

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

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

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17 **Keywords:** Phosphorus; Total Maximum Daily Load; Best Management Practice; Optimization

18 **Introduction**

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

30 To address this issue, researchers have applied optimization techniques to select BMPs and
31 determine load allocation strategies at the farm and field scale. These techniques include a
32 multiobjective genetic algorithm (GA) and a watershed simulation model to select and place
33 BMPs (Maringanti et al. 2009), a GA to search the combination of BMPs that minimized cost to
34 meet pollution reduction requirements (Veith et al. 2004), and an optimization model based on
35 discrete differential dynamic programming to locate BMPs in a watershed considering economic
36 analysis (Hsieh et al. 2007). While useful, the approaches require complex solution techniques,
37 long computation times, and have seen limited use by decision makers and regulators. Here, we
38 present a simple linear optimization tool to identify cost-effective BMPs to implement at the sub-

39 watershed scale that meet the allocation required by a TMDL. We also test allocation feasibility
40 and show how to spatially reallocate loads among sub-watersheds to improve feasibility and
41 lower costs. The utility of this tool is presented in the context of a pending TMDL for
42 phosphorus at Echo Reservoir in Utah, U.S. Here, we consider the non-point sources and load-
43 reduction strategies identified by the pending TMDL for Echo Reservoir; however our tool is
44 general and can accommodate other point- and non-point sources and remediation strategies.

45 **Study Area and Pending TMDL**

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

55 According to the pending TMDL, the target load reduction for the three primary non-point
56 sources (Land Applied Manure, Private Land Grazing and Diffuse Runoff) is 8,067 kg per year.
57 Here, loads refer to total sub-watershed loads delivered to the sub-watershed outlet rather than
58 loads delivered to the receiving water body of concern (i.e., Echo Reservoir). The load reduction
59 is calculated based on a permissible load of 19,800 kg phosphorus per year at the inlet to the
60 Echo Reservoir to restore or maintain its beneficial use. This permissible load was identified

61 through a modeling effort (hereafter referred to as the instream water quality model) that
62 simulates the major physical, chemical, and biological processes affecting total phosphorus and
63 dissolved oxygen concentrations within the stream and reservoir (Adams and Whitehead, 2006).
64 After determining the permissible load, UDEQ sought public involvement and investigated
65 existing plans in the study area to implement Best Available Technologies (BATs) and BMPs
66 (for point and non-point sources, respectively). Using available BATs and BMPs, they allocated
67 phosphorus loads among sources and between the three sub-watersheds. Interestingly, the
68 pending TMDL allows point sources to maintain their current discharges (many have already
69 implemented BATs) and focuses phosphorus reduction efforts only on non-point sources. While
70 the pending TMDL prescribes the total load allocations for non-point sources at the sub-
71 watershed level, it does not present a specific plan to achieve these load reductions nor does it
72 consider the feasibility to meet required reductions.

73 **Simple Optimization Tool**

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

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

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

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

89 Potential BMPs to reduce phosphorus from non-point sources in the Echo watershed include
90 actions such as (i) retiring land, protecting grazing land, cover cropping, grass filter strips,
91 conservation tillage, managing agricultural nutrients, and switching to sprinkler irrigation. All of
92 these BMPs can be implemented on available land (Table 1). Additionally, we consider, (ii)
93 fencing and bank stabilization that can be implemented along river and stream reaches (Table 1).
94 Horsburgh et al. (2009) present estimates for unit phosphorus removal costs of each BMP i (u_i ;
95 \$/kg P) and efficiencies (e_i ; kg P/km² or kg P/km) applied in the nearby Bear River basin. We
96 use these estimates in this study to demonstrate the simple optimization analysis.

97 BMP effectiveness to reduce phosphorus also depends on the resources available to implement
98 BMPs in a particular sub-watershed w (b_{gw} ; km² or km). Here, g indicates available land area or
99 stream bank length. For example, to reduce phosphorus loading from private land grazing in the
100 Chalk Creek sub-watershed, we need to identify the area of this specific land use available within
101 the sub-watershed. Similarly, to reduce phosphorus loading from these same land uses by
102 fencing streams, the length of stream that can be fenced must be identified. For this case study,

103 land use areas were taken from the pending TMDL and stream lengths were estimated from
104 widely available stream reach coverage.

