Nutrient Management in the Lake Tai Basin, China – Application of Source water quantity and quality model to Dongshan Peninsula

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Abstract

Lake Tai is the third largest freshwater lake in China, bordering Jiangsu and Zhejiang provinces, providing water to 30 million residents. A severe algal bloom in 2007 led to the development of the Lake Tai Master Plan, launched by the National Development and Reform Commission (NDRC), to improve nutrient management in the basin. Under a joint Australian China Environmental Development Project, the Australian eWater Source Integrated Modelling System (IMS) was applied to model water quantity and quality for a pilot area on the Dongshan Peninsula in the Lake Tai Basin. Source is a powerful modelling platform for environmental management which can integrate many physical processes and human impacts, successfully applied in over 70 basins across Australia.

The aims of the project were to: apply the model to a small pilot area and investigate strategies to improve nutrient (total nitrogen (TN) and total phosphorus (TP)) management in the Lake Tai Basin. Source was applied to the 77 km^2 Dongshan Peninsula. The model consisted of 50 subcatchments with seven major landuse categories including aquaculture (43% of the area), upland and lowland fruit trees (31%), low and high density urban (12%) and vegetables (6%). The daily timestep model was run for the period 2001 to 2010. The flexible nature of the Source software enabled a number of novel modelling approaches to be applied such as simulation of the seasonal variability in runoff and nutrient export from the 33 km^2 of aquaculture ponds on the Peninsula.

The model was parameterised and validated drawing on local knowledge, expert opinion from the Chinese and Australian technical working group and literature from both countries. Three scenarios were investigated. The implementation of a proposed wetland to filter runoff from the aquaculture ponds could reduce TN and TP exports to the lake by 13 and 16% respectively. Other scenarios included the closure of the sewage treatment plant, and the adoption of improved fertilizer management practices in the vegetable and tree cropping areas. The project has provided valuable insights into the dominant nutrient sources exported to Lake Tai, potential nutrient reduction strategies and priorities for future research and data collection.

Keywords: *water quality, catchment modelling, Source*

1. Introduction

Lake Tai is the third largest freshwater lake in China, bordering Jiangsu and Zhejiang provinces, providing water to 30 million residents and covering an area of 2,338 km^2. Rapid industrial and agricultural development in the last 20 years have caused water eutrophication in Lake Tai watershed to become one of most serious environmental issues in Southeast China (Mao *et al*., 2008). A severe algal bloom in the Lake in 2007 led to the development of the Lake Tai Master Plan (NDRC 2008), launched by the National Development and Reform Commission (NDRC), to improve nutrient management in the basin.

Through the Australia China Environment Development Partnership (ACEDP), the Aus Lake Tai Cluster (AUS) led by Earth Systems and the NDRC's International Cooperation Centre (ICC) has implemented the *Lake Tai Water Pollution Treatment Project* in Suzhou, Jiangsu, Huzhou & Zhejiang Provinces. The Project's objective is to strengthen management and policy approaches in the Lake Tai basin by increasing awareness of Integrated River Basin Management (IRBM) and science-based management approaches, and identify priority areas for further assistance.

Non-point source nutrient pollution was identified as a major but still poorly understood source of pollution for the Lake. Municipal officials raised concerns that while they have mobilized significant resources, understanding of the impact and effectiveness of their investments is lacking. They indicated that approaches that enable better informed and evidence based government policy and decision making are needed.

Modelling is one of a number of strategies used to assist in identifying and prioritizing management practices to reduce both point source (PS) and non-point source (NPS) pollution to the Lake. The Australian eWater Source Integrated Modelling System, Source (Delgado *et al*., 2001), is a flexible modeling platform for dealing with the complex water quantity and quality management rules and integrates many physical processes and human impacts into the model. Source has been successfully applied in over 70 catchments across Australia (eWater CRC 2011).

The aim of this project was to construct a Source model for a pilot area in the Lake Tai basin, the Dongshan Peninsula, to demonstrate how this particular model could be used to investigate strategies to improve nutrient (total nitrogen (TN) and total phosphorus (TP)) management. This paper outlines the model development and presents key findings from the modelling related to a number of the planned strategies for reducing nutrient export on the peninsula.

