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Prioritizing lakes for conservation in lake-rich areas

Paul Radomski and Kristin Carlson

Minnesota Department of Natural Resources 1601 Minnesota Drive, Brainerd, MN 56401

ABSTRACT
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Identifying lakes in which to invest water quality conservation efforts can help more effectively target efforts and more efficiently utilize limited resources. The objective of this study was to compare different approaches to prioritize Minnesota lakes primarily for water quality protection or restoration. Lakes were objectively ranked using a multi-criteria values-based model that included phosphorus-loading resilience, level of watershed degradation, and feasibility of water quality protection or restoration. We explored how the list of priority lakes might change when incorporating benefit:cost ratios that used a hedonic model to predict land value increases with total phosphorus loading reductions. In addition, we examined the influence of including data on lakes with unique or high-quality biological communities. The multi-criteria values-based model was moderately correlated with the benefit:cost ratio approach; however, the exclusion of benefits and cost in the prioritization would likely result in the loss of a modest amount of potential benefit (∼20%). A focus on impaired waters would likely result in considerable forgone benefit (∼80%) and substantially higher costs. We provide recommendations on how to combine prioritization approaches along with a peer review process to produce lake priority lists that are both defensible and practical.

KEYWORDS
Policy; resource economics; watershed management

As threats to Minnesota's lakes continue to mount, it is becoming increasingly important to prioritize where limited conservation funds could best be directed. Within the state, about $34 million/year has been spent on water quality monitoring and impaired waters assessment research and programs, under the requirements of the United States Clean Water Act for state agencies to identify impaired lakes and to study the pollution loads for those waters. Appropriations from Minnesota's Clean Water Fund, which funds a substantial portion of lake and water quality restoration and protection within the state, total about $110 million/year. From 2009 to 2017, 80% of this fund has been spent on restoration projects for impaired waters.

Determining how and where to allocate those funds are critical questions. On which lakes should the state invest its Clean Water Fund? How much funding should go to implement lake protection efforts on unimpaired waters versus restoration efforts on impaired waters? There are many opportunities for lake protection or restoration beyond existing regulatory controls (Radomski and Van Assche 2014). Identifying on which lakes to invest some of these water quality conservation dollars can help more effectively target efforts and more efficiently utilize limited resources. A number of information tools are available for prioritizing and targeting conservation efforts. A systematic approach seems critical in any prioritization (Game et al. 2013). Two of the most common approaches to conservation prioritization are values-based models and benefit:cost ratios.

Values-based models use a compilation of individual criteria (valuable features) and aggregated criteria with an objective function to prioritize places on the landscape for conservation (Moilanen et al. 2009). The use of an additive or multiplicative benefits objective function in a value model allows for the retention of as many conservation features as possible. This approach allows the investigator to recognize that attempts to

CONTACT Paul Radomski paul.radomski@state.mn.us
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solve clean water needs are not separate from our other conservation needs; some places could provide multiple conservation benefits. Value models provide a reasonable approach when costs are unknown or have high uncertainty; however, they do not provide good guidance on the most cost-effective places to implement different types of projects.

Ranking benefit:cost ratios assesses the benefits and costs of projects while explicitly acknowledging that there is a budget constraint on conservation. Several economic studies using hedonic models have shown a relationship between lake water quality and lakeshore property prices (Maine Department of Environmental Protection 1996, Michael et al. 1996, Krysel et al. 2003), so the monetary benefits of water quality protection or restoration efforts may be assessed. Costs to protect or improve lake water quality can often be estimated based on recent conservation efforts. However, environmental problems are often system problems, and the funds available will likely only deal with part of the system or a portion of the problem. The higher the benefit:cost ratio generally means the better the conservation investment, but there are several shortcomings to this approach. First, it does not address nonmonetary benefits, costs, or consequences. These nonmonetary items may be valuable to a community, and the difficulty in adequately assessing worth of intangibles is often nontrivial. Second, the discount rates, risk premiums, or project risks and feasibilities used in the analysis have a large influence on the calculated result. The strength of this approach is that it attempts to include a measure of the benefits of any projects that might be implemented to protect or restore a conservation feature or asset (Joseph et al. 2009, Pannell et al. 2012, Beher et al. 2016).

