orthophosphate (kg P per year) | 1.93 | 1.93 |
| Condensed phosphorus (kg P per year) | 3.13 | 3.13 |

soluble orthophosphate and 20% of the particulate phosphorus concentrations. For Lake Vanda, that "available" fraction would be about 34% of the total phosphorus load. It is likely, however, that some portion of the influent particulate phosphorus would be removed in "Vanda Bay" before it enters the main body of the lake. Because we doubt that a greater portion of the total phosphorus load would become available than that measured as condensed phosphorus, but rather, some fraction of the condensed phosphorus would likely remain unavailable for algal growth, we used the condensed phosphorus loading estimate instead of the total phosphorus load in the application of the Vollenweider-OECD eutrophication models. This approach is further justified by the fact that the proportion of the total phosphorus load represented by condensed phosphorus (30% for Lake Vanda) is about the same as the estimated available phosphorus loading using the formula of *Lee et al*. [1980].

Using the estimated condensed phosphorus load of 3.13 kg P per year and the average chlorophyll concentration measured in the mixed layer (0.06 µg $L^{-1}$), the position of Lake Vanda for the austral summer of 1980-1981 on the updated Vollenweider-OECD model is shown in Figure 11. Extending the line of best fit for the updated model, it is found that Lake Vanda plots well within the family of points making up the relationship. Adding this load-response coupling to the body of data defining the model provides an indication that this model has applicability to ultraoligotrophic waterbodies.

By extending the line of best fit shown on the center figure of Figure 1, it is found that on the basis of normalized condensed phosphorus loading, the Secchi depth of Lake Vanda would be expected to be about 22 m. That was the Secchi depth value measured in the lake during our study. *Kaspar et al*. [1982] reported that the light attenuation coefficient of photosynthetic available radiation through the water of Lake Vanda was 0.055 $m^{-1}$ during their study of Lake Vanda during the austral summer of 1980-1981. It was also about the level reported by *Vincent and Vincent* [1982] for green and white light on December 17, 1980. That value of light extinction, together with the Secchi depth measurement in this study, follows reasonably well the relationship discussed by *Vollenweider* [1974] which indicates that the product of the extinction coefficient and Secchi depth will generally be in the range of 1.4 to 3. From an overall point of view, it can be concluded that there is remarkably good agreement between the measured and estimated trophic state-indicating parameters of planktonic algal chlorophyll and Secchi depth for Lake Vanda on the basis of Vollenweider-OECD eutrophication models.

Using an extrapolation of the line of best fit in Figure l*c* and the estimated normalized phosphorus loading for Lake Vanda, we estimated the hypolimnetic oxygen depletion rate associated with algal decomposition to be about 0.04 g $0_2$ per square meter per day. The area at the surface of the hypolimnion is about 2 $km^2$; the volume of the hypolimnion is about $2.3\times10^7$ $m^3$. If it is assumed

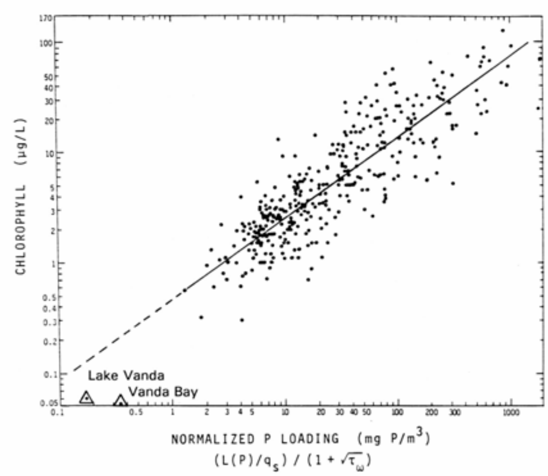


Fig. 11. Vollenweider-OECD normalized phosphorus load–chlorophyll relationship showing positions of Lake Vanda and Vanda Bay. (Model from *Jones and Lee* [1986].)

that the initial concentration of dissolved oxygen in the bottom waters was 10 mg $L^{-1}$ when they became isolated from the atmosphere, it would take only 7.5 years for the dissolved oxygen to be depleted within the hypolimnion due to the decomposition of algae produced in the mixed layer. Therefore even though the productivity of Lake Vanda's mixed layer is quite low, it is still sufficient to cause anoxic conditions to develop in the brine layer and to maintain these conditions against the diffusion gradient of supersaturated oxic conditions in the mixed layer.

