A multiobjective model for non-point source pollution control for an off-stream reservoir catchment

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Abstract Phosphorus loads from agricultural non-point source pollution (NPSP) significantly degrade reservoir water quality, making adequate control of agricultural NPSP necessary for improving the water quality. Controlling NPSP is generally accomplished using various Best Management Practices (BMPs). The present study applies the Agricultural Non-Point Source Pollution (AGNPS) model to simulate NPSP loading and BMP efficiencies and establishes an enhanced multiobjective mixed-integer programming model for NPSP control strategy analyses based on these results. Cost, phosphorus load, sediment load and equity are the four major objectives considered. A case study for the Posan reservoir is presented. Four commonly proposed and applicable BMPs are chosen. Non-inferior solutions obtained using the constraint method and trade-off relationships among different control objectives are described and discussed. Compared with a previously proposed fertilizer control model, results show that the model established herein is more cost-effective and achieves better phosphorus and sediment loading reduction and equity goals. Furthermore, the current model is expected to facilitate decision-making analysis for development of an appropriate cost-sharing program to encourage adoption of appropriate BMPs by farmers.

Keywords Best management practices; environmental systems analysis; multiobjective model; non-point source pollution; optimization

Introduction

Reservoirs are vital water sources in Taiwan, and significantly influence the livelihood of the people as well as the national economy. However, reservoir water quality in Taiwan suffers adverse impacts from non-point source (NPS) pollutants discharged from upstream development and other human activities, which accelerate eutrophication and silting of the reservoir, affect normal water use and increase the cost of water treatment (USEPA, 1992). Agricultural activity, the major source of NPS pollution, accounts for over 70% of all phosphorus pollution to reservoir 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.

Monitoring data revealed a clear deterioration in water quality in the Posan Reservoir, an off-stream reservoir located in north Taiwan, due to agricultural and development activities in its watersheds. Proper strategies to control NPS pollution are required to remedy the eutrophic condition. Our previous study (Kao and Tsai, 1997) developed a multiobjective model based primarily on phosphorus load, zonal management strategies, and fertilizer application control. However, sediment is also an important pollution type that should be considered. The present study therefore expands the previous model to include sediment control as a primary management objective. Furthermore, the land management unit (LMU) control strategy proposed by Bouzaher *et al*. (1990, 1994) is adopted to replace the sub-watershed zonal management strategy proposed by Kao and Tsai (1997), because the cultivated area occupies only a small portion of a sub-watershed, with the remainder dominated by relatively easily managed natural forest or grassland.

Various Best Management Practices (BMPs) are widely applied to control NPS pollutants (*BMP Manual*, 2000). However, the effectiveness of different BMPs generally varies depending on the soil, cropping, runoff, and erosion characteristics of an agricultural land unit. Some BMPs may be effective in controlling erosion to reduce sediment, but ineffective for phosphorus nutrient control; and vice versa. In the previous model (Kao and Tsai, 1997), only a non-structural BMP, control of fertilizer application, was considered. The current model incorporates four BMPs generally proposed for local watersheds.

Management effectiveness and performance are primarily evaluated in terms of cost, phosphorus load, sediment load, and equity (Brill, 1979). However, these objectives are often contradictory. For example, significantly improving water quality (in terms of phosphorus or sediment load) requires an increased cost for reducing NPS loads. A focus 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. Therefore, it is necessary to examine the trade-off relationships among different objectives to facilitate a proper decision.

The present study uses the Agricultural Non-Point Source (AGNPS) (Young *et al.*, 1987) model to simulate pollutant loading from all LMUs, derive water quality impact coefficients, and simulate the control efficiency of applying a BMP. A multiobjective programming model containing four objectives (cost, total phosphorus load, total sediment load and equity) is thus established. Results for the trade-off relationships among objectives are compared and discussed. In addition to evaluating the effectiveness of management strategies, the proposed model is also suitable for use in facilitating analysis for development of an appropriate cost-sharing program to encourage the adoption of appropriate BMPs by farmers, although this strategy is implemented in another study.

Study area

The 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 the Hsinchu area. Phosphorus levels in the reservoir are around 22–42 ppb. Based on the Carlson (1977) standard, the reservoir is eutrophic and an appropriate management strategy is required. Figure 1 illustrates the relative location of the reservoir, its watersheds (Posan Reservoir watershed and Chutong watershed) and the Chutong Channel. This channel transports water into the reservoir from Shangping Creek and supplies the irrigation water required in the Chutong watershed. According to the modeling results reported by Kao *et al.* (1998), agricultural operations, although occupying a relatively small 12.5% of the watershed area, contribute up to 70% of the total phosphorus in the reservoir, with the remaining phosphorus coming primarily from internal loading. Proper management of agricultural activities is therefore necessary to control NPS pollution.

