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CASE STUDY ON WATER QUALITY MODELLING OF DIANCHI LAKE, YUNNAN PROVINCE, SOUTH WEST CHINA

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ABSTRACT

The main aim of this work was to construct and validate a mathematical water quality model of the Dianchi lake, so that by altering input total phosphate (TP) loads the projected changes in the lake water TP concentrations could be estimated. Historical information had indicated deteriorating lake water quality with increasing TP concentrations. The model was based on a simple annual mass balance, relying on 3 years (wet, average and dry) data with all TP loads quantified, 7 years of lake water quality, and 36 years of flow data. All lake processes were considered within a single variable, R. Planning TP removal at STWs and within fertilizer plants, coupled with interventions to reduce non-point TP loads from all land run-off by 50%, suggested future lake water TP concentrations could be stabilised at about 0.3 mg TP/l, i.e. the estimated limit for producing algal concentrations that would cause major problems in water treatment plants. The TP load reductions envisaged as realistic would only stabilise the lake water quality by about the year 2008; interventions, unfortunately, could not return the lake to its former pristine condition. The accuracy of the predictions was ± 0.1 mg TP/l, so collection of better data was needed. © 1999 IAWQ Published by Elsevier Science Ltd. All rights reserved.

KEYWORDS

Dianchi Lake; lead reduction; modelling; restoration; total phosphate, water quality.

INTRODUCTION

Lake Dianchi has been considered a 'precious pearl' in the Yunnan Plateau, and thus been a focus for the development of Kunming (the provincial capital of over 2 million inhabitants) and the surrounding area. Despite being in southwest China and thus somewhat inaccessible, it has been an attraction for Chinese visitors for many years, and one of the very famous national poets has written of its beauty and appeal. Historically, the Dianchi lake water has been used for domestic supply, agriculture, (irrigation and livestock watering), fisheries, recreation and navigation, whilst the lake itself has provided a means of water storage and flood control. More recently with the rapid growth of Kunming, economically and industrially, along with modernisation of agriculture in the lake catchment, there has been a considerable deterioration in the lake water quality. The maintenance of a sufficient water supply is now crucial, and has been addressed within the ODA funded Yunnan Environmental Project (YEP) jointly by Montgomery Watson and local Chinese. The main objective of the YEP was to identify the appropriate mitigation measures that would produce the most significant improvements in the water quality of Dianchi lake, and thereby restore (all) the benefits of the "historically pristine environment".

Clearly, an adequate appreciation of the various factors that were contributing to the poor water quality in Dianchi lake as well as the processes taking place in the lake itself, was needed. This required an overview of the historical events that created the present environmental conditions, and identification of which factors and processes would be the most critical in the future when the proposed mitigation measures were implemented. To quantify the various factors and processes in the lake would involve a mathematical modelling approach, particularly to confirm the effectiveness of individual project interventions on the possible improvements that would be anticipated in the Dianchi lake water quality. Such studies were undertaken by the Yunnan Environmental Project Office (YEPO) and the DRA Consultants (Montgomery Watson) during 1995, with the main points from that work outlined below (Montgomery Watson, 1996e).

DETERIORATING WATER QUALITY

Ancient documents indicate that about 700 to 800 years ago, Lake Dianchi had an area of over 1000 km^2. Gradual siltation through sediment transport from the upper catchment areas of Dianchi lake, reduced this to 320 km^2 by about the 1940s, and to around 300 km^2 by the 1990s (Montgomery Watson, 1996a).

In the 1950s the lake water was still very clear (being oligo- to meso-trophic), and many Kunming residents swam in it. The fish were largely indigenous species and the zooplankton populations were sufficient to control any algal blooms by grazing. The edges of the lake had gently sloping gradients and these promoted large areas of littoral macrophyte communities, apart from other submerged macrophytes which covered significant portions of the deeper water sediments in this relatively shallow lake (about 4 metres deep).