Lake restoration and protection prioritizations are readily available. Several biodiversity-based lake prioritizations have been developed (e.g., Duker and Borre 2001, Minnesota Department of Natural Resources 2015) and Heiskary (1997) proposed a lake prioritization approach emphasizing protection of Minnesota's unimpaired waters ranked by lake size. Jacobson et al. (2016) developed and implemented a framework to prioritize Minnesota watersheds to protect lake fish habitat. However, there are few studies that compare different conservation prioritization approaches (Joseph et al. 2009, Pannell and Gibson 2014) and few assessments on lake restoration and protection benefit:cost ratios.

The objective of this study was to compare different approaches to prioritize Minnesota lakes primarily for water quality protection or restoration. Lakes at greatest risk of becoming degraded or further degraded were identified and objectively ranked based on their phosphorus-loading resilience, level of watershed degradation, and feasibility of water quality protection or restoration. We explored how the list of priority lakes might change when incorporating benefit:cost ratios. In addition, we examined the influence of including data on unique or high-quality biological communities associated with a subset of these lakes. The resulting information can be used to identify lakes that may benefit from well-designed phosphorus loading reduction projects in their watersheds.

Material and methods

Study lakes and environmental data

We used 2732 Minnesota lakes in the analysis (Fig. 1). These lakes were selected based on the availability of water chemistry data and lake morphological information. A subset of the lakes ($n = 1127$) was used in the benefit:cost analysis; these lakes were selected based on the availability of land value data. Study lake distribution roughly corresponded with the natural distribution of lakes in Minnesota. Using the Level II Ecoregion Classification (Omernik 1987), 50% of the study lakes were located in the Northern Lakes and Forests ecoregion, 40% in the North Central Hardwood Forests ecoregion, and 6% in the Western Corn Belt Plains ecoregion. The median lake surface area was 79 ha. Most lakes (80%) were between 20 and 406 ha. Most of the lakes (69%) were deeper-water lakes, where the maximum depth was greater than or equal to 4.6 m.

Water chemistry focused on summer conditions, which generally included the period from mid-June to mid-September. In-lake total phosphorus (TP) summer mean concentrations were averaged across all available years for each lake. Water clarity as measured by Secchi disk transparency depth (SDT) was also used. Regression

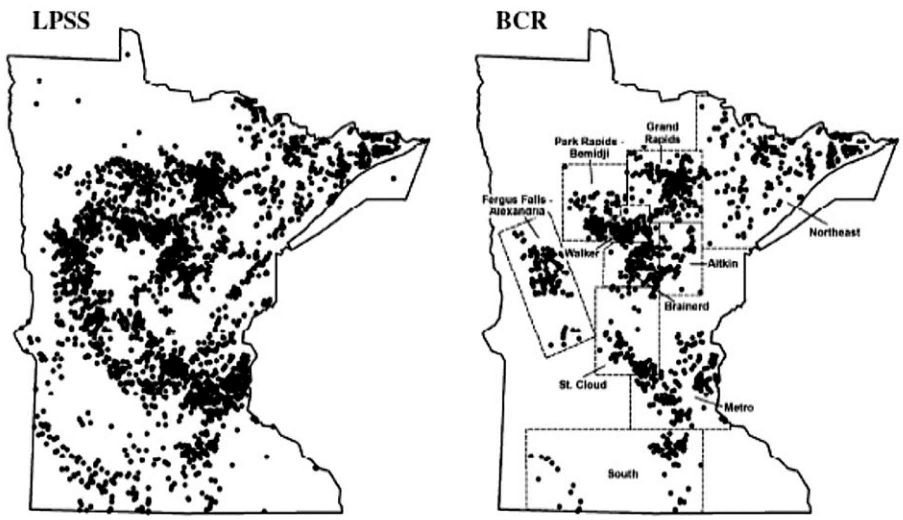

Figure 1. Locations of lakes used in the lake phosphorus sensitivity significance (LPSS) values-based model and benefit:cost ratio (BCR) analysis. Dotted lines on BCR map represent approximate regional real estate markets. Walker = Walker–Hackensack.

analysis was used to generate an equation of log-transformed mean SDT and average summer mean TP. To determine SDT trends, a seasonal Kendall statistical test was used to determine whether the data for each lake exhibited any trend. Years with 4 or more SDT readings were used, and only lakes with at least 8 yr of data were analyzed. A total of 128 lakes had a decreasing water clarity trend, and 222 had an increasing trend. For use in the value model, a trend score (T) was assigned to each lake based on the significance of the test and the number of measurement years. Lakes with evidence of a negative trend were given one of four scores (0.25, 0.5, 0.75, 1), with the highest value assigned to lakes with strongest evidence of declining water clarity. Lakes with no evidence of a negative trend were given a score of 0.