AGNPS

The single storm event version of the AGNPS model (Young *et al.*, 1987) was employed to simulate NPS loading distribution. The study area was divided into a set of 120 m × 120 m grids. Various model parameters collected from aerial photographs, regional data, model-related documents and manuals, and field investigation data were prepared for each grid. Runoff and water quality related parameters for the watershed outlet and each grid were output, including runoff volume, peak runoff rate, total nitrogen, total phosphorus, and sediment.

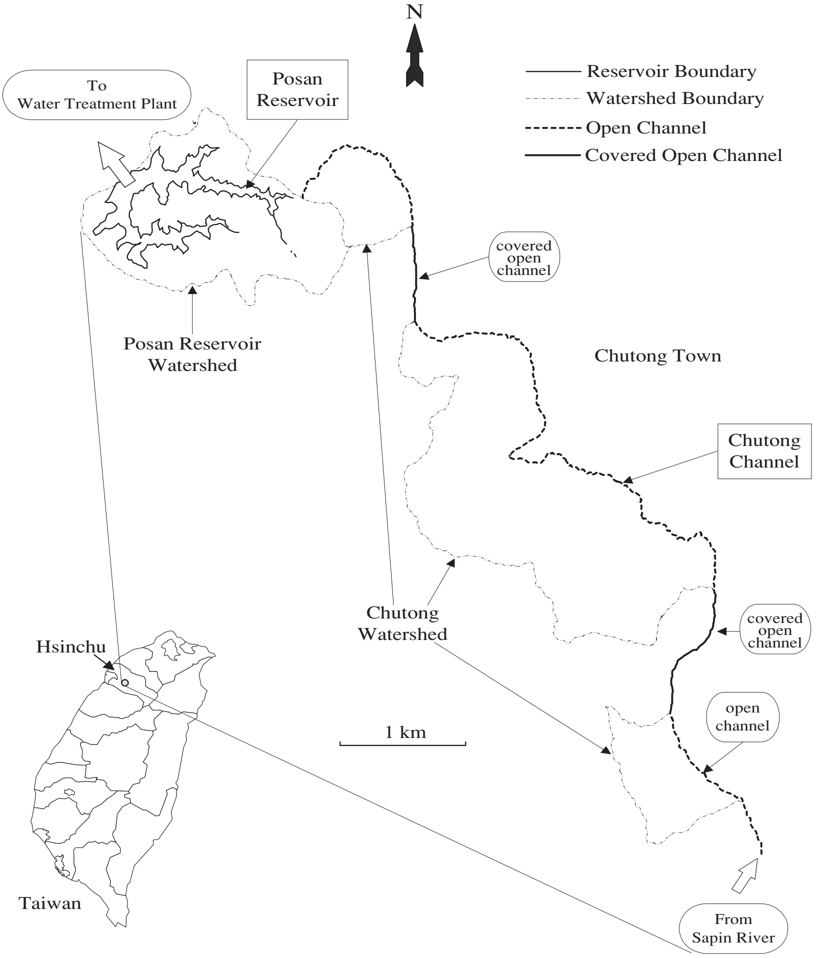

Figure 1 Location of Posan Reservoir and Chutong input channel

Multiobjective model development

In this section, the land management unit (LMU), the fertilizer control model, and BMP selection and effectiveness simulation are described first. The enhanced multiobjective model developed in this study is then presented at the end of this section.

Land management unit (LMU)

The LMU used herein is similar to that defined by Bouzaher *et al*. (1990, 1994). A LMU is defined as a group of land grids with similar cropping practices in the same sub-watershed. Grids for forest, waterbodies, and other natural lands are not included because these areas are not major sources of pollution and are relatively easy to manage. There are 41 LMUs within the study area.

Fertilizer control (FC) model

This model was proposed by Kao and Tsai (1997) on the basis of phosphorus load reduction through fertilizer application control and is modified in this study for the LMU strategy. The model is as follows:

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

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

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

Subject to

$$0 < x_l < 1$$

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

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

(all variables are non-negative)

where l is the LMU index number, L is the total number of LMUs; j is the crop number, J is the total number of crops; W_l is production loss incurred from reduced unit phosphorus fertilizer application; P_l is annual phosphorus fertilizer application in LMU l ; x_l is the rate of phosphorus fertilizer reduction required for LMU l, the variable to be solved in this model; IP_l is the water quality impact coefficient for unit reduction of phosphorus fertilizer application in LMU l, determined using the AGNPS model; x_{pa} is the average phosphorus fertilizer application reduction rate, and u_l and v_l are respectively the negative and positive deviations of x_l to x_{pa}.

