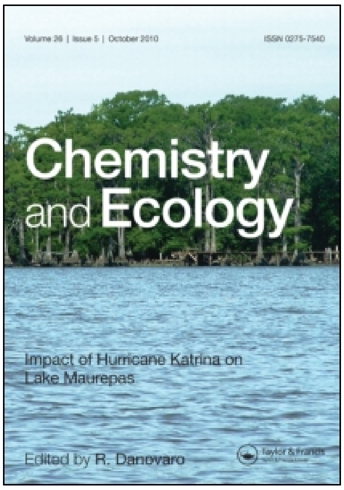

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EUTROPHICATION OF TWO LAKES IN KINMEN ISLAND (TAIWAN)

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Water quality was monitored for 12 months in Lake Tai and Lake Zon on Kinmen Island, Taiwan, and physico-chemical conditions were analyzed. No vertical temperature stratification was observed in these shallow lakes. pH is neutral to alkaline and associated with vigorous algal growth. Nitrogen levels are high and present in various forms due to progressive nitrification. Green and blue-green algae play an important part in the process of nitrification.

Assessment of lake eutrophication was made by the use of the N:P ratio, the Trophic State Index (TSI) and the US EPA Eutrophic Screening Model. The result of these calculations indicates eutrophic conditions in both lakes. It is advised that lake restoration be initiated and available techniques are listed.

KEY WORDS: Entrophication, nutrients, nitrification, lakes, Kinmen Island (Taiwan).

INTRODUCTION

Rapid economic growth, as well as population increase, is associated with industrialization and urbanization, degrading the quality of Taiwan's natural environment. This widespread degradation is serious and steadily increasing, leading to a variety of population problems, of which eutrophication of lakes and rivers is one. Most of the lakes in Taiwan, either natural or man-made, are undergoing eutrophication, a phenomenon caused by the enrichment of nutrients in surface waters, the so-called "nutrient pollution". The heavy pollution load originates from domestic sewage, agricultural runoff, and industrial and maricultural wastes and are major sources of nutrient pollution. The process of eutrophication is aggravated by the accmulation of sediment in the lakes, decreasing water depth and development of an oxygen deficit at the lake bottom, with anaerobic conditions which kill fish and other aquatic biota. Abundant algal growth in the littoral zone also causes algal blooms. These phenomena can be a great threat to public health and call for action to restore the lake conditions.

The purposes of our study were to: 1) to establish the current water quality of the lakes; 2) to establish background data for the lakes; 3) to determine the level of eutrophication; 4) to recommend a lake restoration strategy.