Physical attributes of the lakes included mean depth, maximum depth, lake volume, hydraulic inflow rate, and a disturbance index of the lake's watershed. Lake volume was available for 1821 lakes, and for the rest lake volume was estimated by multiplying lake area by maximum depth and 0.464 (Wetzel 2001). Lake hydraulic inflow was estimated using equation 1 in Wilson and Walker (1989), which is a mass balance equation that uses the lake's watershed size and ecoregion-specific runoff coefficients. Land disturbance within the watershed was estimated by summing the area of land in cultivated and developed land use classes (2011 National Land Cover Data) within the lake's immediate catchment divided by the total land area in the catchment. The mean proportion of watershed disturbance was 0.05 (standard deviation = 0.05) for the lakes in the Northern Lakes and Forests ecoregion, 0.42 (standard deviation = 0.22) for lakes in the North Central Hardwood Forests ecoregion, and 0.69 (standard deviation = 0.17) for lakes in the Western Corn Belt Plains.

The Minnesota Pollution Control Agency (MPCA) impaired lake classification was also used within these analyses. Recreational use impairment designation is a weight of evidence decision based on review of a lake's water quality (TP, Chlorophyll *a*, and SDT data) compared to the regulatory ecoregion-specific thresholds for impairment. The regulatory ecoregion-specific recreational use eutrophication impairment thresholds are documented in Heiskary and Wilson (2005).

Values-based model prioritization

A values-based model was formulated to represent the objective of "focusing on high quality lakes at greatest risk of becoming impaired or further degraded." The values-based model is based on both a multiplicative and an additive benefit function, and all lakes were ranked on the resulting priority score. The model had 3 components. First, the model included a measure of TP loading sensitivity. Several statistical models were developed to predict annual TP loading using the dataset from Brett and Benjamin (2008), which included 305 temperate lakes from North America and Europe. The influence of TP concentration, hydraulic inflow rate, lake volume, lake depth, and flushing rate were analyzed as fixed effects. The best model in the suite of models developed was then used to predict annual TP loading for the 2732 Minnesota lakes. A lake's TP loading sensitivity index (*S*) was estimated using the mass balance limnological equation from Cheng et al. (2010: equation 6), which predicts in-lake TP as a function of annual TP loading and the lake's mean hydraulic retention time. To determine the sensitivity of each lake to additional loading, increasing TP loads were entered into the mass balance equation and predicted SDT depths were made for each increasing load. The TP loading sensitivity was then expressed as the loss of SDT in inches per 45.36 kg (100 pounds) of TP added.

The second component was an index, denoted as TP loading sensitivity significance (*SS*), which was computed using the TP loading sensitivity index (*S*) times 3 multipliers. For lakes where the ratio of the predicted TP load (L_p) to the TP load threshold (L_t) was one or less, a lake's TP loading sensitivity significance was calculated by:

$$SS = S \times A/TP \times L_p/L_t \times D$$

where the multipliers were the ratio of lake surface area (*A*, acres) to the in-lake summer mean TP concentration (*TP*), the ratio of predicted TP load (L_p) to the TP load threshold (L_t), and the proportion of the lake's watershed that was disturbed (*D*; proportion developed plus the proportion cultivated). These lakes could be generally considered assets to protect.

For lakes where the predicted TP load to TP load threshold ratio was greater than one, TP loading sensitivity significance index (*SS*) was calculated by:

$$SS = S \times A/TP \times \left[1 - \left(L_p/L_t - Min\left(L_p/L_t\right)\right) / \left(Max\left(L_p/L_t\right) - Min\left(L_p/L_t\right)\right)\right] \times D_n$$

where the predicted TP load to TP load threshold ratio was normalized to between 0 and 1 and the proportion of the lake's watershed that was disturbed was multiplied by a normal probability density function with a mean of 0.4 and a standard deviation of 0.2 and then normalized between 0 and 1 (D_n). The latter multiplier placed more significance on lakes with moderate watershed disturbance, as the results of Cross and Jacobson (2013) showed a critical threshold of anthropogenic land use disturbance at 40% that, once exceeded, could significantly alter in-lake TP concentrations. These lakes could be generally considered assets to restore.