105 With known phosphorus load reduction targets, BMP costs, effectiveness, and available land
106 area or stream length for implementation, we can formulate and implement the linear
107 optimization program. The program determines phosphorus mass removed (P_{iws} ; kg P/year) and
108 implementation levels (B_{iws} ; km² or km) for each BMP in each sub-watershed for each source to
109 minimize costs and achieve the phosphorus load reduction target. Mathematically, the objective
110 function minimizes the sums of removal costs for all BMPs i in all sub-watersheds w and for all
111 sources s ,

$$\min \sum_{iws} (u_i \times P_{iws}) \quad (1)$$

112 and is subject to:

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

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

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

$$\sum_i (c_{is} \times P_{iws}) \geq p_{ws}; \forall w, s \quad (3)$$

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

$$\sum_s \sum_i (c_{is} x_{gi} B_{iws}) \leq b_{gw}; \forall g, w \quad (4)$$

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

$$\sum_i (c_{is} \times P_{iws}) \leq l_{ws}; \forall w, s \quad (5)$$

- 121 • Non-negative decision variables

$$P_{iws} \geq 0; \forall i, w, s ; B_{iws} \geq 0; \forall i, w, s \quad (6)$$

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

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

$$\sum_i \sum_w (c_{is} \times P_{iws}) \geq \sum_w p_{ws}; \forall s \quad (7)$$

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

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

144 **Results and Discussion**

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

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

175 Beyond verifying that shifting loads across sub-watersheds still meets the reservoir standard, we
176 note that these results rely on available linear estimates of BMP unit costs and effectiveness.
177 These linear estimates mean that the model assumes the load at a sub-watershed outlet scales
178 linearly irrespective of where the BMP will be located in the sub-watershed. While this

179 assumption is likely appropriate when a BMP is implemented over all the available land or
180 stream bank resource in a sub-watershed, there are cases where locating a BMP near a stream
181 and/or the sub-watershed outlet can significantly affect load reductions. In this case, we assume
182 that each site contributes a variable load reduction that, on average, reflects the modeled unit
183 effectiveness value. However, when model results suggest available land or stream-bank
184 resources go unused, managers and regulators must apply their local expert knowledge to select
185 farm, field, or stream bank sites where BMP implementation will most effectively reduce the
186 load at the sub-watershed outlet.

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

195 **Conclusion**

196 We developed a simple linear optimization tool that identifies cost-effective strategies to reduce
197 phosphorus loads from sources to prescribed targets. We applied this tool to Echo Reservoir on
198 Weber River, Utah and showed that BMPs for non-point private land grazing, diffuse runoff, and
199 land applied manure sources can feasibly reduce phosphorus loads to sub-watershed target levels
200 identified within the pending TMDL. Relaxing the sub-watershed reduction targets suggests a

201 global reduction target for the reservoir, which can be reached at lower cost. This global strategy
202 still requires further verification using more detailed instream water quality modeling. This
203 optimization tool offers a simple way to test the implementation feasibility of a proposed TMDL
204 allocation, and suggest how loads can be spatially redistributed among sub-watersheds to lower
205 phosphorus loads and reduce costs.

206 **Acknowledgments**

207 We thank Carl Adams and Kari Lundeen from the Utah Division of Water Quality for the
208 information they provided, comments, and feedback.

209 **Notation**

210 The following symbols are used in this technical note:

- 211 b_{gw} = resources available to implement BMPs in a particular sub-watershed w .
- 212 B_{iws} = implementation levels for each BMP i in each sub-watershed w for each source s .
- 213 c_{is} = a binary parameter that takes the value 1 if BMP i can be applied to source s and
214 0 otherwise.
- 215 x_{gi} = a binary parameter that takes the value 1 if implementing BMP i precludes
216 implementing another BMP on the same land parcel or stream reach segment g ,
217 and 0 otherwise.
- 218 e_i = estimate for unit phosphorus removal efficiencies for each BMP i
- 219 g = row on the model to select available resource (parcel area or reach length).
- 220 i = best management practice.
- 221 l_{ws} = existing phosphorus load in sub-watershed w from source s .
- 222 p_{ws} = phosphorus reduction targets for sub-watersheds w and non-point source s .
- 223 P_{iws} = phosphorus mass removed by each BMP i in each sub-watershed w targeted at
224 each phosphorus source s .
- 225 s = non-point phosphorus source.
- 226 u_i = estimate for unit phosphorus removal costs for each BMP i
- 227 w = sub-watershed

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

Source	Description	Applicable BMPs
Direct runoff 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.

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 252
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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

254 ^aWBW= Weber below Wanship, WAW= Weber above Wanship.

255 ^b BMP to reduce phosphorus loading from private land grazing source.

256 ^c BMP to reduce phosphorus loading from diffuse runoff source.

257 ^d BMP to reduce phosphorus loading from land applied manure source.