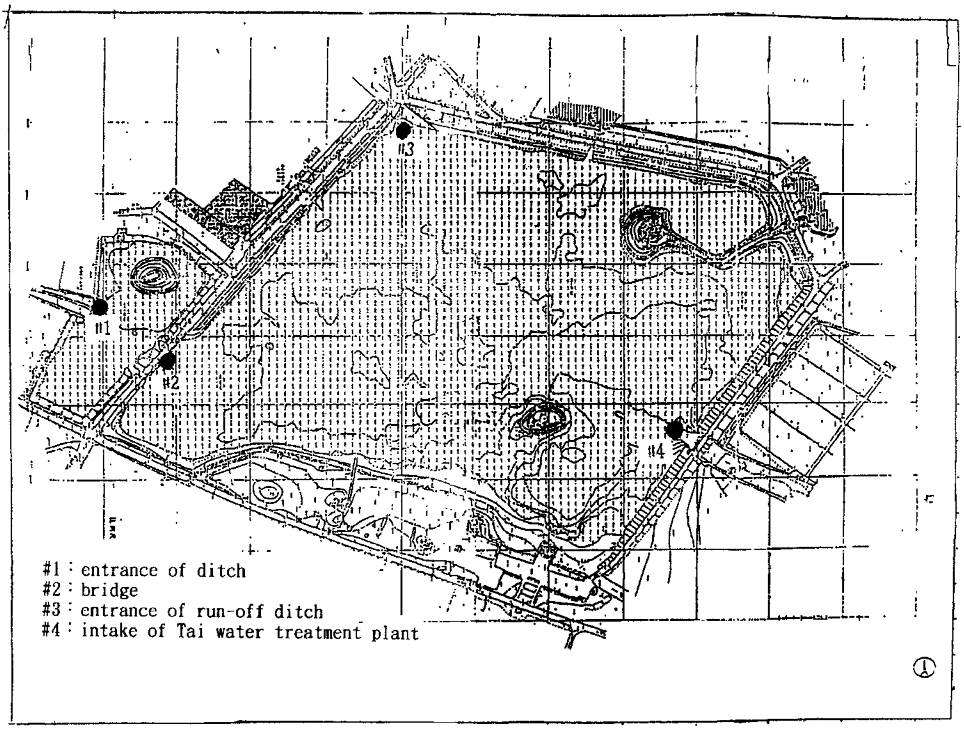

Figure 1 Sampling points in Lake Tai.

DESCRIPTION OF STUDY AREA

Kinmen is one of the largest offshore islands of Taiwan, only 8 km distant from China (P.R.C.), and separated by 277 km by Taiwan Strait from Taiwan itself. Its total area is 150 km^2 with a population of 50,000. Two lakes are investigated in this study. Lake Tai, located in the southeast of the island, is a man-made lake, completed in September 1967. It has an area of 38 ha and a mean depth of 5 m, with a volume of approximately 836,000 m^3. It supplies drinking water of 4,000 m^3 each day. It is composed of two basins (Fig. 1), a south basin used as a flashing pond of 3.2 ha, and a north basin, area 34.8 ha supplying the major drinking water source for the island. A man-made ditch enters Lake Tai on the southwest shore (#1) and another, smaller, runoff ditch to the northwest of the lake (#3). Lake Zon is also a man-made lake, located in the northeast of Kinmen; it has a surface area of 12.8 ha, mean depth 4 m and its total volume is 72,000 m^3. In Lake Zon (Fig. 2), a small river enters from the eastern shore (#7) and several runoff ditches from the northern side (#6). Since evaporation is in excess of rainfall, runoff is present only during the rainy season (April–September).

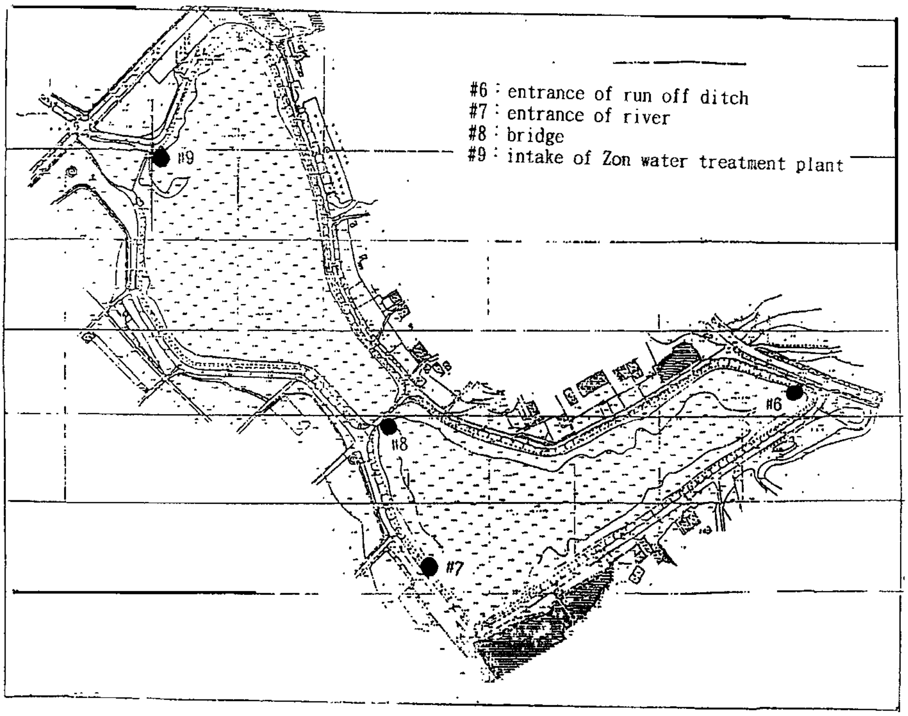

Figure 2 Sampling points in Lake Zon.

