# 行政院國家科學委員會補助專題研究計畫成果報告

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**計畫主持人： 高正忠**
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**共同主持人：**

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**執行單位：國立交通大學環境工程研究所**

**中　華　民　國** 90 **年**　08 **月** 20　**日**

# 行政院國家科學委員會專題研究計畫成果報告
## 非點源污染分區管理方案評估(I)
## Assessment of zone management strategies for non-point source pollution control (I)

**計畫編號**：NSC 89－2621－Z－009－007
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### 一、中文摘要

**農業非點源污染所帶來的總磷量占污染水體中總磷量的大部分，故被列為改善水庫、湖泊水質及優養化之重要管制項目。在之前一個針對寶山離槽水庫的非點源污染控制策略分析中，結果顯示在三個控制策略中，以子集水區**(Subwatershed, SW)**為管理單位的控制策略有較多優點，該策略把整個子集區當做一區來管制，然而事實上，人為農業活動區域往往只佔一個子集水區的一小部分，其他地區大部分是天然林或植被，這些地區，在管理上並不困難，因而希望以較符合現況的土地管理單位**(Land management unit, LMU)**來管制，將每一個相鄰的農作區域視為一個管理單位。本研究比較分別以** LMU **與** SW **為管理單位之差異性。首先以案例區較新的資料，應用農業非點源污染** AGNPS **模式模擬水庫集水區之非點源污染負荷，然後分別建立** LMU **及** SW **為單位之多目標分析模式，然後針對案例區分析二個管理方式之差異。結果顯示，雖然** LMU **的管理單位數稍比** SW **方式稍多，但其在水質、成本及公平性之結果均不亞於** SW **方式，以** LMU **來取代** SW **對案例區而言，應是適當地決策。**

**關鍵詞：非點源污染、分區管理、環境系統分析**

### Abstract

Phosphorus loads from non-point source (NPS) pollution significantly degrade the water quality of a reservoir. Adequate control of NPS pollution is therefore necessary to improve the water quality and avoid the progression of eutrophication. In our previous analysis of NPS pollution management strategies for Posan Reservoir, the control strategy entailing sub-watershed (SW) as a management unit was observed to be the most effective among three alternatives analyzed. However, the area of human agricultural activity occupies only a small portion of a SW zone, and the remainder is primarily natural forest or grassland that is relatively easy to manage. The control strategy administered based on the land management unit (LMU), which views adjacent crop areas as a LMU, is therefore explored herein. This study compares the NPS management performance of SW and LMU control strategies. The AGNPS model is employed to simulate NPS pollutant loading. Multiobjective models are established for both strategies to evaluate their effectiveness in terms of water quality, cost and equity. Modeling results indicate that the LMU strategy performs as efficiently as the SW strategy. Adopting LMU in place of SW as a NPS control strategy is a viable decision for the study area.

**Keywords**: non-point source pollution, zone management strategy, environmental systems analysis.

### 二、緣由與目的

Reservoirs are vital water sources in Taiwan and significantly influence the livelihood of the society and national economy. However, reservoir water quality is suffering adverse impacts from the non-point source (NPS) pollutants discharged from upstream development and other human activities, accelerating eutrophication and silting of the reservoir, affecting normal water use and increasing the cost of water treatment [1]. Agricultural activities, the major origin of NPS pollution, result in a wide and complex range of pollutants, including nutrients, soil erosion and pesticides. As for total phosphorus loading, agricultural activities account for over 70% of all phosphorus pollution of waterbodies. Adopting proper cropping and management strategies for agricultural activities in a watershed to reduce the NPS pollutant loading on a reservoir is thus important in controlling pollution.

For reservoirs in Taiwan with significant eutrophication, phosphorus is often the major limiting factor for algae growth [2]. Monitoring data revealed a clear deterioration in water quality of the Posan Reservoir due to agricultural and development activities in its upstream watersheds. Proper strategies to control NPS pollution should be explored to remedy the eutrophic condition. Our previous study [3] found the sub-watershed (SW) strategy the most effective among the three phosphorus zone control strategies that were investigated. However, the cultivated area occupies only a small portion of a SW, with the remainder dominated by relatively easily managed natural forest or grassland. This study thus explores a possible alternative based land management unit (LMU) [4][5] to replace the SW strategy. Each LMU views a group of adjacent areas with similar cropping practice as an independent management unit. This study compares the management effectiveness and performance of the SW and LMU strategies.

The management effectiveness and performance of both strategies is primarily evaluated in terms of cost, water, and equity [3]. However, these three objectives are often contradictory. For example, significantly improving water quality requires increasing the cost for reducing NPS loads. Focusing on reducing pollution loads from major sources is generally regarded as a cost-effective strategy, but it may be difficult to implement if not all pollution sources are fairly treated. These conflicts make it difficult for analysts to reach a consensus decision. Therefore, it is necessary to examine the trade-off relationship among different objectives to facilitate decision making.

