Simple Optimization Method to Determine Best Management Practices to Reduce Phosphorus Loading in Echo Reservoir, Utah

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Abstract: This study develops and applies a simple linear optimization program to identify cost effective Best Management Practices (BMPs) to reduce phosphorus loading to Echo Reservoir, Utah. The optimization program tests the feasibility of proposed Total Maximum Daily Load (TMDL) allocations based on potential BMP options and provides information regarding the spatial redistribution of loads among sub-watersheds. The current version of the TMDL for Echo reservoir allocates phosphorus loads to existing non-point phosphorus sources in different sub-watersheds to meet a specified total load. Optimization results show that it is feasible to implement BMPs for non-point sources in each sub-watershed to meet reduction targets at a cost of $1.0 million. However, relaxing these targets can achieve the overall target at lower cost. The optimization program and results provide a simple tool to test the feasibility of proposed TMDL allocations based on potential BMP options and can also recommend spatial redistributions of loads among sub-watersheds to lower costs.

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Introduction

Many U.S. water bodies are impaired due to excessive nutrients. Excess nutrients such as phosphorus and nitrogen stimulate algae growth, reduce dissolved oxygen, and negatively impact aquatic habitat and water supplies for downstream urban and agricultural users. The Total Maximum Daily Load (TMDL) program provides a mechanism to improve the water quality of impaired water bodies and meet the associated in-stream water quality standards and designated uses. Typically TMDLs provide information regarding the current pollutant loads to an impaired water body and then present a plan to reduce and reallocate loads among pollutant sources to meet the in-stream water quality standard. TMDLs often require the use of best management practices (BMPs) to reduce contaminant loads from non-point sources such as farms, range land, and animal feeding operations. In these instances, identifying, selecting, and locating BMPs is a concern (Maringanti et al. 2009).

To address this issue, researchers have applied optimization techniques to select BMPs and determine load allocation strategies at the farm and field scale. These techniques include a multiobjective genetic algorithm (GA) and a watershed simulation model to select and place BMPs (Maringanti et al. 2009), a GA to search the combination of BMPs that minimized cost to meet pollution reduction requirements (Veith et al. 2004), and an optimization model based on discrete differential dynamic programming to locate BMPs in a watershed considering economic analysis (Hsieh et al. 2007). While useful, the approaches require complex solution techniques, long computation times, and have seen limited use by decision makers and regulators. Here, we present a simple linear optimization tool to identify cost-effective BMPs to implement at the sub-watershed scale that meet the allocation required by a TMDL. We also test allocation feasibility and show how to spatially reallocate loads among sub-watersheds to improve feasibility and lower costs. The utility of this tool is presented in the context of a pending TMDL for phosphorus at Echo Reservoir in Utah, U.S. Here, we consider the non-point sources and load-reduction strategies identified by the pending TMDL for Echo Reservoir; however our tool is general and can accommodate other point- and non-point sources and remediation strategies.

Study Area and Pending TMDL

Echo Reservoir is located on the Weber River in northeastern Utah (Figure 1). There are two upstream reservoirs, Wanship and Smith & Morehouse, and three main sub-watersheds that drain to Echo: Weber River above Wanship, Weber River below Wanship, and Chalk Creek. In response to sustained dissolved oxygen concentrations below 4 mg/L and phosphorus concentrations above the state standard of 0.025 mg/L in Echo Reservoir, the Utah Department of Environmental Quality (UDEQ), Division of Water Quality has submitted a TMDL for Echo Reservoir (Adams and Whitehead, 2006; hereafter, the "pending TMDL"). The pending TMDL identifies several major non-point sources of phosphorus (Table 1). Additional phosphorus sources to the reservoir were identified as internal reservoir loading and several point sources.

According to the pending TMDL, the target load reduction for the three primary non-point sources (Land Applied Manure, Private Land Grazing and Diffuse Runoff) is 8,067 kg per year. Here, loads refer to total sub-watershed loads delivered to the sub-watershed outlet rather than loads delivered to the receiving water body of concern (i.e., Echo Reservoir). The load reduction is calculated based on a permissible load of 19,800 kg phosphorus per year at the inlet to the Echo Reservoir to restore or maintain its beneficial use. This permissible load was identified through a modeling effort (hereafter referred to as the instream water quality model) that simulates the major physical, chemical, and biological processes affecting total phosphorus and dissolved oxygen concentrations within the stream and reservoir (Adams and Whitehead, 2006). After determining the permissible load, UDEQ sought public involvement and investigated existing plans in the study area to implement Best Available Technologies (BATs) and BMPs (for point and non-point sources, respectively). Using available BATs and BMPs, they allocated phosphorus loads among sources and between the three sub-watersheds. Interestingly, the pending TMDL allows point sources to maintain their current discharges (many have already implemented BATs) and focuses phosphorus reduction efforts only on non-point sources. While the pending TMDL prescribes the total load allocations for non-point sources at the sub-watershed level, it does not present a specific plan to achieve these load reductions nor does it consider the feasibility to meet required reductions.