During the 1960s and 1970s the lake water became turbid and the fish community was then dominated by (previously introduced) carp. The 20 main feeder rivers and streams, many of which flowed through the urban areas of Kunming and the surrounding towns, were subjected to increasing discharges of polluting materials, due to the spreading industrialisation of the area. Other factors including land abuse, erosion processes, land reclamation at the shore line, over-fishing and introduction of exotic edible fish, resulted in turbid lake waters, carp dominating the fish community, and blue-green algae proliferating along with water hyacinth in particular areas. The inner lake (the Caohai, with about 3% of the surface area of the whole lake), had chlorophyll α concentrations increased to 120 and 150 µg/l whilst the main lake (the Waihai) exhibited values in the 20 to 50 µg/l range (Montgomery Watson, 1996a).

More recently, due to the burgeoning growth in and around Kunming, the uncontrolled discharge of domestic and industrial effluents has seriously contaminated the sediments in the Caohai, and polluted the Waihai to the extent that submerged macrophytes have been virtually eliminated, and very few areas exist with macrophytes whose coverage is sufficient to sustain fish spawning and juvenile nurseries. The Caohai is now choked by the water hyacinth, which by light shading and oxygen depletion has produced anaerobic muds and unpleasant hydrogen sulphide and mercaptan malodours.

The main causes of the deteriorating lake water quality can be listed as (Montgomery Watson, 1996e,f):

i) rapid growth of population and industry expansion around the Kunming urban area in the past 10 years;
ii) lack of domestic sewage treatment, and industrial effluent control and/or treatment, with wastes discharged directly into the lake, or via the major watercourses, mainly (but not exclusively) in the Kunming urban area;
iii) destruction of lake macrophytes and their self-purification capacity;
iv) significant increase in nutrients exported from anthropogenic activities in the catchment, including
    (a) agricultural intensification of food production with fertilizers;
    (b) surface phosphate mining in upstream areas of feeder rivers;
    (c) major deforestation, with consequent soil erosion.

QUANTIFYING THE PROBLEM

In recent studies, total P was identified as probably being the limiting nutrient (Montgomery Watson, 1996e). Water column concentration data from surface water samples taken in the Waihai over various seasons (shown in Figure 1 below), suggest this.

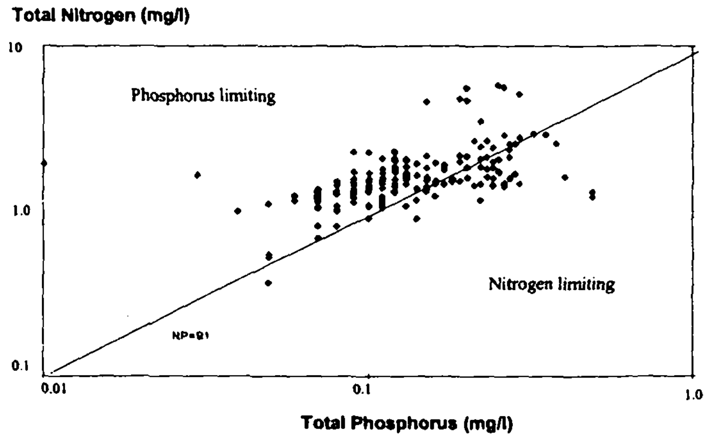

Figure 1. Nutrient limitation for eutrophication (Waihai).

The major deterioration in lake water quality was consequently quantified in terms of increased nutrient and phytopigment (chlorophyll α) concentrations. The annual averaged total P concentration increased from 0.10 to 0.22 mgP/l between 1988 and 1994, and was accompanied by significant algal biomass production, (from about 12 $\times 10^6$ to 50 $\times 10^6$ clumps/litre, as shown in Figure 2 below). Major water treatment problems were anticipated if total P concentrations increased to 0.30 to 0.35 mgP/l .

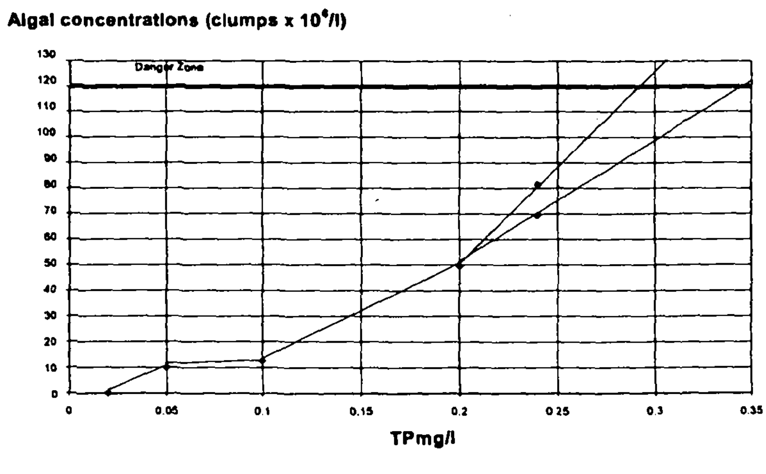

Figure 2. Annual average algal and total phosphate concentrations for the Waihai.

