Management of Phosphorus and Nitrogen Inputs to Lake Rotorua, New Zealand

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Abstract: The water quality of Lake Rotorua has deteriorated since the 1960s because of excessive phytoplankton growths caused by increased inputs of phosphorus and nitrogen from the Rotorua city sewage treatment plant. Removal of phosphorus alone may produce no measurable improvement in lake condition unless it can be made the limiting nutrient. Even then, this may take a number of years, because of recycling of phosphorus already in the lake system. Removal of nitrogen alone may reduce phytoplankton growth in the short term (say 5–10 yr) but is not recommended because the algal community may become dominated by heterocystous blue-green algae, which can meet their nitrogen requirements by fixing dissolved molecular nitrogen and form dense unsightly assemblages. Thus, removal of both nitrogen and phosphorus is recommended. A suggested aim is to restore the lake condition to that which prevailed prior to the 1960s, before widespread public concern about phytoplankton growths developed. The scientific view is that this lake condition is achievable and will reduce the frequency and magnitude of nuisance algal blooms, maintain reasonable water appearance and clarity for recreational purposes, minimize periods of deoxygenation, and reduce internal nutrient inputs. Removal of all sewage effluent from the catchment is expected to achieve the nutrient load reduction that is required. Any sewage discharge increases the risk that the lake condition will be unsatisfactory, but this risk is probably low if the sewage inputs are less then 3 tonnes (t) of phosphorus and 30 t of nitrogen per year.

Introduction

Lake Rotorua is a large (surface area = 81 km^2), shallow (mean depth = 10.7 m), eutrophic lake which has important recreational and Maori cultural values. It is situated on the central volcanic plateau of the North Island of New Zealand. Of the catchment (424 km^2), 30% is unmodified and 70% is pastoral farmland, exotic forest, or urban area. Treated sewage effluent from Rotorua City (pop. 60,000) is discharged into the lake. There has been a steady deterioration of lake water quality from 1976 to the present associated with an increased sewage nutrient load (Rutherford 1984). Lake Rotorua stratifies intermittently during November–March, typically for periods of 3–10 days but occasionally for >20 days. During stratification, hypolimnetic oxygen depletion and nutrient release from the sediments (internal nutrient inputs) have been observed (Fish 1975; White et al. 1978).

The objectives of this paper are to review recent trends in some of the water characteristics of Lake Rotorua, to comment on its external and internal inputs of nitrogen and phosphorus, to discuss the recommended external nutrient input targets set for the lake, and to estimate the likely recovery rate of the lake following nutrient diversion.

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Water Quality Trends

Sewage nitrogen and phosphorus inputs have both increased steadily since 1976 (Fig. 1), but phosphorus input has increased by a greater percentage than nitrogen input (Table 1). Nutrient inputs from streams are unlikely to