Vollenweider's normalized phosphorus loading term is theoretically equivalent to the mean in-lake concentration of phosphorus. *Rast et al*. [1983] and Vollenweider [*OECD*, 1982] defined the actual correlation that existed on the basis of data upon which the model was developed. The measured soluble orthophosphate concentration of the mixed layer during our study was 0.6 µg P per liter; the concentration computed on the basis of the normalized condensed phosphorus load was 0.45 µg $L^{-1}$. There was therefore good agreement between the phosphorus concentration estimated by the modeling approach and that which was measured in the lake. This provides additional confidence in the application of the models to Lake Vanda.

It is interesting to examine the role of the previous years' phosphorus inputs in planktonic algal growth. This can be done to some extent by determining the phosphorus residence time in the mixed layer. The residence time of phosphorus is computed by dividing the total mass of phosphorus present in the water column by the annual inflow of phosphorus. On the basis of total phosphorus load, the phosphorus residence time for the mixed layer of Lake Vanda is calculated to be 125 years. That residence time is considerably longer than the year or so generally found for lakes [*Sonzogni et al*., 1976]. Typically, the phosphorus that enters a lake during 1 year is removed during that year to sediments or through the outflow; therefore the primary driving force for planktonic algal biomass during a particular year is generally the phosphorus brought in earlier that year. Because of the longer residence time of phosphorus in Lake Vanda, the concentration present at any time is not simply a function of the recent phosphorus loading but rather represents a considerable accumulation over many years. To determine the phosphorus residence time more accurately, the soluble orthophosphate content of the water column would have to be determined at least biweekly before, during, and after the growing season. Changes in the mass of phosphorus in the water column during the growing season (about 4 months in Lake Vanda when sunlight is adequate) would show the role of planktonic algal growth during a particular season in influencing the phosphorus concentration in the water column by removing phosphorus from the mixed layer.

***"Vanda Bay"***

Using the basic approaches outlined above, the phosphorus load—eutrophication-related water quality response of "Vanda Bay" can also be estimated. The characteristics of this portion of Lake Vanda that were used to normalize the loading are summarized in Table 4. Because of the issues of the algal availability of the total phosphorus load to Lake Vanda discussed above, we determined it to be most appropriate to assess the load-response relationship for "Vanda Bay" on the basis of the soluble orthophosphate load from the Onyx River. As discussed above, that load during the austral summer of 1980-1981 was 1.93 kg $yr^{-1}$. With that estimate and the measured chlorophyll concentration of 0.05 µg $L^{-1}$ (Table 3), the load-response coupling for "Vanda Bay" was plotted in Figure 11. "Vanda Bay" also appears to plot within the family of points composing the model, although not as close to the line of best fit as the main body of Lake Vanda.

## CONCLUSIONS

The hydrological and temperature structures of Lake Vanda make it one of the most unusual bodies of water in the world. It is evident that those unusual properties, however, do not cause the lake to have relationships between its phosphorus load and its eutrophication-related water quality characteristics that are different from those found for waterbodies around the world, provided that the unusually large proportion of algal-unavailable phosphorus entering the lake is properly taken into account. This is to be expected because the theoretical concept behind Vollenweider's model is the relationship between in-lake phosphorus concentration and planktonic algal chlorophyll which, in turn, is the basis of the use of phosphorus by planktonic algae for their growth.

The capability of the Vollenweider-OECD nutrient load-eutrophication response models to predict the impact on planktonic algal-related water quality of altering the phosphorus load to a waterbody has been demonstrated for more fertile waterbodies [*Jones and Lee*, 1982; *Rast et al*., 1983; *Jones and Lee*, 1986]. Demonstration of the applicability of this modeling approach to Lake Vanda extends the utility of these models to ultraoligotrophic waterbodies. This supports the use of the models to assess improvement in eutrophication-related water quality characteristics of a waterbody as its phosphorus load is reduced to low levels.

*Acknowledgments*. We wish to acknowledge the assistance of T. Chinn in providing the hydrological information on the Onyx River and of W. Vincent in making his data available to us. The comments which Chinn and Vincent provided on an early draft of this manuscript were also appreciated. The assistance provided by W. Green, D. Canfield, and A. Palmisano in the McMurdo laboratory is also gratefully acknowledged. Numerous other individuals at McMurdo and Vanda stations, as well as other locations also contributed to this study. Their assistance is also greatly appreciated. This investigation was supported in part by the National Science Foundation's Division of Polar Programs through grant DPP 79-20860.

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(Received May 29, 1989;
accepted June 1, 1992)