Collation of data on nutrients exported into the lake included quantification of pollutant loads from point, non-point, and internal sources, i.e. urban and rural effluents (domestic and industrial), all agricultural materials (manures, night-soil, fertilizers), land run-off (soils, mining spoils), rain, and dust. Sources of phosphate loads which were essentially internal (i.e. from within the lake itself), e.g. releases from sediments, fish excreta and other biomass degradation (including vegetation in the river waters, etc.), could not be easily quantified and thus were only considered at a later stage in the mathematical modelling.

Information about population totals in discrete areas was used to provide estimates of total phosphate loads from the domestic sewage. Surveys of a few domestic housing areas were also carried out to confirm the per capita flows and pollutant loads used in load estimations. Projections were also made for future year situations with allowances made for a variation in the population growths (due to unpredictable population movement from the rural community into urban areas) and improved living standards, including better diets and the proliferation of automatic washing machines using detergents. Differences between the rural and urban communities were made in the per capitas applied (0.3 and 0.6 g P/person/day for 1993) (Montgomery Watson, 1996b).

With the development of the proposed sewerage system, but only a gradually increasing population coverage via actual connections, then allowances were made in the % population whose effluents were captured into the conveyance system, and treated in individual STWs. The percentage connections used in the projections were as follows for the 1996, 2000, 2010 and 2020 years: domestic (city) 90%, 90%, 95%, 100%, (suburbs) 0%, 50%, 75%, 90%; and industrial (city) 70%, 80%, 90%, 100%, (suburbs) 0%, 50%, 70%, 80% (Montgomery Watson, 1996b).

Industrial effluent loads from all the major sources were known to a certain degree and further refinement of the data was necessary through additional on-site surveys. The major portions of the industrial pollutants loads were in the Kunming area, but significant nutrient loads were discharged in the effluents from a few other very large fertiliser factories in the southern region of the Waihai catchment (Montgomery Watson, 1996c).

Estimates of nutrient export from other sources, including the atmosphere (rain and dust) were made using data collected from the chemical analysis of samples of both.

The amounts of nutrient loads entering the Waihai from the 10 major rivers had been monitored in detail for several storm flow periods in 1988, and correlations established between river flows and nutrient concentration for the different rivers. Estimates were then made of the total nutrient loads that were attributable to the land run-off. It was recognised that this total load comprised material which originated in some river's upper catchments from phosphate mining activities, whilst in the middle catchment areas where deforestation had occurred then natural soils were being eroded, and in the lower catchment areas the run-off contained soils that had been treated with significant and increasing amounts of man-made fertilisers (use of which had been promoted in China in recent years rather than natural manures and night soil).

MATHEMATICAL MODELLING APPROACH

With the deterioration in lake water quality, particularly over the past 20 years, and the requirement to provide an adequate water supply of sufficient quality, there was an immediate need to develop a management tool which could predict future water quality, including the "do-nothing scenario" and the likely responses to specific interventions proposed within the YEP.

It was recognised that a mathematical model was required (of a dose-response type) linking the nutrient loads entering the Waihai with the lake water algal biomass, or chlorophyll α concentrations resulting. To construct such a model required a knowledge of the lake water column biological available phosphate (BAP) concentrations, and corresponding algal biomass or chlorophyll α concentrations. Whilst approximations of the BAP values could be made if both total phosphate (TP) and either particulate phosphate (PP) or soluble reactive phosphate (SRP) concentrations were known, only TP data was available, so that a water quality model based on TP information was developed, rather than algal concentrations.

A simplified approach was adopted as there were very limited data sets available, especially for processes occurring internally within the lake. These included releases from sediments, fish excreta and other biomass degradation (including vegetation in the river waters, etc.). An overall mass balance for total P was developed, which incorporated the major flows, and associated TP load elements into and out of the lake.