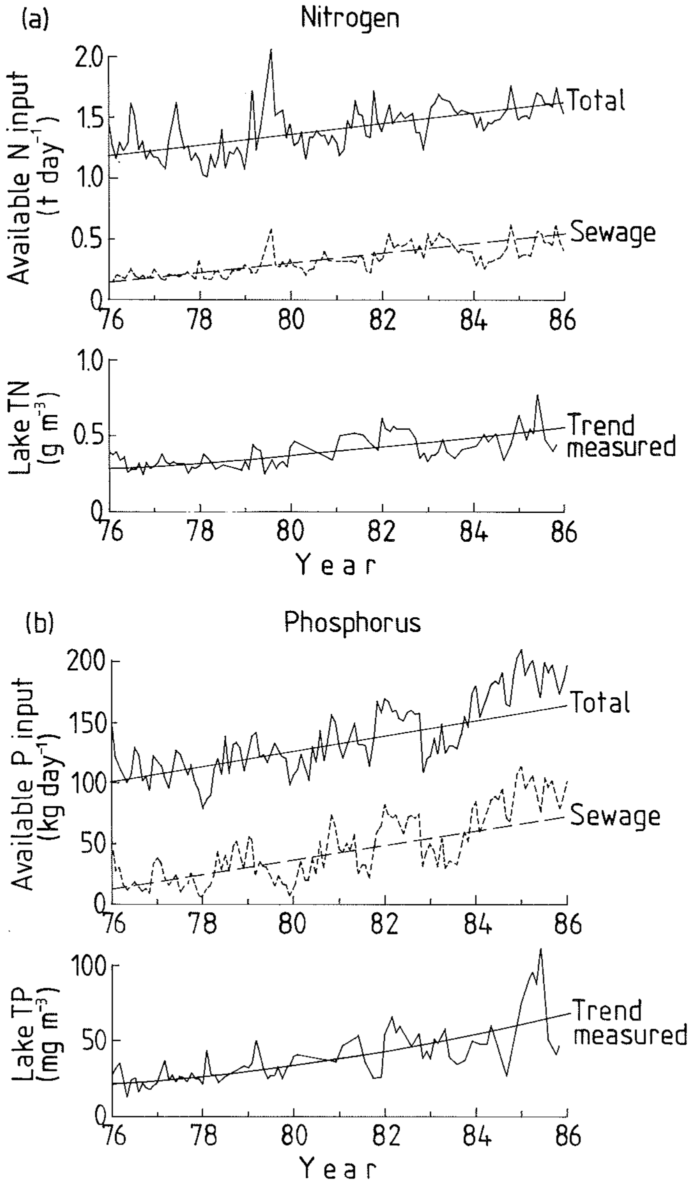

FIG. 1. Trends in External Loads and Lake Concentration: Total Nitrogen and Total Phosphorus

TABLE 1. Lake Rotorua Nutrient Inputs and Water Quality

Factors (1)	1965 (2)	1976–77 (3)	1981–82 (4)	1984–85 (5)	Target (6)
Population	25,000	50,000	52,600	54,000	—
Phosphorus inputs (t/yr)					
Raw sewage	5	18	30	47	—
Treated sewage	5	7.8	20.6	33.8	3
Stream	34	34	34	34	34
Internal	0	0	20	35	0
Total	39	41.8	74.6	102.8	37
Nitrogen inputs (t/yr)					
Raw sewage	34	100	170	260	—
Treated sewage	20	72.5	134	150	30
Stream (including septic tanks)	455	485	420	415	405
Septic tanks	50	80	15	10	0
Internal	0	0	140	>260	0
Total	475	557.5	694	>825	435
Average lake water quality					
Total phosphorus (mg/m^3)	—	23.8	47.9	72.6	20
Total nitrogen (mg/m^3)	—	310	519	530	300
Chlorophyll (mg/m^3)	—	5.5	37.8	22.6	10
Chlorophyll a (peak; mg/m^3)	—	28	62	58	17–24
Secchi disc (m)	2.5–3	2.3	1.9	1.7	2.5–3
Oxygen depletion rate ($g/m^3/day$)	—	0.4	0.7	0.9	0.25

Note: Catchment area = 424 km^2; surface area = 81 km^2; mean depth = 10.7 m; volume = 0.865 km^3; outflow rate = 18.5 m^3/s; and residence time = 1.5 year.

have altered significantly since they were measured in 1976–1977 (Hoare 1980). Consequently, sewage nutrients now make a much larger contribution to the total external input (e.g., 50% for P and 27% for N in 1984–85) than they did in 1975–76 (19% for P and 13% for N).