Simple Optimization Tool

We developed a simple optimization tool that identifies the cost minimizing mix of BMPs to implement within sub-watersheds to achieve required phosphorus load reduction targets for non-point phosphorus sources in a watershed. Two scenarios were analyzed: first, include reduction targets for each non-point source in each sub-watershed as specified in the TMDL. Second, we relax and combine the sub-watershed reduction targets to generate global, watershed-wide reduction targets for sources across all sub-watersheds. Both scenarios can be formulated as a linear program as follows:

1. Identify phosphorus sources and reduction targets by sub-watershed,

2. Identify potential BMPs for each source, characterize BMP unit cost and reduction efficiency, and determine the available land area or reach length to implement BMPs in each sub-watershed, and
3. Formulate and implement the linear optimization program.

Step 1 was prescribed in the pending TMDL and our analysis considers reduction targets (p; kg P/year) for three non-point phosphorus source types s in three sub-watersheds w as mentioned above.

Potential BMPs to reduce phosphorus from non-point sources in the Echo watershed include actions such as (i) retiring land, protecting grazing land, cover cropping, grass filter strips, conservation tillage, managing agricultural nutrients, and switching to sprinkler irrigation. All of these BMPs can be implemented on available land (Table 1). Additionally, we consider, (ii) fencing and bank stabilization that can be implemented along river and stream reaches (Table 1). Horsburgh et al. (2009) present estimates for unit phosphorus removal costs of each BMP i (u_i; \$/kg P) and efficiencies (e_i ; kg P/km^2 or kg P/km) applied in the nearby Bear River basin. We use these estimates in this study to demonstrate the simple optimization analysis.

BMP effectiveness to reduce phosphorus also depends on the resources available to implement BMPs in a particular sub-watershed w (b_{gw}; km^2 or km). Here, g indicates available land area or stream bank length. For example, to reduce phosphorus loading from private land grazing in the Chalk Creek sub-watershed, we need to identify the area of this specific land use available within the sub-watershed. Similarly, to reduce phosphorus loading from these same land uses by fencing streams, the length of stream that can be fenced must be identified. For this case study, land use areas were taken from the pending TMDL and stream lengths were estimated from widely available stream reach coverage.

With known phosphorus load reduction targets, BMP costs, effectiveness, and available land area or stream length for implementation, we can formulate and implement the linear optimization program. The program determines phosphorus mass removed (P_{iws}; kg P/year) and implementation levels (B_{iws}; km^2 or km) for each BMP in each sub-watershed for each source to minimize costs and achieve the phosphorus load reduction target. Mathematically, the objective function minimizes the sums of removal costs for all BMPs i in all sub-watersheds w and for all sources s,

$$min \sum_{iws} \left(u_i \times P_{iws}\right) \tag{1}$$

and is subject to:

- Definition of phosphorus mass removed by each BMP i in each sub-watershed w and at each phosphorus source s,

$$P_{iws} = e_i \times B_{iws} ; \forall\ i, s, w \tag{2}$$

- Phosphorus removal must meet or exceed load reduction targets for each source s in each sub-watershed w,

$$\sum_i \left(c_{is} \times P_{iws}\right) \geqslant p_{ws} ; \forall w, s \tag{3}$$

- BMP implementation is limited by available land area or stream length g in each sub-watershed w as well as other BMPs already implemented,

$$\sum_{s} \sum_{i} \left(c_{is}\; x_{gi}\; B_{iws}\right) \leqslant b_{gw}; \forall g, w \tag{4}$$

- Phosphorus removal must not exceed the existing load (l_{ws}; kg) in each sub-watershed w and for each source s, and

$$\sum_{i} \left(c_{is} \times P_{iws}\right) \le l_{ws}; \forall w, s \tag{5}$$

- Non-negative decision variables

$$P_{iws} \geqslant 0; \forall\, i, w, s\;\; ; B_{iws} \geqslant 0; \forall\, i, w, s \tag{6}$$

In Equations (3-5), c_{is} is a matrix whose elements take the binary value 1 if BMP i can be applied to source s and 0 otherwise. Each column of c has at least one non-zero element because at least one BMP can be implemented for each source. x_{gi} is also a matrix whose elements take the binary value 1 if implementing BMP i precludes implementing another BMP on the same land parcel or stream reach segment g, and 0 otherwise. Each row g also has at least one non-zero element corresponding to one or more BMPs. Note, BMPs are applied on either an area or stream length basis. Corresponding implementation levels and removal units must be used in Equations (2) and (4).