The final component of the values-based model aggregated priority by summing 2 attributes:

$$Priority\ Score = 0.5 \times T + SSn$$

where the lake phosphorus sensitivity significance (LPSS) priority score for the lake for protection or restoration is equal to one-half of the decreasing water clarity trend score *T* plus the normalized TP loading sensitivity significance index *SSn*. The water clarity trend score, *T*, is based on the *P* value of a seasonal Kendall test applied to June through September transparency data for the lake. Values range from 0 to 1 with 0 showing no trend and 1 having strong evidence for a negative trend (see Heiskary and Egge 2016). The priority score was then normalized between 0 and 100. All normalization, or rescaling, followed the general formula:

$$X' = (X - min(X))/(max(X) - min(X)) \times ((U - L) + L)$$

where X is the original value, X′ is the normalized value, U is the upper scale range, and L is the lower scale range.

Benefit:cost ratio analysis

Benefit:cost ratios were developed using information from 1127 lakes. The lakes used in these analyses were a subset of those used in the values-based model ($n = 2732$ lakes), and they were generally representative of the full dataset (Table 1). As with the values-based model, lakes were ranked or prioritized; in addition, for the benefit:cost ratio analysis each lake also had explicit project activities assigned. County parcel data available to the MDNR were used to calculate the mean shoreline parcel value ($) and mean shoreline parcel length (m) for each lake, as well as total lake shoreline value. Parcel value was

Table 1. Attributes of the 2 lake datasets used to develop the values-based model and the benefit:cost ratios (BCR).

Attribute	Number of lakes used for values-based model	Number of lakes in the BCR subset
Managed fish lakes	2355 (86%)	1127 (100%)
Recreational use impaired lakes	522 (20%)	208 (18%)
Large lakes (>500 ha)	583 (21%)	133 (12%)
Lakes of Biological Significance	779 (29%)	418 (37%)

defined as estimated land value in order to eliminate the effect of wide differences in building values and to include undeveloped parcels. In some cases, because of gaps in the parcel data, land values were not available for the entire shoreline of a lake; lakes with parcel data for less than 50% of the shoreline were excluded from further analysis. Based on location, lakes were assigned to one of 10 regional real estate markets.

Economic models were developed to predict land values across a range of Minnesota lakes. Hedonic linear regression models were used employing a generalized least squares approach; this approach extends regression by modeling the heterogeneity with covariates. The model development strategy followed the suggestions of Zuur et al. (2009), with mean land value per shoreline frontage ($/shoreline m) as the response variable. The influence of lake size (m^2), maximum lake depth (m), lake mean summer TP concentration (μg/L), proportion of frontage in private ownership, ecoregion, mean shoreline parcel length (m), and real estate market were analyzed as fixed effects. After initial testing to determine significant fixed effects, candidate models were developed that addressed variance covariate structure. The changes in the AIC score were used to select a preferred model (Burnham and Anderson 2002). Statistical analyses were conducted using R (R Development Core Team 2017).

The benefits of water quality protection or restoration activities were calculated for each lake using the preferred economic model to estimate increases in land value ($/shoreline m) with management activities that were assumed to reduce TP loading by 5%. For unimpaired lakes, a 5% load reduction goal is currently being recommended by Minnesota agencies as a reduction in the amount of pollution entering a lake that watershed partners can reasonably strive for in guiding local stewardship practices.

The costs of water quality protection or restoration activities assigned to each lake depended on the lake and its watershed characteristics. For minimally disturbed lakes in forest watersheds (watersheds with no land in cultivation and less than 10% in developed land use and little or no shoreland development), protection costs were based on the amount of riparian land necessary to maintain a portion of shoreland in forest based on differences between TP loading from woods and developed lakeshores to achieve the 5% TP load reduction and the typical Minnesota conservation easement cost for state agencies. The estimated TP load difference was 0.3 kg/ha/yr (0.46 kg/ha/yr in residential development −0.14 kg/ha/yr in forest [0.3 pounds/ac/yr]) (Graczky et al. 2003, Radomski and Van Assche 2014). The Minnesota cost of acquiring and enforcing conservation easements for each lake was estimated by multiplying the riparian area (61 m [200 ft] landward) needed to achieve the 5% reduction for the lake by 60% of the observed mean land value for the lake per hectare (Minnesota Office of the Legislative Auditor 2013). For lakes with disturbed watersheds, a lake's restoration cost was the cost of agricultural and stormwater best management practices (BMPs) per kilogram TP removed, assessed proportionally based on agricultural and developed land use within the lake's watershed, multiplied by the 5% load reduction goal (kg/yr) for the lake. For agricultural BMPs, the cost per kilogram was assessed at $39/kg ($18/pound) (Johansson et al. 2004), which is within the range of projected costs for a variety of BMPs appropriate for Minnesota (Lazarus et al. 2015). For stormwater BMPs, the cost per kilogram was assessed at $46,298/kg ($21,000/pound) (Hunt et al. 2012, Houle et al. 2013).