The rate at which the bottom waters of the lake lose oxygen during calm summer conditions has doubled since 1970, in parallel with increasing sewage nutrient inputs (Fig. 2). In Fig. 2, volumetric hypolimnetic oxygen demand (VHOD) is the rate of decrease of oxygen concentration measured over short periods when the lake stratifies and when hypolimnion temperature remains constant, implying negligible vertical mixing. The fully mixed increase in BOD in the lake caused by the sewage is estimated to be 0.2 g/m^{-3}, which would make a negligible contribution to deoxygenation. By stimulating phytoplankton growth, however, sewage nutrients increase the lake deoxygenation rate. Whereas 14 days of calm weather were required to produce anoxia in the bottom waters in 1970, now only 7 days are required. Oxygen depletion in the bottom waters and the problems it causes (trout driven inshore and nutrients released from the sediment) now occur more frequently.

When the bottom waters of the lake become anoxic, phosphorus and nitrogen are released from the sediments (internal nutrient inputs), and when the lake mixes again these nutrients stimulate phytoplankton growth. Internal nutrient inputs have increased since 1976 in response to increased external inputs (Fig. 3). The internal inputs in 1981–82 and 1984–85 were compa-

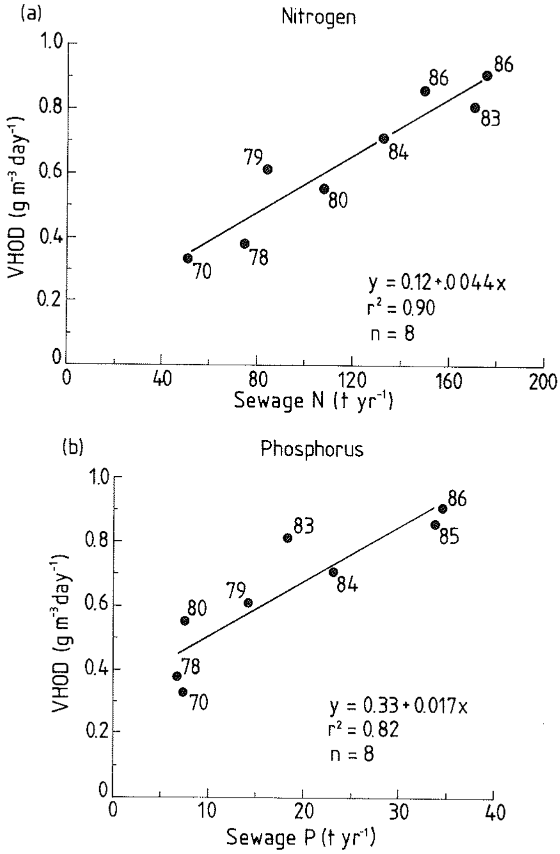

FIG. 2. Deoxygenation Rate and Sewage Loads: Total Nitrogen and Total Phosphorus

rable to the sewage nutrient input. To restore lake quality quickly, internal inputs must be substantially reduced. Conversely, if, by reducing external inputs, internal inputs can be reduced, then lake quality can be expected to improve markedly.

Lake phosphorus and nitrogen concentrations have increased since 1976 (Fig. 1).

The increased nutrient inputs from sewage influence lake nutrient concentration in two ways: (1) Directly, by increasing the total external nutrient input; and (2) indirectly, by increasing the rate of deoxygenation and hence the likelihood and magnitude of sediment nutrient release. The abundance of phytoplankton, as measured by chlorophyll a concentration, has been very high following nutrient releases from the sediment. Secchi disc depth has decreased (Table 1), partly because of higher concentrations of phytoplankton and associated detritus, although non-algal suspended solids also affect water clarity (Vant and Davies-Colley 1986).