This study compares the LMU and SW strategies from the perspectives of cost, water quality and equity to assess the viability of replacing SW with LMU. The agricultural non-point source (AGNPS) [6][7] model was employed to simulate the pollutant loading from all SWs and LMUs and to derive their water quality impact coefficients [3]. Multiobjective programming models entailing three objectives of cost, total phosphorus and equity were established for the SW and LMU strategies, respectively. The results for the trade-off relationship among objectives of the two models were compared, and the suitability of replacing SW with LMU strategy was also discussed.

Posan Reservoir, situated in Hsinchu County, is an off-stream reservoir with water mostly transported from Shang-ping Creek. It is one of two major public drinking water resources in Hsinchu area. Phosphorus levels in the reservoir water are around 22-42ppb. According to Carlson [8] standard, the reservoir is in the eutrophy status stage and an appropriate management strategy is required. Our previous studies [3][9] of total phosphorus control strategy and internal loading estimation analyses used data for 1986-1988. Since land use in the watershed has gradually changed after the earlier study, regional data for 1991-1995 were thus re-collected for use in the present work. Chutong Channel transports water into the reservoir from Shangping Creek and supplies irrigation water required in the Chutong watershed. According to the modeling result reported by Kao et al. [9], the areas for agricultural operations, although occupying a relatively small portion at 12.5 % of the entire watershed, contribute up to 70% of the total phosphorus into the reservoir, with the remaining phosphorus coming primarily from internal loading. Proper management of agricultural activities is therefore necessary to control NPS pollution. The single storm event version of the AGNPS model [6][7] was employed to simulate NPS loading distribution. The study area was divided into a set of 120mx120m grids. Various model parameters collected from aerial photographs, regional data, model related documents and manuals, and field investigation were prepared for each grid. The modeling output included runoff and water quality related parameters for the watershed outlet and each grid, including runoff volume, peak runoff rate, total nitrogen, total phosphorus, and sediment. The model estimated the phosphorus loading generated by each SW and LMU and its impact on water quality.

## 三、模式

The descriptions below first define sub-watershed and land management unit, then the phosphorus fertilizer control model developed by Kao and Tsai [3] for the SW strategy is presented. Lastly, the multiobjective model established based on three objectives of cost, water quality and equity for the LMU strategy is described with relevant constraints.

*SW and LMU*

In the SW strategy proposed by Kao and Tsai [3], all grids in the same sub-watershed drain into the same outlet. In the study area, Chutong Channel watershed is divided into 12 SWs and Posan Reservoir watershed is divided into 9 SWs, totaling 21 SWs. Land grids close to the Chutong Channel are grouped as a special SW, SW 9 of the Chutong Channel watershed.

The LMU used herein is similar to that defined by Bouzaher et al. [4][5]. A LMU is defined as a group of land grids with similar cropping practices in the same sub-watershed. Grids for forest, waterbody, and other natual lands are not included because these areas are not major sources of pollution and relatively easy to manage. In the study area, Chutong Channel watershed is divided into 26 LMUs and Posan Reservoir watershed is divided into 15 LMUs, totaling 41 LMUs.

Annual phosphorus fertilizer applications were estimated for each crop (LMU) in each SW. Associated phosphorus loading on the outlet from each LMU in each SW was simulated by AGNPS.

*Water Quality Impact Coefficients*

The pollution impact of soluble phosphorus in runoff is assumed linearly proportional to the magnitude of fertilizer phosphorus applied. For each SW and LMU, the extent of the impact from fertilizer phosphorus reduction with respect to decreasing the pollution loads for the water body can be expressed with a coefficient. The coefficient multiplied by the amount of the fertilizer phosphorus reduction of a SW or LMU is the phosphorus load reduction on the water body. The coefficient is determined by executing

AGNPS twice (or more) with varied amounts of fertilizer phosphorus for each SW or LMU. Then, the impact coefficient of a SW or LMU is determined by dividing the soluble phosphorus change on the outlet by the difference of two varied amounts of fertilizer phosphorus. The impact coefficients are used to establish multiobjective models for evaluating both SW and LMU strategies.

*Objectives: Water quality, cost and equity*

Three objectives of water quality, cost, and equity are simultaneously evaluated in this study. The water quality objective is achieved by reducing phosphorus fertilizer application. The reduction of phosphorus loading required to attain certain water quality level was obtained from Kao et al. [10]. Cost is determined by total production loss for the amount of phosphorus fertilizer reduction. Equity is another issue to evaluate and is defined as the sum of the deviation [11] of the fertilizer reduction rate of each zone to the average reduction rate. The farther the difference between the reduction rate and the average rate, the worse the equity, and vice versa.