Consistent with methodology outlined by Pannell (2015), the benefit:cost ratio included multipliers for probabilities of a lake's protection or restoration activities being successful. These multipliers adjusted raw benefit:cost ratios based on the likelihood of project success (not all lake protection and restoration projects succeed). These multipliers were impartially, but subjectively, ascribed. The benefit:cost ratio (BCR) was calculated as follows:

$$BCR = \left(\left(LV_{p5\%} - LV_{pe}\right) \times SM\right)/C) \times P_t \times P_{sp}$$

where for each lake the $LV_{p5\%}$ is the predicted mean land value per shoreline frontage with a 5% reduction in TP loading ($/shoreline m), LV_{pe} is the predicted mean land value per m shoreline frontage for existing conditions, SM is the shoreline length (m), C is the cost of water quality protection or restoration activities, P_t is the probability of technical feasibility, and P_{sp} is the probability of social and political willingness to act and fund the lake's protection or restoration. The probability of technical feasibility ranged from 0.4 to 0.9 and it decreased log-linearly based on the amount of disturbed land in the lake's watershed (i.e., lakes with large disturbed watersheds were assumed to be more technically challenging to successfully identify and target agricultural and stormwater BMPs to achieve the 5% TP load reduction). The probability of social and political willingness ranged from 0.1 to 0.9 and it increased log-linearly based on the total riparian land value (i.e., social capacity and political willingness increased as the wealth of the lake community increased). Statistical differences between mean BCR by different classes of lakes were tested with the Mann–Whitney test (SAS 2017).

Lake biological community prioritization

As an example of how nonmonetized benefits may influence prioritization, we included important biological community lakes within the analysis. The Minnesota Department of Natural Resources (MDNR 2015) created a list of high-quality lakes based on dedicated biological sampling for the stated purpose of focusing protection efforts (Lakes of Biological Significance; $n = 1449$ lakes). Lakes were rated and grouped for each of the following communities: aquatic plants, fish, birds, and amphibians. Lakes were assigned one of three biological significance classes (outstanding, high, or moderate). The goal of this list was to identify lakes that exhibit the highest-quality features within any of the 4 assessed biological communities (as opposed to identification of lakes that exhibit diversity across communities). Therefore, a lake needed to meet criteria for only one of the community types (aquatic plants, fish, birds, amphibians) to be identified as a lake of biological significance. Occurrences of high-quality features within the community types determined the biological significance class. About half the lakes on this list were also used in the values-based model.

Comparison of prioritizations

Values-based model and benefit:cost ratio absolute outputs as well as their associated lake rankings were used to generate lists of high-priority lakes. Simple comparisons were then made using the computed scores or ranks. Additional lake priority lists were also developed using 2 or more scores where the distance from the origin in either 2 or 3 dimensions determined the priority rank. This is a simplified multi-criteria decision analysis method, where the highest-priority lake was selected based on the longest geometric distance from the worst solution (i.e., the origin, which has a zero score for all criteria). Distance from the origin was calculated using the Pythagorean distance formula, and dimensions included the normalized LPSS priority score from the values-based model, normalized score of BCR, and classes of Lakes of Biological Significance (0 for not designated, 0.33 for moderate, 0.67 for high, and 1 for outstanding lakes).

Results

Values-based model prioritization

Lake TP concentrations were generally lowest in the Northern Lakes and Forests ecoregion and higher in the Western Corn Belt Plains ecoregion (Fig. 2). The best model to predict TP loading was a linear log-log regression model, with in-lake TP concentration, lake volume, and hydraulic inflow rate as input variables (multiple $R^2 = 0.9689$; adjusted $R^2 = 0.9685$; Table 2). The fitted values showed no bias with regard to the observed values, and the average absolute percent difference between the observed and fitted values was 44% (standard deviation =38%). The prediction intervals for the 2732 Minnesota lakes were