As presented in the pending TMDL, phosphorus reduction targets in Equation (3) are source and sub-watershed specific. However, these sub-watershed specific reduction targets can be relaxed and combined to give global reduction targets across the entire watershed for each source (Equation 7).

$$\sum_{i} \sum_{w} \left(c_{is} \times P_{iws}\right) \geqslant \sum_{\mathrm{w}} p_{ws}; \forall s \tag{7}$$

These global targets allow reductions and re-allocations among sub-watersheds and assume phosphorus loadings from each sub-watershed strictly and linearly add to produce the total load to the receiving body, Echo Reservoir. This assumption is appropriate since the TMDL sub-watershed targets were determined by linearly decomposing the target load for the reservoir (Adams, pers. comm., 2010).

Equations (1) through (6) represent the sub-watershed specific load reduction scenario 1, dictated by the pending TMDL whereas Equations (1), (2), and (4 – 7) represent scenario 2, a more relaxed scenario, where reductions can be shifted across sub-watersheds. Equations for both scenarios can be solved using either the Excel add-in Solver or other linear program software packages.

Results and Discussion

The optimization program results for the first scenario suggest that BMPs for private land grazing, diffuse runoff, and land applied manure phosphorus sources can feasibly reduce phosphorus loads in Chalk Creek, Weber River below, and Weber River above Wanship sub-watersheds to targets prescribed by the pending TMDL (Table 2, Scenario 1). These reductions are achieved by implementing protecting grazing land, stabilizing stream banks, and managing agricultural nutrients BMPs in all sub-watersheds and conservation tillage in Chalk Creek. When considering reduction targets specific for each sub-watershed, the available BMPs can achieve the overall reduction target at a cost of \$1.0 million. Sensitivity range-of-basis results indicate all BMP cost and removal efficiency parameters (except conservation tillage in Chalk Creek) can increase by factors of 1.7 and more before changing the optimal mix of BMPs (results not shown for brevity).

There may be cases where there is insufficient land area or stream length to implement BMPs in a specific sub-watershed. Or, it may be more cost effective to implement BMPs in other locations. When considering these instances, we can relax sub-watershed specific reduction targets, and instead specify an overall reduction target for the entire watershed. For the Echo Reservoir watershed, we can feasibly achieve the watershed-wide reduction target at a lower cost (Table 2, Scenario 2) by curtailing more expensive conservation tillage and increasing the less expensive BMP to manage agricultural nutrients in the Weber Basin below Wanship. Additionally, the program shifts protecting grazing land, stream bank stabilization, and some managing agricultural nutrients to the Chalk Creek and Weber below Wanship sub-watersheds. However these later shifts do not affect the overall implementation costs since the model assumes BMP costs are the same across sub-watersheds. These changes are all possible because there is additional land area and stream length available to implement BMPs in the Chalk Creek and Weber Basin below Wanship sub-watersheds beyond those needed to meet sub-watershed reduction targets prescribed by the pending TMDL. Since this reallocation of loads only provides information regarding the total watershed loads to Echo Reservoir rather than delivered loads, the second scenario requires further use of the instream water quality model to verify that the reservoir standard is still met. In the case of Echo Reservoir, specifying overall source reduction targets for the entire watershed may allow managers to shift BMP implementation among sub-watersheds to meet the overall reduction target for Echo Reservoir at a lower cost.

Beyond verifying that shifting loads across sub-watersheds still meets the reservoir standard, we note that these results rely on available linear estimates of BMP unit costs and effectiveness. These linear estimates mean that the model assumes the load at a sub-watershed outlet scales linearly irrespective of where the BMP will be located in the sub-watershed. While this assumption is likely appropriate when a BMP is implemented over all the available land or stream bank resource in a sub-watershed, there are cases where locating a BMP near a stream and/or the sub-watershed outlet can significantly affect load reductions. In this case, we assume that each site contributes a variable load reduction that, on average, reflects the modeled unit effectiveness value. However, when model results suggest available land or stream-bank resources go unused, managers and regulators must apply their local expert knowledge to select farm, field, or stream bank sites where BMP implementation will most effectively reduce the load at the sub-watershed outlet.