*Multiobjective Model: SW*

The SW multiobjective model applied herein is identical to that established by Kao and Tsai [3]. The SW model is formulated as follows.

$$\text{Min}\sum_{i=1}^{I}[\sum_{j=1}^{J}(W_j)(P_{ij})](x_i) \qquad \text{(Cost)}$$

$$\text{Max}\sum_{i=1}^{I}[\sum_{j=1}^{J}(IP_{ij})(P_{ij})](x_i) \qquad \text{(Load Reduction)}$$

$$\text{Min}\sum_{i=1}^{I}(u_i+v_i) \qquad \text{(Equity)}$$

Subject to

$$0 < x_i < 1$$

$$\sum_{i=1}^{I}(x_i) = Nx_{ave}$$

$$x_i - u_i + v_i = x_{ave} \quad \forall i$$

all variables are non-negatvie.

where $i$ denotes the SW index number, $I$ is the total number of SWs (12 for Chutong Channel watershed and 9 for Posan Reservoir watershed); $j$ is the crop number, $J$ is the total number of crops (4 in Chutong Channel watershed and 3 for Posan Reservoir watershed); $W_j$ is production loss incurred to crop $j$ from reducing unit phosphorus fertilizer application; $P_{ij}$ is the annual normal phosphorus fertilizer application of crop $j$ in SW $i$; $x_i$ the rate of phosphorus fertilizer reduction required for SW $i$, the variable to be solved in this model; $IP_{ij}$ is the water quality impact coefficient for unit reduction of phosphorus fertilizer application for crop $j$ in SW $i$, determined using the AGNPS model by Kao and Tsai [3]; $x_{ave}$ is the average reduction rate of phosphorus fertilizer application; $u_i$ and $v_i$ are respectively the negative and positive deviations of $x_i$ to $x_{ave}$; and N is the number of SWs, N is equal to 21.

*Multiobjective Model: LMU*

The multiobjective model for the LMU strategy is similar to the model discussed above for the SW strategy, except that the management unit is changed from SW to LMU. The LMU model is formulated as follows.

$$\text{Min}\sum_{l=1}^{L}\sum_{j=1}^{J}(W_j)(P_l)(x_l) \qquad \text{(Cost)}$$

$$\text{Max}\sum_{l=1}^{L}(IP_l)(P_l)(x_l) \qquad \text{(Load Reduction)}$$

$$\text{Min}\sum_{l=1}^{L}(u_l+v_l) \qquad \text{(Equity)}$$

Subject to

$$0 < x_l < 1$$

$$\sum_{l=1}^{L}(x_l) = Lx_{ave}$$

$$x_l - u_l + v_l = x_{ave} \quad \forall l$$

all variables are non-negatvie.

where $l$ denotes the LMU index number, $L$ is the total number of LMUs (26 for the Chutong Channel watershed and 15 for the Posan Reservoir watershed); and all other variables are defined same as those for the SW model.

## 四、結果與討論

The SW and LMU multiobjective models are solved by CPLEX [12] with the Constraint Method described by Cohon [13]. The results reveal that the higher the requirement for water quality (lower phosphorus concentration), the higher the cost. Comparing the results for the both SW and LMU models, the LMU strategy achieved the same water quality level as the SW model at a lower cost. For results with the equity (E) objective, both solutions are the same because they are required to remove the same percentage of pollution load in each SW or LMU.

When the cost is limited below $5,000,000, the equity level of both strategies is about equal. However, The LMU strategy with optimal phosphorus level as the objective (LMU[P]) achieves worse equity than the SW strategy (SW[P]) when the cost limit exceeds $5,000,000. Notably though, the water quality target achieved with the same cost limit differs between the SW and LMU strategies. The LMU strategy achieves a better water quality level for the same cost limit.

With the same cost limit, higher equity (a smaller equity level) is achieved at the expense of a lower water quality target. According to the results, under the same cost limit, the LMU strategy can achieve better water quality target, and a similar result is also obtained when the limitation is on the same equity level instead.

Controlling NPS pollution generated from the upstream watershed is essential to reducing the water quality impact on the receiving reservoir waterbodies. Pollution control is particularly important if the reservoir is designated for public drinking water supply. Given the complexity of NPS pollution management, the environmental protection authority must assess conflicting objectives and come up with a suitable and viable management strategy. In one of our previous studies, using sub-watershed as a management unit was found to be a desirable approach. However, human agricultural activities occupy only a small portion of the sub-watershed area and the remaining natural area is easy to manage. This study therefore explores the applicability of replacing the SW strategy with the LMU strategy. Multiobjective models based on three major objectives of cost, water quality, and equity were established to assess the effectiveness of both strategies. The LMU strategy generates more management units than the SW strategy, but the actual management area is smaller. Multiobjective analysis for Posan Reservoir reveals that LMU achieves better water quality targets than SW for the same cost or equity constraints. Using LMU in place of SW as a management unit is desirable, at least for the study area. Future studies will focus on improving the multiobjective model by considering both phosphorus and sediment loads. Different Best Management Practices applicable for the study area will be also evaluated.

## 五、成果自評

**本計畫成果符合原進度規劃，部分成果已被環工學刊接受**[14]**，另有一篇論文正準備中**[15]**，預計投稿國際知名期刊。所得的模式亦適用於分析集水區非點源污染控制方案。其中最主要待改進的部分，是國外模式在國內之本土性適用性問題，**AGNPS **在國外本土的適用性並不是很好，雖然非點源污染模式模擬結果誤差一般不小，但國內實有必要發展適合本土的模式，唯要建立一個適當的本土化模式，將需要不少學者投入，期望未來能組成研究群長期發展之。**

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