Two fairly severe but short-lived blue-green algal scums occurred on the

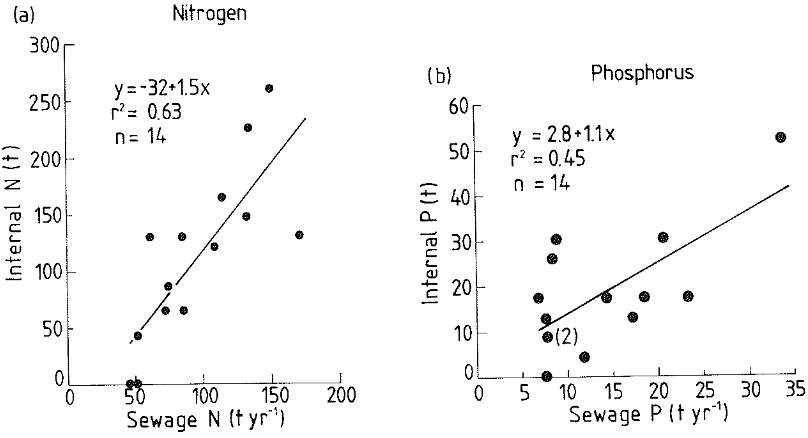

FIG. 3. Internal and Sewage Loads: Total Nitrogen and Total Phosphorus

lake in December 1985 and February 1986. The lake continues to support a good trout fishery: the stress which may have been placed on trout by the more frequent anoxia has not been quantified. Concern has been expressed by anglers that lake appearance has become degraded and that trout caught in the lake are not edible.

Phosphorus and nitrogen enrichment is not considered to cause excessive growths of introduced aquatic macrophytes ("oxygen weeds") in Lake Rotorua (Howard-Williams et al. 1986). Indeed, lake management aimed at reducing phytoplankton growths and improving water clarity in Lake Rotorua may cause the present macrophyte beds to become more vigorous and expand in area. Established procedures are available which can deal with such problems, albeit at a continuing cost (e.g., Coffey 1987).

Recommended Nutrient Reductions

At present, the level of phosphorus in Lake Rotorua is in excess of that required for phytoplankton growth (White et al. 1988). Removal of phosphorus alone may produce no measurable improvement in lake conditions unless phosphorus can be made the limiting nutrient in the lake. Even then, this may take a number of years because of recycling of phosphorus already in the lake system (especially the lake bed). Removal of nutrient alone may reduce phytoplankton growth in the short term (say 5–10 yr), but it is not recommended for two reasons. Firstly, nitrogen fixing organisms could gradually increase the nitrogen content of the lake, thereby negating the nitrogen input control measures (Schindler 1977). Secondly, nitrogen control would reduce the N:P ratio in the lake. This in turn could favor those blue-green algae which can fix atmospheric nitrogen, although other factors, such as mixing regime, transparency, temperature, and iron and carbon availability may also affect the abundance of blue-green algae. Blue-green algae are renowned for forming unsightly scums and producing odors and offensive metabolites (Pridmore and Etheredge 1987) and are undesirable in Lake Rotorua. Thus, removal of both nitrogen and phosphorus is recommended.

The degree of phosphorus and nitrogen removal required for Lake Rotorua will depend on the water quality targets selected. A suggested aim which appears to have considerable public support is to restore the lake condition to that which prevailed prior to the 1960s, before widespread public concern about phytoplankton growths developed.

The desired lake quality and nutrient input levels are given in Table 1. Several different approaches were used to derive the target values.

Historic Nutrient Inputs

Sewage nutrient inputs in 1976–77 were 7.8 t/yr^{-1} P and 72.5 t/yr^{-1} N, with perhaps another 80 t/yr^{-1} N from septic tanks (Table 1). Lake quality was satisfactory in 1976–77, but meteorological conditions favored high lake quality—temperatures were colder and winds stronger than average (Rutherford 1984). Lake quality may not have been satisfactory in other years with these nutrient inputs.

Likely sewage nutrient inputs for the early 1960s were 5 t/yr^{-1} P and 70 t/yr^{-1} N (Table 1). These estimates, however, are imprecise, and sewage inputs prior to the 1960s could have been appreciably lower. There is a risk that with sewage nutrient inputs of 5 t/yr^{-1} P and 70 t/yr^{-1} N lake quality would not be satisfactory.