It should be noted that the main focus of this modelling exercise, was to demonstrate how this model could be applied in China to explore alternative nutrient management strategies. Model results presented in this paper should only be taken as indicative estimates of pollutant loads for the Dongshan Peninsula. Further work will be required to refine and improve model outputs as further local data becomes available.

2. Source Modelling Framework

The Source catchment water quantity and quality modelling framework is not a single model but a collection of models whereby the user chooses runoff, pollutant generation, filter and in stream model components that best describe the catchment hydrology and pollutant generation processes occurring in their catchment. Pollutant generation models are applied to a "functional unit", typically a specific landuse or hydrological response unit within a subcatchment. All flows and pollutant loads for each functional unit in a subcatchment are aggregated at a subcatchment outlet node. Runoff and pollutant loads are routed through a series of nodes and links (Figure 2) representing the stream network to the catchment outlet (Delgado *et al*., 2011).

In addition to the standard range of models available within Source, the user can also add their own mathematical equations or "expression" at any node or link within the model to calculate and record any range of variables. The Dongshan model was developed incorporating physical processes at a level of complexity appropriate to the current knowledge and data available for the area.

3. Donghsan Peninsula

The Dongshan Peninsula is located in the south eastern corner of Lake Tai (N 31°05', E 120°24') (Figure 1). The catchment area of interest covers 77 km^2. It is located in a subtropical monsoon zone. The Peninsula consists of a low mountain range with steep slopes, surrounded by lowlands mostly occupied by aquaculture ponds. Average temperatures range from 4^o Celsius in January to 28^o Celsius in July with the average annual rainfall of 1,113 mm and average lake evaporation of 984 mm. Approximately 60% of the annual rainfall occurs over the Spring and Summer periods.

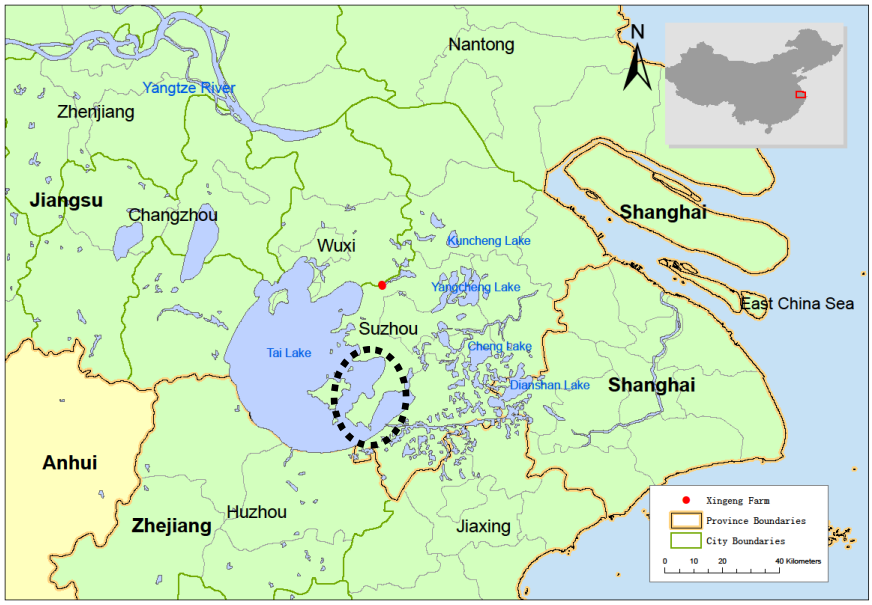

Figure 1: Location of Dongshan Peninsula indicated by dashed circle

The soils of the upland ridges of the Peninsula are shallow red loess, used for growing pine forests only and are protected from further development to minimize erosion. The intermediate and lower slopes, used for growing fruit and tea trees are a clay loam (30% clay fraction), have slopes between 15^o – 25^o, pH 5-6, and a soil depth of 0.40-1.0m. The flat areas close to the lake shore are

predominately used for aquaculture, vegetables and paddy fields, are clay loam with some fine sands and sandy loam soils present.