Since it was not possible to separate all the various processes occurring (including sedimentation, algal uptake, TP releases from sediments, fish and other materials degradation, chemical reactions, etc.), all of these were grouped together into one "variable-constant", the overall variability being due to year-to-year ecological and also meteorological changes, but otherwise it was adjudged they should remain reasonably constant within a limited number of years. Without a good appreciation of the hydrodynamic mixing occurring in various regions of the lake, it was not possible to consider a segmented lake model. It had therefore to be viewed as a completely mixed system, and so was somewhat limited in the precision of the projected future TP concentrations estimated for different mitigation measures advocated.

Given these particular assumptions, the following TP mass balance equation was developed, considering the TP load entering and being discharged from the lake, i.e.:

$$[Pi] = [Po] * (1- \propto/V) + R*Lin/V$$

where Pi, Po annual total P lake concentrations in the projected and previous years respectively;
$\propto$ total outflow, including the total abstracted water volume;
V lake volume, which varied with lake surface operating level;
R residual total P lake concentration after all impacting processes, (e.g. sedimentation, algal uptake, chemical reactions);
Lin total annual P load entering lake.

As Pi and Po were known from all the lake monitoring surveys (carried out at a minimum of 16 lake locations, and over a period of several years) $\propto$ and V were available from a lake water balance model, (Montgomery Watson, 1996d) and Lin values had been calculated separately (from per capita values and population data, industrial effluent information, and non-point source data) for various years, then R was the only model "variable-constant" which was unknown.

MODEL CALIBRATION, VALIDATION AND SENSITIVITY ANALYSIS

Approach

In the present work very little data was actually available, with only three years of measured input loading data, and seven years of Waihai water quality information, independently monitored which included phosphorus concentrations (from 1988 to 1994 inclusive). Consequently, with only one overall process variable being employed in the model, and the considerable data limitations, calibration was undertaken using all seven years data. For each year, the value of the model co-efficient, R, was estimated from the model equation, and then an overall average R value calculated, which was approximately 0.14.

Sensitivity

A series of R values were chosen (0.25, 0.20, 0.15 and 0.12) and modelled Waihai total phosphate concentrations calculated for the years 1989 to 1994. These were then compared with the annual averaged Waihai monitored values and the relative % errors calculated.

Optimisation procedure

As the model R value is presumably related to the hydrodynamics within the system, and the inflow volume in any particular year, a correlation of the individually calculated R values (for each year from the model equation) was made with the measured inflow volumes to the Waihai. Interestingly the 1988, 1993 and 1994 years represented dry, average and wet hydraulic years respectively, and a correlation of R with lake inflow (Qin) indicated a reasonable linear relationship, i.e.:

$$R = 0.000405 * (Qin) - 0.057935 \text{ (with } r^2 = 0.9036)$$

By employing this regression equation to calculate the R value for input into the model, minimum errors in the modelled output P concentration values were produced, as indicated in Figure 3.

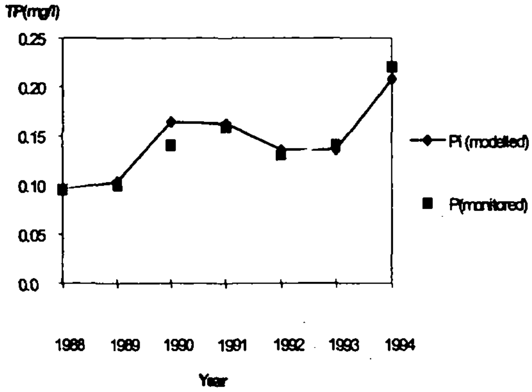

Figure 3. Validation of model predictions.

MODEL LIMITATIONS

Model structure

The model formulation, of necessity, could not possibly include the representation of all the indivi processes occurring, which affect the water column phosphorus concentration, including:

1. the degree and extent of hydrodynamic mixing, and effects of wind speed, direction and duration on s
2. the effect of varying rainfall in the catchment and inflow variations on the hydrodynamics of the syste
3. the speciation of phosphate present, (soluble/insoluble fractions), and sedimentation, and/or resuspen (occurring at various times during the year and at different locations);
4. the uptake of biodegradable phosphate by the plants and algae within the Waihai; and
5. the release of phosphate from anaerobic sediments and from fish excreta.