Chlorophyll-Nutrient Models

The target annual mean chlorophyll a concentration is 10 mg/m^{-3}, which is thought to reflect lake conditions prior to the 1960s. The problem is estimating what annual mean total phosphorus concentration (TP) will achieve this target chlorophyll a value (assuming phosphorus can be made the limiting nutrient). Two models have been used: (1) The shallow lake model of Pridmore et al. (1985), which predicts that a TP of 17 mg/m^{-3} is required; and (2) the model of White et al. (1988), which estimates that a TP of 19.7 mg/m^{-3} will suffice. The two models adopt slightly different approaches, but yield a similar result. Hence a TP of 20 mg/m^{-3} appears to be a worthy target value.

For a lake TP of 20 mg/m^{-3}, we would expect a maximum chlorophyll a of about 14 mg/m^{-3} (95% confidence interval, 5–38 mg/m^{-3}) based on worldwide data (Pridmore and McBride 1984); and 17–24 mg/m^{-3} based on New Zealand lake data (Pridmore, unpublished).

Using a nutrient budget model calibrated for Lake Rotorua (Rutherford 1988) it can be estimated that to achieve a lake TP of 20 mg/m^{-3}, the total available TP input must be 37 t/yr^{-1}. Stream inputs average 34 t/yr^{-1} (Table 1) and, provided internal inputs are zero, sewage inputs should not exceed 3 t/yr^{-1}.

Internal Nutrient Inputs

There is a closer relationship between the sewage and internal inputs for nitrogen than for phosphorus (Fig. 3). The scatter in Fig. 3 arises from differences of meteorological conditions between years: the internal input for the same sewage nutrient input is higher in a long, hot summer, when the lake stratifies, than in a cold, windy summer.

The x-axis intercept in Fig. 3 indicates that the internal nitrogen input will approach zero as the sewage nitrogen input approaches 21 ± 23 t/yr^{-1} (mean ±95% confidence interval). The highest probability of having zero internal input will occur if sewage inputs are reduced to zero. At a sewage nitrogen input of 30 t/yr^{-1}, the internal nitrogen input, 13 ± 31 t, has a high probability of exceeding 10% of the stream nitrogen input of 405 t/yr^{-1} (Table 1), and hence making a significant contribution to the total input. The recommended maximum allowable sewage nitrogen input is 30 t/yr^{-1}. The relationship between sewage phosphorus input and internal phosphorus input is not precise enough to deduce a recommended limit on phosphorus input directly.

Lake Deoxygenation Rate

Summer lake temperature seldom exceeds 23° C, at which temperature the dissolved oxygen saturation concentration is 8.6 g/m^{-3}. Nutrient release from the sediment has been observed when bottom water dissolved oxygen concentrations drop below 4 g/m^{-3} (W. N. Vant, personal communication). The lake seldom stratifies for more than 20 days, and so to prevent internal nutrient inputs the volumetric hypolimnetic oxygen demand (VHOD) should not exceed $(8.6 - 4)/20 = 0.23$ $g/m^{-3}/day^{-1}$. This requires the sewage nitrogen input to remain below 25 t/yr^{-1} (Fig. 2). It is not possible to deduce the sewage phosphorus input at which VHOD does not exceed 0.23 $g/m^{-3}/day^{-1}$ (Fig. 2).

In conclusion, removal of all sewage effluent from the catchment is expected to achieve the nutrient input reduction which is required. If complete removal proves impractical, a less satisfactory option is the highest level of reduction that can be achieved for both phosphorus and nitrogen. Any nonzero sewage discharge increases the risk that lake condition will be unsatisfactory and requires an ongoing commitment by the Rotorua District Council to maintain very high nutrient removal efficiencies. The risk of unsatisfactory lake conditions is probably low if the sewage inputs are always less than 3 t/yr^{-1} phosphorus and 30 t/yr^{-1} nitrogen.

Recovery Rate

Assuming that a substantial reduction is made to the external nutrient input (e.g., by improved sewage treatment), we can attempt to estimate how long it will take the lake to reach a new "equilibrium." The important governing factors are the flushing time of the lake, nutrient settling rates, the change with time of sediment nutrient release (internal nutrient inputs), and the meteorological conditions.