The dominant landuse is aquaculture (predominantly used for crab farming) covering approximately 43% of the area. Upland and lowland fruit trees occupy 31% of the area, high and low density urban (12%), vegetables (6%) with the remainder industrial and forested land. Dongshan Peninsula has a population of 53,000, of which around 44,000 people are in rural or low density urban areas. Runoff to Lake Tai is from both rainfall and controlled drainage from the aquaculture ponds. Runoff enters the Lake via a combination of streams and constructed canals. Gates are located at each exit point and many of the canals are interconnected. When Lake levels increase to 3.45m or greater, all gates are closed to prevent flooding of the low lying areas and runoff is then pumped to the Lake via pump stations located at four of the 13 exit points to the Lake.

4. Model Development Process

The eWater CRC Best Practice modelling guidelines (Black *et al*., 2011) were used to guide the project development process. Five of the key steps in the project development process are described in the following section.

4.1 Problem Definition

It was important at the project inception to clearly describe and reach agreement on the problem to be addressed. This was achieved through iterative consultation with a range of stakeholders involved including policy staff, scientists, and other technical experts.

4.2 Technical Working Group

A project technical working group was established comprised of Australian experts from eWater Cooperative Research Centre (eWater) and Earth Systems Australia & China; Chinese technical experts and scientists from Suzhou Municipality, the Taihu Basin Authority (TBA) and the Nanjing Institute of Geography and Limnology (NIGLAS). A series of workshops and training activities were conducted both in China and Australia to build capacity in the development and use of the Source modelling framework. The working group took an active role in identification of priority landuses, catchment drainage configuration, collation of local literature, validation data and scenario development.

4.3 Conceptual Model Development

Once all relevant information was collated, site visits and discussion with local experts completed, a conceptual model of the hydrology and nutrient generation and transport processes was constructed. This was achieved through a half day workshop to develop maps and flow diagrams on a whiteboard. There were numerous iterations from the initial design and agreement was reached on an appropriate model with a level of complexity appropriate to the data availability and project time constraints.

4.4 Scenario Development

A key objective of the project was to demonstrate how the model could be applied to assess different management options to reduce nutrient export to the Lake. The scenarios selected were based on Lake Tai Basin policies or projects proposed in regional plans. Numerous scenarios were considered by the

working group with three selected for detailed investigation based on their practicality and potential for implementation. The three scenarios proposed were:

1) **Improved Point Source Management** – There were two components to this scenario, formulated from recommendations in the Lake Tai Master Plan (NDRC 2008). Firstly, decommissioning of the Sewage Treatment Plant (STP) for the Dongshan Peninsulas with sewage from Dongshan township transferred to Wuzhong District STP. Secondly, in recent years 80% of low density urban areas were upgraded with secondary treatment facilities as part of the Master Plan. In the scenario, we assume the remaining 20% of household septic systems were also upgraded.

2) **Improved Diffuse Source Management** – There were two components to this scenario based on recommendations in the Lake Tai Master Plan (NDRC 2008). Firstly, the plan recommends that improved farming practices such as precision application of fertilizer, modifying the timing of fertilizer application and crop rotations could reduce nitrogen and phosphorous fertilizer inputs by 20-30% & 10-20% respectively. Currently, only a small portion of the agricultural areas (<10% of fruit tree crops for example) are implementing these practices. For this scenario the assumption was made that the nutrient generation rates were positively correlated with the rate of fertilizer application (Wang *et al*., 2008) in the Lake Tai Basin. A 20% reduction in TN and 10% reduction in TP generation rates for the two farming practices occupying the greatest area on the Peninsula (lowland vegetables and upland fruit trees) were therefore applied. Secondly, with 43% of the area of the Peninsula used for crab farming it was important that this industry be included in the scenario. Local technical experts suggested that the majority of existing crab ponds were using traditional farming practices used in the district for many years. Based on local knowledge, the technical working group estimated that improved crab farming operations could reduce pond nutrient concentrations exported to the canals by as much as 25-30%. For this scenario we assumed all ponds were upgraded to reduce TN and TP exports by 25%.