Clearly an 'overall rate-constant' (R in the model) can only provide a rather coarse 'averaged' v representing the historical mixing and phosphate speciation in the Waihai.

For this modelling approach to realistically predict future total P concentrations, the phosphate reduc within the lake water column must continue as previously in 1988 to 1994. This may not occur, s interventions could change the ratio of particulate P to total P considerably.

Currently, point source total P tends to be predominantly soluble (originating from domestic sewage industrial effluents), whereas non-point source total P may be particulate (from agricultural manures, r soil, fertilizer residues or soil particles, mining spoil and land run-off). With removals of some soluble interventions at source, and reductions in the non-point sources particulate P through feeder river w treatment schemes, changes in the ratio of particulate P to total P in the lake water column would s likely, but the degree would be very difficult to estimate. Uncertainty also exists about the amounts o loads from land runoff which actually enters the lake. Varying cropping patterns in sub-catchment a result in the relative individual magnitudes of fertiliser additions, whilst both animal manures and nigh applications are not possible to quantify.

Continual striving for economic improvement within Yunnan Province requires greater food productio decreasing land areas, so encouraging greater application of chemical fertilisers, organic manures pesticides. This may exacerbate the nutrient runoff loads as well as altering the P speciation within s These factors are likely to affect the model co-efficient, R, value in the future, necessitating fu recalibration.

MODEL RESULTS

Approach adopted

Interventions to reduce point source TP loadings are the easiest to implement. Priority was therefore given to mitigation measures involving sewage treatment and sewerage provision (including secondary connections), as well as industrial wastewater treatment and waste minimisation measures, where the effluents contained significant TP loads (e.g. phosphate and chemical fertilizer plants). Reduced TP loads (due to anthropogenic and meteorological reasons), in land run-off, had been (and were continuing to be) investigated, so such possibilities were also included within the modelling options considered. A selection of particular mitigation measures were then defined and these used to calculate input values from which future modelled projections were estimated. A few other extreme (and unrealistic) conditions were also considered for comparative purposes (i.e. no increase in TP load from the 1995 values, and the zero load situation) (Montgomery Watson, 1996g).

Options considered

Six main scenarios were considered, as follows:

Scenario 0: No treatment measures at all (for comparative purposes).
Scenario 1: 2 Kunming STWs with TP load reduction in 1996.
Scenario 2: 4 Kunming STWs (to 0.5 mgTP/l); 2 small STWs (50% reduction); 2 fertilizer plants (to 1 mgP/l).
Scenario 3: As 2 above plus 25% reduction in land run-off.
Scenario 4: As 2 above plus 50% reduction in land run-off.
Scenario 5: As 2 above plus 75 % reduction in land run-off.

The above scenarios were modelled with maximum, average and minimum hydraulic loadings (using 36 years of lake records), and land run-off and atmospheric deposition being both zero, or 2 % and 1%.

Modelled TP projections

Scenario 0: Modelled results indicate Waihai TP concentrations will rapidly increase to 0.78 to 1.3 mg TP/l (with increasing run-off, etc.) or 0.66 to 0.92 mg TP/l (with constant run-off, etc).

Scenarios 1 and 2: Modelled results indicate interventions will decrease the rate at which Waihai water quality deterioration should occur, with the ranges reduced to 0.59 to 0.87 mg TP/l and 0.43 to 0.67 mg TP/l respectively for scenarios 1 and 2, (and assuming increasing run-off, etc.).

Scenarios 3, 4 and 5: Further reductions in the rate of Waihai water quality deterioration are indicated for the modelled decreases in land run-off. Results ranges were 0.36 to 0.54 mg TP/l and 0.21 to 0.31 mg TP/l, (for scenarios 3 and 5, respectively).

Comparison of Scenarios 1 to 5: Assuming only small increases in non-point source TP loads and average hydrological conditions, then approximately stabilised TP concentrations occur by about the year 2007, as indicated in Figure 4.