METHODS

Water sampling was conducted monthly from 30 September 1992 through to 28 October 1993 in Lake Tai and Lake Zon; monthly samples were collected from various points in the lakes as shown in Figures 1 and 2, and taken to the EPA certified laboratory for analysis. The chemical measurements included pH, temperature, turbidity, conductivity, dissolved oxygen, ammonia-N, nitrite-N, nitrate-N, alkalinity, suspended solids, total phosphorus, chlorophyll-a, all according to the Apha standard methods (Apha, 1985). (All other methods, heavy metals, chloride, pesticides, anion surface agents, are all confined also to Apha techniques.)

RESULTS

During the 12 months of sampling, water temperatures varied with climate, generally within the range 13–33°C, with 16°C difference between summer and autumn. Turbidity in the lake waters was caused by the presence of suspended matter of various sizes, generally in the range 17–36 NTU (Nephelometric units) (Tab. I). Conductivity, a measurement of the ability to conduct an electric charge by movement of ions, expressed as μmho/cm, was 280–500 μS in Lake Tai, 360–900 μS in

Table I Chemical characteristics of Lake Tai and Lake Zon.

Parameters	*Lake Tai*					*Lake Zon*				
	#1	*#2*	*#3*	*#4*	*Range*	*#6*	*#7*	*#8*	*#9*	*Range*
Temperature (°C)	23.9	23.7	23.9	23.9	13–33.3	23.5	23.5	23.7	23.6	13–322.3
Turbility (NTU)	18.6	20.1	18.5	17.0	9–35	26.0	32.1	21.0	15.4	3–38
Conductivity (μmo/cm	278.3	311.7	313.3	309.2	270–550	680.8	682.5	678.3	682.4	360–900
Alkalinity (μg/l)	95.1	67.3	67.6	65.6	20–108	67.6	66.4	65.3	64.9	88–88
Suspeaded Solids (mg/l)	36.1	32.4	33.7	31.4	11–73	23.6	27.8	19.7	31.4	5–73
pH	8.3	9.1	8.9	9.2	7.1–10.5	8.2	8.4	8.2	8.4	6.3–9.9
NH_3-N (mg/l)	1.779	0.987	1.08	1.009	0.334–2.678	1.004	1.134	1.019	1.085	0.31–2.39
NO_2-N (mg/l)	0.465	0.046	0.51	0.086	ND–1.820	1.047	0.005	0.024	0.148	ND–1.070
NO_3-N (mg/l)	2.004	0.382	0.413	0.401	ND–4.970	0.205	0.173	0.361	0.841	ND–4.58
Dissolved Oxygen (mg/l)	8.76	9.36	9.89	8.23	5.5–18.2	7.52	7.96	7.70	7.28	4.4–8.5
Total phosphorus (mg/l)	0.659	0.302	0.290	0.380	0.088–1.410	0.206	0.252	0.187	0.137	0.045–0.49
Chloride (mg/l)	89.9	75.2	66.8	64.1	52–100	190.8	193.9	192.3	192.2	67–342
Chlorophyll-a (μg/l)	362.2	217.5	216.4	182.3	59–656	479.5	146.2	111.6	119.3	39–327

Lake Zon, indicating a greater concentration of dissolved salts in the latter. Alkalinity, the capacity of the water to neutralize acid hydrogen ions, caused principally by carbonate, bicarbonate and hydroxyl ions, has an average concentration of 60 $\mu g\ l^{-1}$, range 20–108 $\mu g\ l^{-1}$. Both lakes have a surface water pH ranging from 7.1 to 10.5, i.e. neutral or alkaline conditions.

Nitrogen is present in various forms–ammonia (NH_3-N), nitrite (NO_2-N), nitrate (NO_3-N), compounds which play an important part in the biological processes occurring in natural waters. The lake surface waters have a concentration of NH_3-N in the range 0.3–3.8 mg l^{-1}, with highest concentrations found in both lakes in July. Nitrites are transition compounds in the process of nitrification, being oxidized from ammonia nitrogen in aerobic conditions; the mean values range from a trace to 0.2 mg l^{-1} in Lake Zon, and up to 1.8 mg l^{-1} in Lake Tai. Nitrate is an essential nutrient for all aquatic organisms, and is the final product of nitrification (following atmospheric N fixation by blue-greens) in which *Nitrobacter* converts nitrite to nitrate in aerobic conditions; the concentrations in both lakes range from a trace to 4.9 mg l^{-1}. The reverse process of denitrification (in which N_2 gas is returned to atmosphere) occurs only in anaerobic conditions.