This model does not consider sediment loads and only the non-structural BMP of fertilizer application control is included. This model is therefore not appropriate for comprehensive analyses of management alternatives and subsidy strategies. An enhanced model is thus explored and developed in this study.

BMP selection and effectiveness simulation

Four generally proposed BMPs for local watersheds are selected: terrace, grass waterway, filter strip, and diversion. The effectiveness of each BMP is estimated based on several local field experimental studies (e.g. Fan *et al.*, 1995–1997). The cost required to build each BMP is computed based on a local soil and conservation manual.

As in Kozloff *et al.* (1992), post-BMP effectiveness is simulated using the AGNPS model by adjusting related model parameters. For each LMU, several different AGNPS runs (164 in total) were done for different BMPs to estimate the magnitude of phosphorus and sediment load reduction in each case.

The enhanced multiobjective (EM) model

Based on the phosphorus and sediment reduction rates estimated using the AGNPS simulation model for various BMPs, as well as cost information and an equity measure, an enhanced multiobjective (EM) model is developed as follows:

$$\text{Min}\sum_{l=1}^{L}\sum_{c=1}^{C}(COST_{lc})(x_{lc}) \qquad \text{(Cost)}$$

$$\text{Max}\sum_{l=1}^{L}\sum_{c=1}^{C}(P_{lc})(x_{lc}) \qquad \text{(Phosphorus Load Reduction)}$$

$$\text{Max}\sum_{l=1}^{L}\sum_{c=1}^{C}(S_{lc})(x_{lc}) \qquad \text{(Sediment Load Reduction)}$$

$$\text{Min} \sum_{l=1}^{L} (u_{lp} + v_{lp} + u_{ls} + v_{ls}) \ \text{(Equity)}$$

subject to

$$x_{lc} \in \{0,1\}$$

$$\sum_{c=1}^{C} x_{lc} < 1 \quad \forall l$$

$$\sum_{l=1}^{L} \sum_{c=1}^{C} (RATE_{pc})(x_{lc}) = Lx_{pa}$$

$$[\sum_{c=1}^{C} (RATE_{pc})(x_{lc})] - u_{lp} + v_{lp} = x_{pa} \quad \forall l$$

$$\sum_{l=1}^{L} \sum_{c=1}^{C} (RATE_{sc})(x_{lc}) = Lx_{sa}$$

$$[\sum_{c=1}^{C} (RATE_{sc})(x_{lc})] - u_{ls} + v_{ls} = x_{sa} \quad \forall l$$

(all variables are non-negative)

where c denotes the BMP index number; l is the LMU index number and L is the total number of LMUs; x_{lc} is a binary [0,1] integer variable, where a value of 1 means LMU l applies BMP c; P_{lc} and S_{lc} are phosphorus and sediment load reductions, determined by the AGNPS model, for LMU l applying BMP c; x_{pa} and x_{sa} are average reduction rates of phosphorus and sediment loads; u_{lp} and v_{lp} (u_{ls} and v_{ls}) are the negative and positive deviations to x_{pa} (x_{sa}) respectively (Brill, 1979); and $RATE_{pc}$ and $RATE_{sc}$ are phosphorus and sediment load reduction rates for applying BMP c.

Results and discussion

The FC and EM models were both solved by Lp_solve (Berkelaar and Dirks, 1999; Schwab, 1996). The constraint method described in Cohon (1978) was applied to generate non-inferior solution sets for the multiobjective models with varied cost constraints. Figures 2–5 illustrate results for phosphorus load reduction versus cost, sediment load reduction versus cost, equity measure based on phosphorus load reduction rate deviation, and equity measures based on sediment load reduction rate deviation.

Figure 2 shows phosphorus concentration versus cost results for optimization of both phosphorus level and equity level for the FC model and both phosphorus and sediment load reductions for the EM models. The range between two sets of solutions can be regarded as the possible decision space for the problem and solutions outside the space are inferior and are not included. The magnitude of the difference between two sets of solutions gives an indication of further multiobjective analyses. If the difference interval is large, the decision will not be obvious and may require further multiobjective analyses. However, if the interval is small with not much difference between two sets of solutions, further multiobjective analysis is generally not required. According to the results, given equal targets for phosphorus load reduction, the EM model gives better results at a lower cost compared to the FC model. Figure 3 shows sediment load vs. cost results for optimization of both phosphorus and sediment load reduction for the EM model. The FC model does not consider sediment load and thus only results for the EM model are shown in the figure. The decision space shown in Figures 2 and 3 is still significant and require further analyses to make the final decision.