Clearly the implementation of the point source TP load reductions for Scenario 2 indicates Waihai TP concentration may be stabilised around 0.5 mgTP/l, during the first decade after commissioning the facilities (i.e. for years 2000 to 2010), but that further significant water quality improvements will probably only be possible through reductions in TP loads from land run-off, and other non-point sources. A 50% land run-off reduction may result in Waihai water TP concentrations being stabilised around 0.3 mg TP/l, whilst 75% reductions would be required to reduce the value to about 0.25 mg TP/l (i.e. similar to the 1994 year monitored conditions).

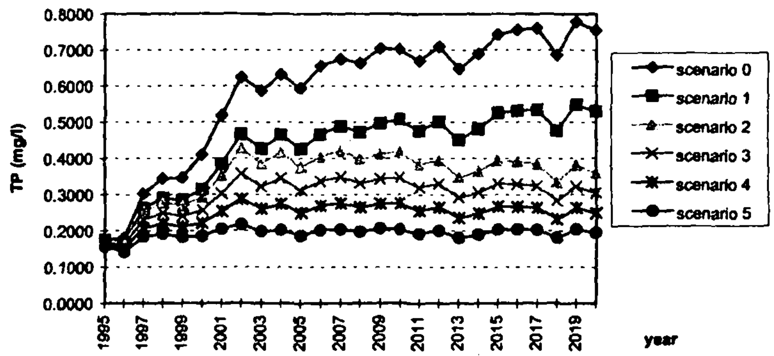

Figure 4. Projected average TP concentrations in Waihai for all scenarios.

Extreme situation projections

(a) No TP load increase: Results indicate stabilisation of Waihai TP concentrations by about the year 2000.
(b) Zero TP load: Wash out conditions would be complete by about year 2008.

Reliability of projections

The possible 'errors' associated with the projected values are probably ± 0.1 mg TP/l.

Annual TP load and Waihai TP concentrations

Using the first few years of the Scenario 0 values, an excellent straight line correlation of the modelled Waihai TP concentrations with annual TP loads entering, was indicated.

TP (mg/l) = 0.0008 (TP load in tonnes/yr) - 0.0098

This suggests that to achieve the previously unpolluted conditions in Waihai of some 30 years ago, would necessitate an annual TP load of around 60 tonnes per year, i.e. about 10% of the present value.

CONCLUSIONS

The main conclusions from the modelling work need to be set within what is judged to be the most realistic future situation of changes in the Lake Dianchi catchment area (Mongomery Watson, 1996g). The following scenarios are thought to be realistic:

i) only a slight increase in non-point source TP loadings will occur:
ii) 50% reduction in potential non-point source TP loadings could be achieved:

Projections using the foregoing assumptions have been presented in Figure 5.

Further work is clearly needed in order to refine the results from this modelling work, since:

a) the 'do-nothing more' scenario would not be acceptable;
b) it will be impossible to return the Waihai to its original pristine ecological state which existed 30 years ago;
c) overall, it will be difficult to do more than halt the increase in total P concentrations in the lake.

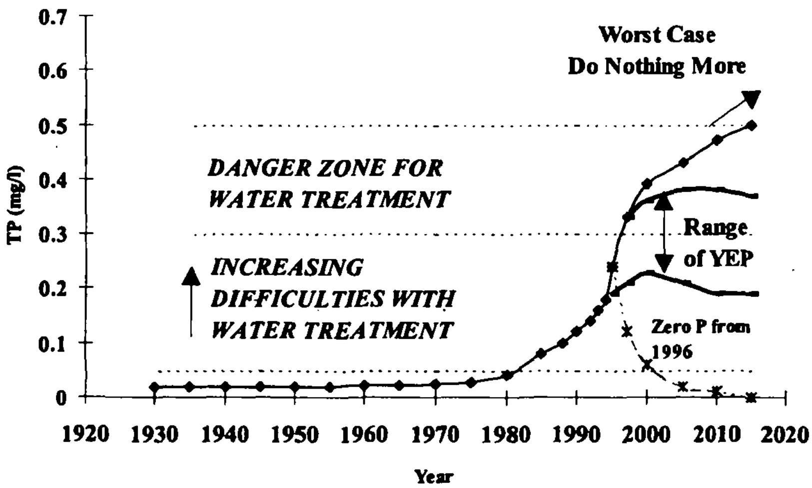

Figure 5. Predictions of effects of implementation of realistic intervention.

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