Phosphorus is essential for aquatic organisms, providing energy for cellular activity; it is present in small amount in natural lakes – concentrations in both lakes were significantly low (0.1–0.6 mg l^{-1}).

Chlorophylly-a was measured to define algal abundance (the degree of eutrophication); concentrations in Lake Tai were twice that of Lake Zon, indicating the more vigorous growth of algae in Lake Tai.

Dissolved oxygen in both lakes was high (up to 10 mg l^{-1}), evidence of good aerobic conditions in these non-stratified lakes.

DISCUSSION

In many lakes stratification occurs due to the difference in temperature between surface and bottom waters, often separating the lake water seasonally into three layers – a surface layer or epilimnion in equilibrium with atmosphere, a mid-depth transition layer below with a small decline in temperature, the metalimnion, and the lowest colder layer, or hypolimnion. Although annual variations in temperature in the two lakes were substantial, they were not deep enough to stratify, so no annual cycle of temperature occurred.

The pH value of natural waters is usually in the range 6.5 to 8.5; these lakes were somewhat alkaline, especially in summer, because of the presence of carbonates. Carbonates are derived from three sources – absorption of carbon dioxide from atmosphere, with solubility dependent on water temperature, plankton photosynthesis during daylight, and weathering of carbonates rock (Dojlido and Best, 1993). With the presence of an abundant algal community in the lakes, photosynthesis is activated, taking up the dissolved carbon dioxide, and leading to a rise in pH in summer to a maximum of pH 10.5.

Alkalinity (carbonate, bicarbonate and hydroxide ions) is generated by a variety of processes such as photosynthesis, respiration, precipitation.

Ammonia may be a decomposition product of phytoplanton; in aerobic conditions, it is transformed by nitrifying bacteria to nitrite as an intermediate form, and then almost immediately oxidised further to nitrate. This process is termed "nitrification", evident from the presence of the three forms of nitrogen present. A high level of NH_3-N is derived primarily from point sources and runoff, especially in Lake Tai which has recently become polluted, but also from the fixation of atmospheric nitrogen. This is carried out by green and blue-green algae, such as *Anabaena* spp., present in both lakes. Nitrogen is needed for phytoplankton growth which is generally limited by the phosphorus available.

Phosphorus is much less abundant in lakes; it is derived mainly from minerals and soils, while atmosphereic precipitation contributes a little. Phosphorus is taken up by plankton algae for growth and reproduction. Algae also store phosphorus up to 10 times of their normal needs, explaining the rapid loss of phosphorus from open water.

Lake Eutrophication

Eutrophication is the process of nutrient enrichment of lake waters. Typically, a lake is initially poor in nutrients, with low productivity, few plankton species and high levels of dissolved oxygen. This is the phase of oligotrophy. Over time, the lake may gradually accumulate nutrients and increase in productivity, and finally becomes rich in nutrients, high in productivity with depletion of dissolved oxygen and excessive algal growth – the eutrophic phase.

The Law of the Minimum

Nitrogen and phosphorus (C is also one of them, not discussed here) are the elements most important for growth of living organisms. In most waters, nitrogen is present in amounts far in excess of requirements while phosphorus is present in disproportionately small quantity. The abundant nitrogen cannot be utilized due to the lack of phosphorus; thus Ruttner (1972) stated the law of the minimum–"productivity is limited by the nutrient present in least amount". The nutrient of least quantity is the "limiting factor".

Whether nitrogen or phosphorus is growth limiting may be assessed by determining the weight ratio of nitrogen and phosphorus. Since the ratio N:P in the algal mass is approximately 7.2 (by weight), this value theoretically provides a basis for defining the limiting factor. When $N:P > 7.2$, phosphorus is more likely to be limiting than nitrogen. When $N:P > 7.2$, nitrogen is likely to be limiting. In practice, in the two lakes reported here, the following ratios are used:

$N:P > 10$, phosphorus is limiting
$N:P > 5$, nitrogen is limiting
$5 < N:P > 10$, both are limiting.