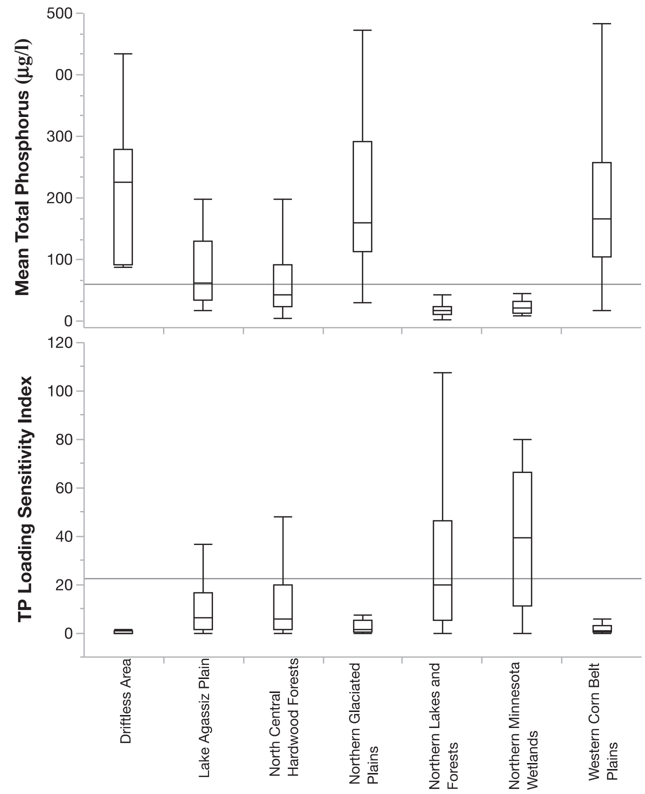

Figure 2. Box plots of lake summer mean total phosphorus (TP) concentrations and TP loading sensitivity index for lakes grouped by ecoregion. The box is the interquartile range. The vertical endpoints are not longer than 1.5 times the interquartile range, and the line within the box is the median. The horizontal line is the mean for all lakes.

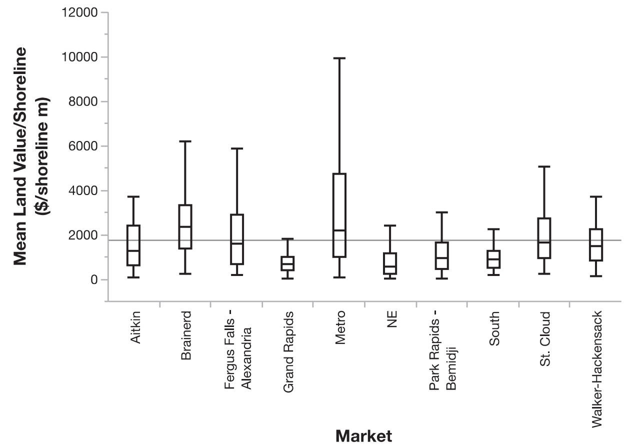

Figure 3. Box plots of mean land value per shoreline distance (m) for lakes grouped by real estate market. The box is the interquartile range. The vertical endpoints are not longer than 1.5 times the interquartile range, and the line within the box is the median. The horizontal line is the mean for all lakes. NE = Northeast.

Table 2. A summary of the linear regression model for TP loading (the log-transformed response variable). The explanatory variables included log-transformed TP concentration (logTP_lake), log-transformed hydraulic inflow rate (logQ), log-transformed lake volume (logV), and one interaction term (*).

Source of variation	Coefficient	SE	*t*	*P*
Intercept	0.3349	0.0585	5.7221	<0.0001
logTP_lake	1.0470	0.0332	31.5394	<0.0001
logQ	0.8169	0.0150	54.5380	<0.0001
logV	0.2986	0.0268	11.1305	<0.0001
logTP_lake*logV	−0.9450	0.0163	−5.7980	<0.0001

wide (80% prediction intervals were −48% to +95%).

The TP loading sensitivity index was generally highest for oligotrophic lakes in the Northern Lakes and Forests ecoregion and lower for eutrophic lakes in the Western Corn Belt Plains ecoregion (Fig. 2). Many lakes with the top LPSS priority scores were located in the ecological transition zone from Detroit Lakes southeast to Minneapolis and in north-central Minnesota. Lake watershed size was an important factor in this index; lakes with large watersheds were less likely to have high indices. As intended, the lake phosphorus sensitivity significance (LPSS) priority score generally produced high values for oligotrophic lakes that were vulnerable to phosphorus loading and near their estimated loading threshold, and low values for small, hypereutrophic lakes with high estimated phosphorus loading and watershed disturbance.