3) **Construction of Large Wetland for aquaculture pond filtering -** Scenario 3 was a remediation project proposed in the Suzhou Environmental Protection Plan. The project was in a very early stage and thus difficult to obtain detailed information and data. The proposed wetland has joint objectives for environmental remediation, landscape transfiguration and recreational use. The location of the proposed wetland is in the southern corner of the Dongshan Peninsula in an area not currently farmed (Figure 2). The objective of this work was to provide a wetland to filter aquaculture pond water prior to discharge to the Lake. The construction is proposed to occur in three stages. Stage 1 – over an area of 3000 mu (2 km^2), Stage 2 - 10,000 mu (6.7 km^2) and Stage 3 - 35,000 mu (23 km^2). The model was modified to divert up to 50% of the drained aquaculture pond water to the Stage 2 wetland prior to release to the Lake over the month of December. With limited details available on the design specifications for the wetland, a number of assumptions were made as to the wetland design specifications and nutrient removal rates based on Australian and Chinese literature ((Melbourne Water (2005), Lu *et al*., (2009), Fei *et al*., (2011))

4.5 Model Construction

Specific details of the development of the Dongshan Peninsula Source model is detailed in Waters *et al.*, (2012), the following is a brief outline of the model configuration. The model contained 45 subcatchments, with subcatchment boundaries based largely on topography for the upland areas,

canals, streams and earthen banks on the lowland aquaculture areas. The node link network was designed to enable reporting of modelled runoff and loads at five nodes or zones of the Peninsula (Figure 2). The model contained nine landuse categories and one STP.