Using a nutrient mass balance model calibrated for Lake Rotorua (e.g., Hoare 1980; Rutherford 1988) and neglecting internal inputs, it can be estimated that following nutrient input reduction to the target levels in Table 1, a new equilibrium would be established within 2 yr, at which time lake total nitrogen concentration will be close to 300 mg/m^{-3} and total phosphorus 20 mg/m^{-3}. This rapid recovery reflects the short flushing time of the lake (1.5 yr). We might expect the lake to recover this quickly only if internal inputs decrease immediately after nutrient diversion. It is likely, however, that internal nutrient inputs will continue for some time. A worstcase scenario is that internal inputs might persist for some years at the high level observed in 1984–85 (when lake total nitrogen concentration increased by 300 mg/m^{-3} and total phosphorus concentration by 60 mg/m^{-3}), in which case the model predicts that a new dynamic equilibrium would be established within 2 yr, in which lake total nitrogen concentrations average 450 mg/m^{-3} (range 340–640 mg/m^{-3}) and total phosphorus average 50 mg/m^{-3} (range 30–90 mg/m^{-3}). Thus, if internal inputs occur following external input reductions, then the recovery of the lake will be delayed.

Studies show that it is difficult to predict how quickly internal inputs will decrease following external input reductions. In Lakes Washington (Edmondson 1972) and Norrviken (Ahlgren 1978), internal inputs were negligible and these lakes recovered at the rates predicted from models of flushing and sedimentation. Lake Sammamish was expected to recover in about 4 yr, but internal inputs took between 7 and 11 yrs to reach a new equilibrium (Welch et al. 1986). Lake Shagawa was expected to recover in 1 to 2 yr, but high internal inputs were documented in the 3 yr following nutrient diversion and recovery was incomplete after 6 yr (Larsen et al. 1981). In Lake Erie, improvements in lake phosphorus and chlorophyll concentration have been observed over the 10 yr since nutrient diversion, but oxygen depletion has not yet reduced to the expected level (Boyce et al. 1987). A likely reason for the delayed recovery of Sammamish, Shagawa, and Erie is that sediment-water interactions are more important in determining lake quality than in Washington and Norrviken, and that the sediments take longer than the water to recover from high historic nutrient inputs.

We can be fairly confident that internal inputs in Lake Rotorua will decrease if external inputs are reduced substantially, but it is not possible to be certain about the rate of recovery. An improvement in lake quality would be expected within 1–2 yr, but complete recovery may take 10 yr.

Meteorological conditions can strongly influence internal inputs: a hot, calm summer will result in prolonged stratification, anoxia, and a large nutrient release, whereas during a cold, windy summer, the lake may not stratify at all, in which case nutrient release will be small. One or more hot, calm summers immediately following the reduction of external inputs would substantially delay the recovery of the lake, whereas one or more cold, windy summers could speed up recovery.

Conclusions

In order to restore Lake Rotorua quality to pre–1960s levels, removal of both nitrogen and phosphorus from sewage is recommended. Removal of phosphorus alone may produce no measurable improvement in lake condition unless it can be made the limiting nutrient. Even then, this may take a number of years because of recycling of phosphorus already in the lake system. Removal of nitrogen alone is not recommended because the algal community may become dominated by heterocystous blue-green, which can fix atmospheric nitrogen and can form dense unsightly assemblages.

Considering historic nutrient inputs, using two nutrient-chlorophyll models and extrapolating from observed trends in deoxygenation rate and internal nutrient inputs, it is estimated that the probability of restoring pre–1960s quality is high if annual sewage inputs are less than 3 t of phosphorus and 30 t of nitrogen. It is estimated that lake quality will show an improvement within 1–2 yr (the lake's flushing time is 1.5 yr), but that complete recovery may take up to 10 yr.

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