Benefit:cost ratio prioritization

Lakes in the Brainerd or Metro real estate markets had the highest land value ($/shoreline m; Fig. 3). These markets also had higher land value variability. The Grand Rapids, Northeast, and South real estate markets had the lowest variability in lakeshore land value. The average lake mean land value was $1750/shoreline m (standard deviation = 2101), and the maximum was $19,224/shoreline m (Lake Minnetonka).

The preferred hedonic model that predicted land values ($/shoreline m) included lake size, maximum lake depth, lake mean summer TP concentration, mean shoreline parcel length, real estate market, several interactions as fixed effects, and an exponential function of the variance covariate for the mean shoreline parcel length (this

Table 3. A summary of the preferred economic hedonic linear regression model using a generalized least squares approach to predict land value (the ln-transformed response variable). Variables include the various real estate markets and several ln-transformed variables: lake size (LN_LAKEAREA), mean shoreline parcel length (LN_MEAN_FF), lake mean summer TP concentration (LN_TP), and maximum lake depth (LN_MAXDEPTH).

Source of variation	Coefficient	SE	*t*	*P*
Intercept	1.2522	1.4830	0.8444	0.3986
Market – Aitkin	0			
Market – Brainerd	0.8287	0.4979	1.6642	0.0963
Market – Fergus Falls-Alexandria	−0.6568	0.4536	−1.4479	0.1479
Market – Grand Rapids	−0.9450	0.5026	−1.8802	0.0603
Market – Metro	0.2916	0.4334	0.6727	0.5013
Market – Northeast	−1.7968	0.4395	−4.0885	<0.0001
Market – Park Rapids-Bemidji	−0.8703	0.5271	−1.6512	0.0990
Market – South	−1.0411	0.5213	−1.9972	0.0460
Market – St. Cloud	−0.3904	0.4958	−0.7876	0.4311
Market – Walker-Hackensack	−0.9033	0.5958	−1.5160	0.1298
LN_LAKEAREA	0.7163	0.1012	7.0795	<0.0001
LN_MEAN_FF	0.0184	0.2711	0.0679	0.9459
LN_TP	1.0823	0.2727	3.9687	0.0001
LN_MAXDEPTH	0.2141	0.0266	8.0467	<0.0001
LN_LAKEAREA*LN_MEAN_FF	−0.0699	0.0180	−3.8865	0.0001
LN_LAKEAREA*LN_TP	−0.0893	0.0193	−4.6397	<0.0001
Market – Brainerd*LN_MEAN_FF	−0.0926	0.1184	−0.7827	0.4340
Market – Fergus Falls-Alexandria*LN_MEAN_FF	0.2290	0.1058	2.1636	0.0307
Market – Grand Rapids*LN_MEAN_FF	0.2078	0.1108	1.8760	0.0609
Market – Metro*LN_MEAN_FF	0.1687	0.1020	1.6535	0.0985
Market – Northeast*LN_MEAN_FF	0.3934	0.0990	3.9726	0.0001
Market – Park Rapids-Bemidji*LN_MEAN_FF	0.2182	0.1183	1.8452	0.0653
Market – South*LN_MEAN_FF	0.3986	0.1164	3.4244	0.0006
Market – St. Cloud*LN_MEAN_FF	0.1905	0.1182	1.6119	0.1073
Market – Walker-Hackensack*LN_MEAN_FF	0.2806	0.1329	2.1114	0.0350

variance structure allowed for an increase in the residual variance for this fixed effect; Table 3). Mean land value decreased with increasing lake mean total phosphorus concentration, and it increased with lake size and maximum depth. (Fig. 4; predictions for Brainerd real estate market).

The median estimated lake protection or restoration costs for management activities that assumed a TP loading reduction of 5% for a set of 1127 Minnesota lakes was $243,000 (Table 4; $32/shoreline m, range: $0.2–$48,000/shoreline m). For most lakes, the cost was below $1 million; several lakes had exorbitant costs and these lakes were impoundments on large rivers or floodplain lakes of large rivers where their watersheds and hydraulic loading volumes were large. Small lakes, in forested watersheds or in watersheds dominated by agriculture, had the lowest cost for protection or restoration. For minimally disturbed lakes in forested watersheds, the median cost of using conservation easements for TP loading protection was $15,626/kg ($7,088/pound), or $66,000/lake ($n = 200$ lakes; $9/shoreline m), where the median conservation easement size was 12 lakeshore ha (28 ac). The median cost for agricultural dominated watersheds (>50% of the watershed disturbed and >75% of the disturbance was due to cultivated crops) was $245,000 ($n = 93$ lakes; $30/shoreline m), and the median cost for urban dominated watersheds (>10% of watershed disturbed and >75% of the disturbance was due to developed land classes) was $422,000 ($n = 92$ lakes; $54/shoreline m).