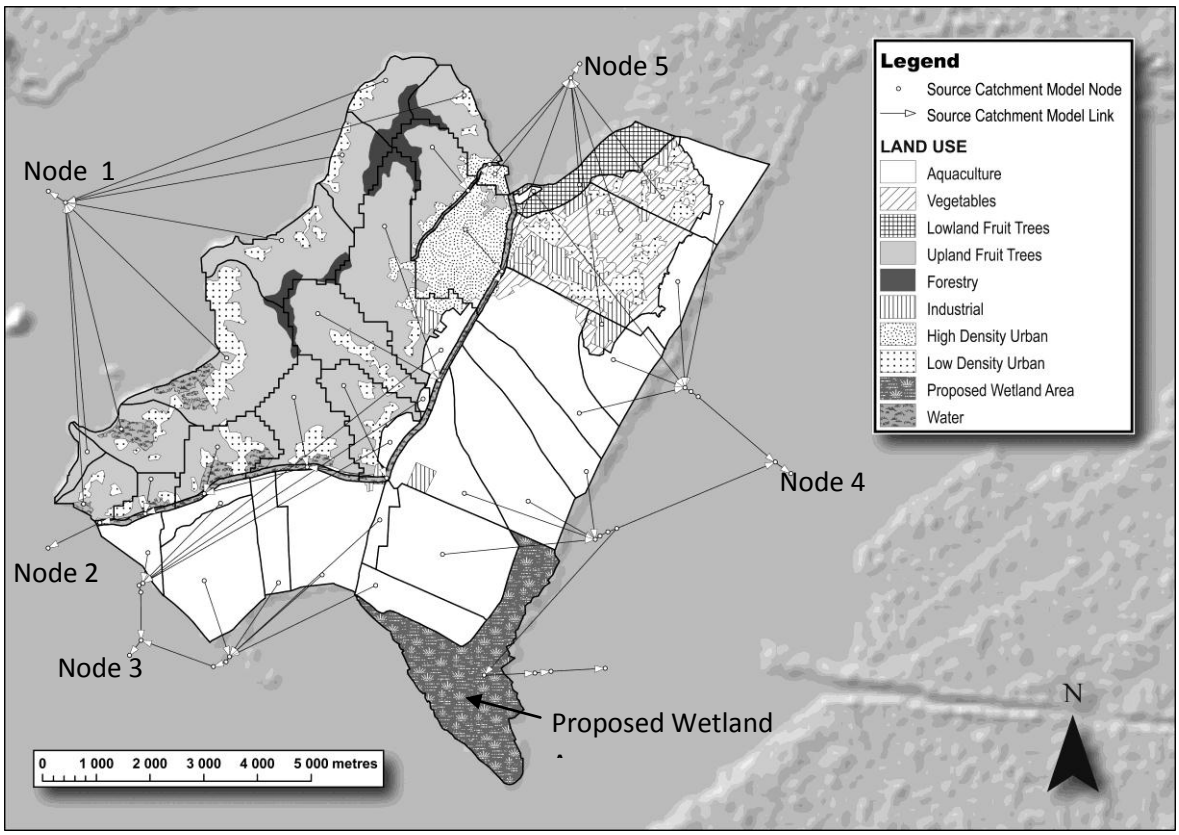

Figure 2: Source Landuse and subcatchment configuration with the node link network overlayed.

The model was run at a daily time step for a 10 year period from 2001 – 2010. Annual rainfall over the model run period ranged from 782-1,280 mm with an annual average of 1,068 mm close to the long term mean. Rainfall and evaporation data were supplied by the Suzhou Environment Institute, Academy of Environmental Science; and the Suzhou Environmental Protection Bureau. Source uses conceptual rainfall runoff models to generate daily runoff estimates. The inputs required are daily rainfall and potential evaporation and typically rely on measured runoff data for model calibration. SIMHYD rainfall runoff model (Chiew et al., 2002) was chosen due to its extensive use across Australia particularly in wet and temperate climates. Due to a lack of measured daily runoff data for the Peninsula, manual calibration was undertaken to ensure the proportion of runoff generated for each landuse corresponded with literature values for the region. Australian literature was also sourced particularly for urban areas where comparisons could be made as an additional source of data to validate the model results (Refer Waters *et al*., 2012 for further details). Through consultation with the technical working group it was agreed that Total Nitrogen (TN) and Total Phosphorus (TP) would be modelled. It was acknowledged that differentiation of the different forms of nitrogen, in particular Ammonia nitrogen (NH3-N), would be useful when considering management strategies outlined in the Master Plan and may be explored in future projects. A mean concentration was assigned to each landuse based on local literature. The input data was predominantly from farm or field scale experiments.

Aquaculture ponds are a major source of both runoff and nutrients entering Lake Tai from the Dongshan Peninsula. It was important therefore that the pond hydrology and nutrient generation processes were appropriately represented in the model. The 33km^2 of aquaculture ponds were aggregated into four large storages with the total volume of the four storages approximating the volume of all individual ponds. Specific expressions were written to simulate filling and draining patterns of the ponds throughout the year.

An additional feature requested to be incorporated into the model was to quantify runoff to Lake Tai from either natural rainfall runoff or pumped runoff as described in section 3. Equations or expressions were written into the model to record the runoff volume and pollutant load entering the Lake as natural rainfall runoff (Lake level below 3.45m) or via the pump stations (Lake level >= 3.45m when gates are a closed). A timeseries file of lake levels was provided for determining pumping periods to the lake.

5. Model Results and Discussion

The base model provides a good representation of the hydrology and nutrient generation processes for the Dongshan Peninsula at a level of complexity appropriate to the level of data available and modelling objectives. The output from the base model provides useful information on the relative contribution of runoff, Total Nitrogen (Figure 3) and Total Phosphorus to Lake Tai from the major landuses represented in the model. The following section summarises the model validation results, modelled runoff and nutrient load estimates and the scenario findings.

5.1 Model validation

There were two sources of data provided for model validation. The first data set was provided from in stream water quality sampling collected at two monthly intervals at two locations in the main stream of the Peninsula collected from 2008-2011 by the Suzhou Environment Institute. The mean TN concentration for the four years was 2.15 mg/l (0.24 -19.0 mg/l). The Source average annual modelled estimate of TN concentrations entering the lake was double the observed concentration at 4.40 mg/l. For TP the mean measured concentration was 0.18 mg/l (0.02 – 2.70 mg/l) with Source at 0.35 mg/l.