The EM model considers both phosphorus and sediment load reductions and therefore yields two equity measures, as illustrated in Figures 4 and 5. For the models used to obtain

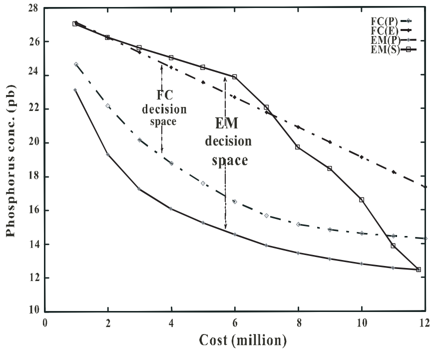

Figure 2 Phosphorus conc. versus cost

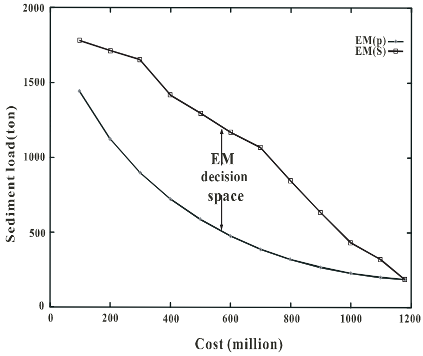

Figure 3 Sediment load versus cost

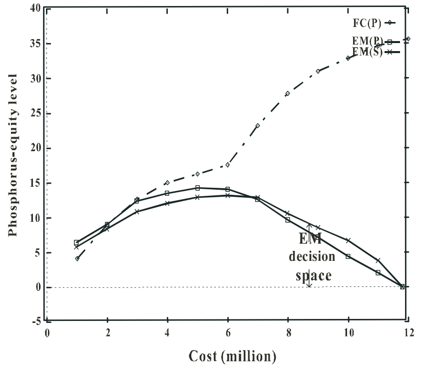

Figure 4 Phosphorus-equity versus cost

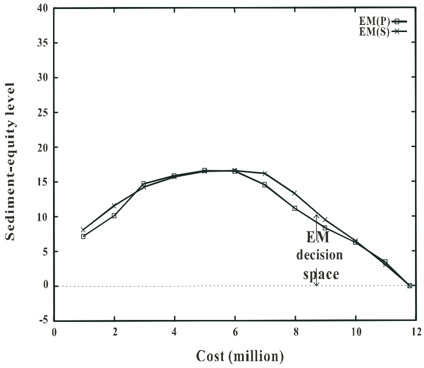

Figure 5 Sediment-equity versus cost

results shown in Figures 4 and 5, the objectives are maximization of phosphorus and sediment load reductions, respectively. The equity measure is defined as the sum of the deviation of the phosphorus or sediment load reduction rate of each LMU from the average reduction rate. The greater the difference between the reduction rate and the average rate, the worse the equity. For the FC model results, the equity measure decreases as budget increases because the model requires critical farm lands to significantly reduce fertilizer application and pollution loads. For the EM model results, a similar trend is observed for budget limits less than 5 or 6 million dollars. However, when more budget is available, most LMUs can adopt the best available BMP and so the difference in reduction rates among LMUs decreases.

Conclusion

Controlling NPSP is critical to protect reservoir water quality, especially for a public drinking water source. Unfortunately, unlike point source pollution, public attention in Taiwan has rarely focused on the NPSP controls until recent years. Various management strategies and regulations are currently under analysis, proposed or to be implemented in the near future. Zonal management and BMP subsidies are two major strategies recently proposed. The models developed in this study are intended to support decision-making analyses and estimates for funding allocation for both strategies. The previously developed fertilizer control model, although capable of facilitating zonal management analysis, is not appropriate for BMP subsidy analyses. An enhanced multiobjective model is therefore developed in this study. Four major objectives (cost, phosphorus load reduction, sediment load reduction, and equity measure based on the sum of deviations of reduction rates from the average) are incorporated into the model. With the same budget limits, according to the results, adoption of proper BMPs is more cost efficient than control of fertilizer application. Trade-off analyses for varied pairs of objectives can be expected to facilitate the decision making process for good zonal management strategies. Furthermore, the multiobjective model can be used to simulate and estimate the performance of a subsidy program under different budget limits and will be reported in another study.

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