In the management of lakes, control of the limiting factor can inhibit algal growth.

In this study, total nitrogen is assumed to be the sum of ammonia-nitrogen, nitrite-nitrogen and nitrate-nitrogen. The ratio of N:P is:

Lake Tai, 4–6 approx.
Lake Zon, 5–15 approx.

Evidently both nitrogen and phosphorus are equally limiting.

Trophic State Index

Recognition of lake eutrophication depends on the biomass, nutrients and other characteristics (including inputs or "loading" of nutrients) of the water body. There are many alternative methods for evaluation; the most common methods applied are the Carlson method (1977) and the US EPA model (US EPA, 1985). In Table II are shown the three variables chosen by Carlson for determining eutrophication status. While this screening method is simple and easy to apply, a wider multivariable index is needed to match the complexity of lakes such as Tai and Zon. A trophic state index (TSI), modified from Carlson's method, is used with different variables (Secchi disc transparency [SD], total phosphorus [TP] and chlorophyll-a [Chl-a]). The empirical equations developed in our study are:

Secchi disc transparency basis –

$$TSI = 60 - 14.4 \ln(SD) \quad (1)$$

total phosphorus basis –

$$TSI = 14.42 \ln(TP) + 45 \quad (2)$$

chlorophyll-a basis –

$$TSI = 9.81 \ln(\text{Chl-a}) + 30.6. \quad (3)$$

Combining equations 1–3, using average values of the three variables, provides a new index (CTSI):

$$CTSI = TSI(SD) + TSI(TP) + TSI(\text{Chl-a}) \quad (4)$$

where CTSI values associated with lake trophic status are:

oligotrophic – $CTSI < 40$
mesotrophic – $CTSI < 50$
eutrophic – $CTSI > 50$.

Annual mean values were used to calculate the univariate indices and these summed to obtain values of CTSI for lakes Tai and Zon; the values obtained were greater than 60, clearly indicating eutrophic conditions.

Table II Carlson's (1977) screening method.

Class	*Total phosphorus (μg/l)*	*Chlorophyll-α (μg/l)*	*Transparency (m)*
Oligotrophic	< 12	< 2.6	> 4
Mesotrophic	12–24	2.6–7.2	2–4
Eutrophic	> 24	> 7.2	< 2

Eutrophic Screening Model

This method was established by US EPA (1985) and uses phosphorus loading (LP) to the lake; the equation derived is:

$$LP = Qi \times \frac{Pi}{A} \qquad (5)$$

where LP is phosphorus loading, Qi is flow (complex and steady-state conditions), Pi is phosphorus loading in inflow, A is lake surface area.

Data from our study showed that the south basin of Lake Tai has an annual phosphorus loading of 31.9 g m^{-2}, while the north basin has LP of 1.35 g m^{-2} and Lake Zon has LP of 1.08 g m^{-2}. In Figure 3, the state of eutrophication for a number of US lakes can be judged from the distribution of points of phosphorus loading vs mean depth/lake residence time. In this data set most of the lakes were found in the eutrophic zone. Phosphorus loading (LP) for the lakes utilized in the equation (5) are:

1) South basis of Lake Tai:

area (A) = 3.2 × 10000 = 32000 m^2
P in inflow (Pi) = 6.59 mg l^2 = 0.659 g l^2
inflow (Qi) = 4250 m^3 day (intake flow of water treament plant).
LP = Qi × Pi/A = 4250 × 0.645 × 365/32000 = 31.9 g m^{-2}

2) North basin in Lake Tai:

A = 348000 m^2
Pi = 0.302 g m^3

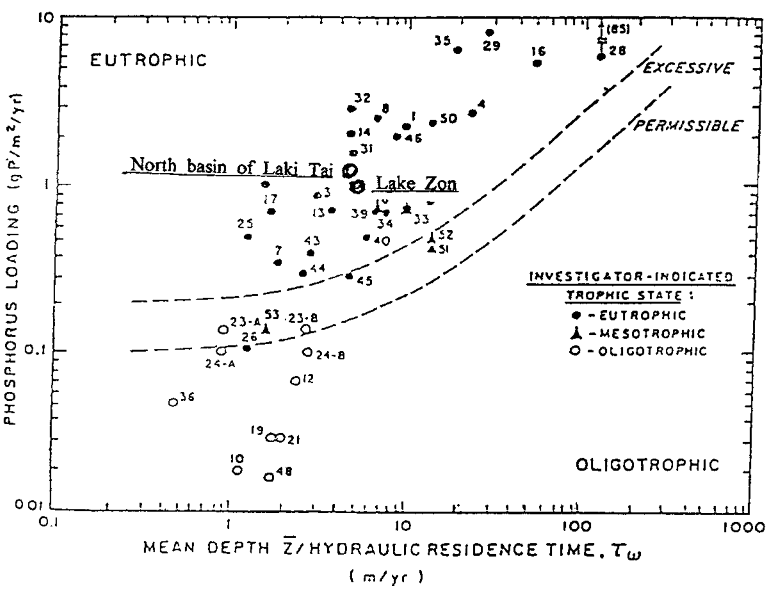

Figure 3 USEPA screen method.

Qi = 4250 m day
LP = 1.345 g m^2 year

3) North of Lake Zon:

A = 128000 m^2
Pi = 0.252 g m^3
Qi = 1500 m day
LP = 1.35 g m^2 year

Calculation for mean depth (Z)/hydraulic residence time (rw) are:

1) South basis of Lake Tai:

hydraulic residence time (rw) = (3.2 × 1000 × 3)/4250
= 23 day
= 0.06 year
mean depth (Z)/hydraulic residence time = 3/0.06
= 50 m/year

2) North basin of Lake Tai:

rw = (34.88 × 10000 × 5)/4250 = 1.1 Yr
Z/rw = 5/1.1 = 4.5 m/year

3) Lake Zon:

Z/rw = 4/0.95 = 4.2 m/year

The LP and Z/rw of the lake is in Figure 3, all of which points set in the eutrophic side. Any process which raises the acidity (reducing pH) will also result in an equivalent decrease in alkalinity. In Figure 3, the state of eutrophication for a number of US lakes can be judged from the distribution of points of phosphorus loading vs mean depth/lake residence time. In this data set most of the lakes were found in the eutrophic zone.

CONCLUSIONS

Research on two lakes on Kinmen Island was carried out over a one year period, with the following conclusions:

1. Lake Tai is more seriously polluted than Lake Zon.
2. From the sources of pollution were primarily for domestic sewage, military waste water, pig farm waste in Lake Tai, and from domestric sewage and agricultural runoff in Lake Zon.
3. The pollutants were mainly nutrients causing eutrophication and encourage excess algal growth.
4. Evaluation using two methods clearly showed that the lakes are eutrophic.
5. Both nitrogen and phosphorus contribute and their control could alleviate or slow the process of eutrophication.
6. Eutrophication may result in water quality unsuitable for drinking water supply.

RECOMMENDATIONS

The surface water of the lakes is the primary source of drinking water in Kinmen Island and improvement in lake water quality has become an urgent requirement for the public water supply agency. There is a variety of lake restoration techniques available. The establishment of a sanitary sewer system is an essential consideration, with routing of domestic sewage to a sewage treatment plant with proper disposal of sewage sludge. Diversion of runoff is also necessary to reduce the transfer of additional nutrients to the lakes.

Lake restoration technologies include:

- dredging amd compaction of lake bottom sludge
- removal and exposure of sludge
- sealing off the lake bottom
- exchange of lake water with clean water from another source
- dilution of polluted water with clean water
- control of lake volume through other (linked) lakes
- control nutrient input, especially the limiting component
- aeration of lake by better circulation or increased turnover (or aerate physically)
- diversion of agricultural runoff
- removal of algal blooms, mechanically or chemically
- control of algal growth by introducing grazer community
- installation of air flotation system and water treatment.

The management of the catchment is also an important concern and the needs of land development, land use, land disposal, crop harvesting, and provision of buffer zones need to be assessed. In addition, shoreline regulations should also be enacted and enforced at the same time.

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