The second data source was from the Lake Tai Master Plan (NDRC 2008). The plan listed average annual measured TN and TP concentrations from rivers entering Lake Tai between 1998-2006 in the Changzhou, Wuxi, Suzhou and Huzhou Municipality's. Measured TN concentrations ranged from 2.57 – 5.75 mg/l. Source average annual TN concentration was within the range reported at 4.40 mg/l. Measured TP concentrations ranged from 0.114 – 0.27 mg/l with Source estimate of 0.35 mg/l slightly higher than the range reported.

The model results were encouraging given the limited local data available to parameterise and validate the model. The over estimation of modelled nutrient concentrations may be due to not accounting for in-stream nutrient losses or nutrient transformation processes. Further data collection to quantify nutrient generation rates for aquaculture, fruit trees and vegetables in conjunction with in stream nutrient sampling during summer runoff periods will greatly improve confidence in model results.

5.2 Base model runoff and load estimates

Aquaculture contributed around two-thirds (66%) of the average annual runoff with the second largest contribution from upland fruit trees (around 15%). Two-thirds of all runoff from the ponds to the Lake occurs in December each year when they are drained. Despite the aquaculture ponds contributing the

majority of the runoff, the ponds and upland fruit trees are contributing similar proportion of TN load 37% and 34% respectively (Figure 3). Whilst fruit trees occupy a smaller area, the combination of above average runoff volumes from the steep slopes and high TN generation rates resulted in similar loads being generated from both landuses. For TP, the model suggests that the majority of the load contribution is from the aquaculture ponds due to their high runoff volume in comparison to the low runoff volumes and low TP generation rates from cropping and urban areas.

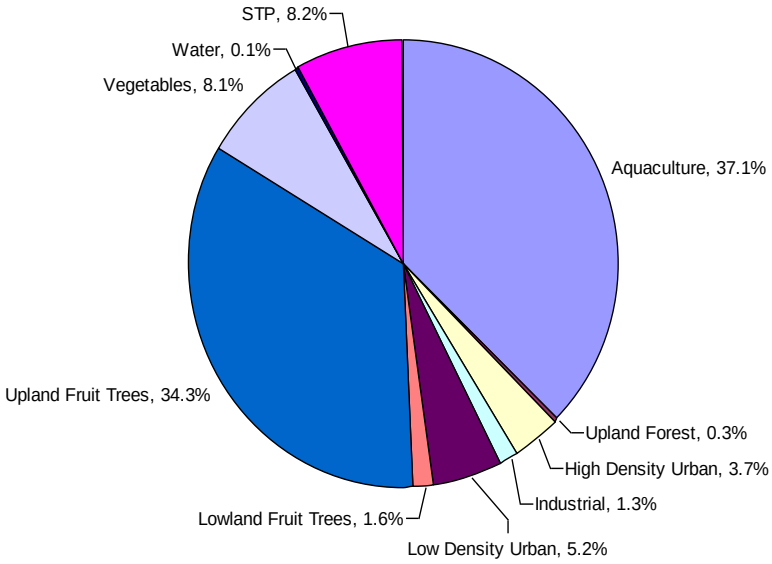

Figure 3: Average annual modelled TN load for each landuse as a proportion of the total load entering Lake Tai from Dongshan Peninsula.

5.3 Management Scenario Results

An important objective of the project was to demonstrate how the Source model could be applied to explore a range of management scenarios to reduce nutrient export to the Lake Tai Basin. The modelling results for the three scenarios are outlined below and in Figure 4.

1) *Improved Point Source Management* - The model suggests that upgrading the remaining 20% of low density urban areas from traditional septic systems to domestic waste units in conjunction with the connection of the Dongshan STP to the main sewage network could achieve a 9% reduction in average annual TN and 13% reduction in TP load to the Lake. The majority of this load (90%) is attributed to the removal of the STP.