We further note that implementing a watershed BMP program may allow for some economies of scales. These economies are readily included in the optimization tool with integer decisions and filling constraints. However, economies-of-scale data are not currently available and sensitivity analyses on the cost and efficiency parameters suggest this level of detail may not be needed. Obviously, the model outputs and results are as good as the input data describing BMP costs, efficiencies, existing loads, reduction targets, and available land and stream bank lengths to implement BMPs; gathering additional information within the Echo Reservoir watershed can increase accuracy and confidence in the optimization results.

Conclusion

We developed a simple linear optimization tool that identifies cost-effective strategies to reduce phosphorus loads from sources to prescribed targets. We applied this tool to Echo Reservoir on Weber River, Utah and showed that BMPs for non-point private land grazing, diffuse runoff, and land applied manure sources can feasibly reduce phosphorus loads to sub-watershed target levels identified within the pending TMDL. Relaxing the sub-watershed reduction targets suggests a global reduction target for the reservoir, which can be reached at lower cost. This global strategy still requires further verification using more detailed instream water quality modeling. This optimization tool offers a simple way to test the implementation feasibility of a proposed TMDL allocation, and suggest how loads can be spatially redistributed among sub-watersheds to lower phosphorus loads and reduce costs.

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Notation

The following symbols are used in this technical note:

b_{gw} = resources available to implement BMPs in a particular sub-watershed *w*.

B_{iws} = implementation levels for each BMP i in each sub-watershed w for each source s.

c_{is} = a binary parameter that takes the value 1 if BMP *i* can be applied to source *s* and 0 otherwise.

x_{gi} = a binary parameter that takes the value 1 if implementing BMP *i* precludes implementing another BMP on the same land parcel or stream reach segment *g*, and 0 otherwise.

e_i = estimate for unit phosphorus removal efficiencies for each BMP *i*

g = row on the model to select available resource (parcel area or reach length).

i = best management practice.

l_{ws} = existing phosphorus load in sub-watershed *w* from source *s*.

p_{ws} = phosphorus reduction targets for sub-watersheds *w* and non-point source *s*.

P_{iws} = phosphorus mass removed by each BMP *i* in each sub-watershed *w* targeted at each phosphorus source *s*.

s = non-point phosphorus source.

u_i = estimate for unit phosphorus removal costs for each BMP *i*

w = sub-watershed

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Table 1. Assignment of applicable BMPs to non-point sources

Source	**Description**	**Applicable BMPs**
Direct run off from AFOs	Animal wastes containing phosphorus from watershed animal feeding operations (AFOs) directly runoff into nearby water bodies.	None
Land applied manure	Animal waste applied on agricultural land as a fertilizer is incorporated into the soil and subsequently washed into a nearby water body.	Grass filter strips, Conservation tillage, Manage agricultural nutrients.
Public land grazing	Animals grazed on public lands leave waste containing phosphorus that is subsequently washed into a nearby water body.	Protect grazing land, Fence streams, Grass filter strips.
Private land grazing	Animals grazed on private lands leave waste containing phosphorus that is subsequently washed into a nearby water body.	Protect grazing land, Fence streams, Grass filter strips.
Septic Systems	Domestic leak wastewater into nearby waterways when septic tanks are installed incorrectly or are too close to a waterway.	None
Diffuse Runoff	Phosphorus loading that arises from fertilizers, pesticides, trails, roads, dispersed camping sites and erosion from up slopes areas.	Retire land, Stabilize stream banks, Cover crops, Grass filter strips, Conservation tillage, Manage agricultural nutrients, Sprinkler irrigation.

Table 2. Summary of required phosphorus load reductions, model-recommended BMPs, load reductions achieved, and costs.

Scen.	Sub-watershed[a]	Required reduction (kg/yr)	Protect grazing land[b] (kg/yr)	Stabilize stream banks[c] (kg/yr)	Conservation tillage[d] (kg/yr)	Manage Ag. Nutrients[d] (kg/yr)	Total reduction (kg/yr)	Total cost ($1000)
1	Chalk creek	2,038	354	915	87	682	2,038	242
	WBW	1,458	155	549		754	1,458	172
	WAW	4,572	372	1,352		2,848	4,572	587
	Total	8,067	880	2,816	87	4,283	8,067	1,000
2	Chalk creek		880	2,816		682	4,379	367
	WBW					942	942	158
	WAW					2,747	2,747	460
	Total	8,067	880	2,816		4,370	8,067	985

[a] WBW= Weber below Wanship, WAW= Weber above Wanship.

[b] BMP to reduce phosphorus loading from private land grazing source.

[c] BMP to reduce phosphorus loading from diffuse runoff source.

[d] BMP to reduce phosphorus loading from land applied manure source.