2*) Improved Diffuse Source Management* - Reduced fertilizer inputs to vegetable and upland fruit growing areas resulted in a 9% and 2% reduction in average annual TN and TP loads respectively directly related to the reduction in generation rates. Adoption of improved practices for aquaculture pond management resulted in a 9% and 23% reduction in average annual TN and TP loads respectively. Therefore the implementation of improved practices in vegetable farming, upland fruit tree areas and aquaculture pond management combined, could result in an approximate 18% reduction in TN export and 25% reduction in TP export to the Lake annually.

3) *Wetland* Filtration- The model suggests that construction of the wetland to filter 50% of aquaculture pond runoff could reduce total exports of TN by approximately 13% and TP by 16%.

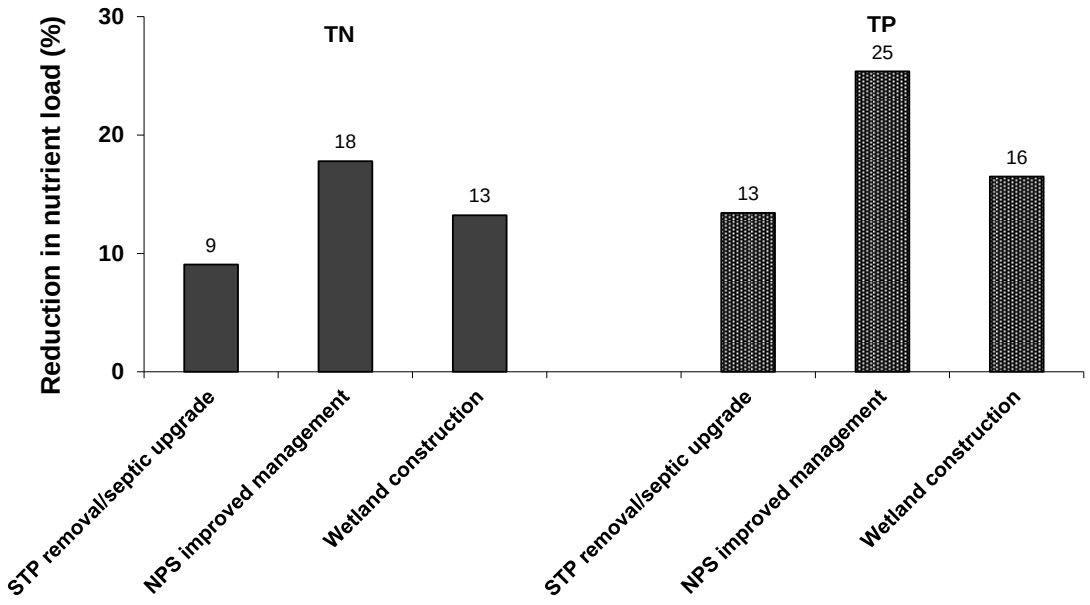

Figure 4: Modelled TN and TP estimates of load reductions to Lake Tai as a result of implementing three different improved practices: point source management, non-point source management and wetland construction.

The scenario results, demonstrate the potential application of Source to explore a range of management strategies. Whilst the results are only indicative, the assumptions used in the model were based on findings from local research and the technical working group. Results suggest that there is potential for significant improvements in water quality to help achieve the short and long term water quality objectives outlined in the Lake Tai Master Plan.

6. Conclusions

A Source model was developed for the Dongshan Peninsula with the flexibility of the model demonstrated through features such as the inclusion of the aquaculture ponds and canal pumping regimes.

The results suggest that the modelled TN and TP concentrations showed reasonable agreement with local data collected from streams within the Peninsula and a number of other rivers entering Lake Tai. The modelling suggests that the Aquaculture ponds and upland fruit trees each contribute between 30-40% of the total nitrogen load to the lake. Three scenarios were modelled with a number of potential management options identified which require further investigation.

The project has demonstrated the potential of models to inform policy and improve our understanding of the impacts and effectiveness of investment in nutrient management strategies for Lake Tai Basin. The success of this project was only possible through the collaborative efforts of the Australia China Environment Development Partnership (ACEDP), the Aus Lake Tai Cluster (AUS) led by Earth

Systems, the NDRC's International Cooperation Centre (ICC), the technical working group members and the eWater CRC.

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