The median benefit, measured as the total land value increase for a lake assuming a successful 5% reduction in TP loading resulting in improved water quality, was $58,000 (Table 4; $n = 1127$; $8/shoreline m; range $0.3–$350/shoreline m). Benefit was correlated to lake surface area ($r^2 = 0.67$, power-law function). Large lakes or lakes in the Metro real estate market were estimated to have benefits of TP load reduction near or over $1 million (e.g., Minnetonka, Leech, Vermilion, Gull, Otter Tail, Pelican). Small lakes (<100 ha) generally had the lowest benefits. There was a poor relationship between cost and benefits ($r^2 = 0.22$).

The median benefit:cost ratios (BCR) by real estate market were highest in the Fergus

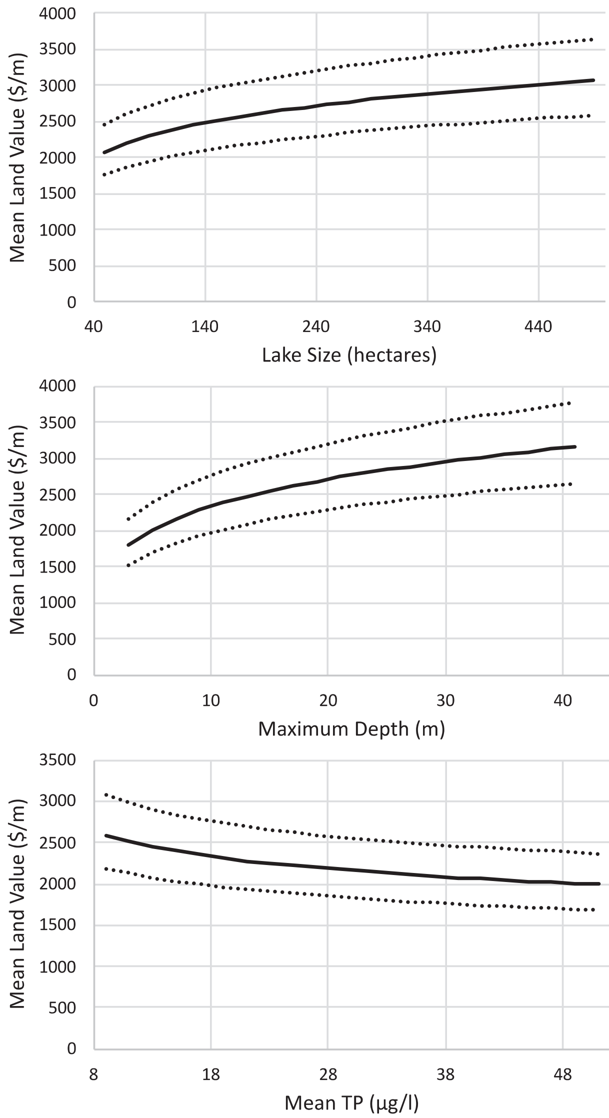

Figure 4. Mean land value ($/shoreline m) as a function of lake size, maximum depth and summer mean total phosphorus (TP) concentration for lakes in the Brainerd real estate market. Upper panel predictions varied lake size with summer mean TP set at 18 µg/L, maximum depth at 10 m, and mean shoreline parcel length at 61 m. Middle panel predictions varied maximum depth with lake size set at 100 ha, summer mean TP set at 18 µg/L, and mean shoreline parcel length at 61 m. Lower panel predictions varied summer mean TP with lake size set at 100 ha, maximum depth at 10 m, and mean shoreline parcel length at 61 m. Dotted lines represent 90% prediction intervals.

Table 4. Quantiles and summary statistics of benefits (total land value increase in $), lake protection, or restoration costs for management activities that were assumed to reduce TP loading by 5%, and benefit:cost ratio (BCR) for 1127 Minnesota lakes. Values rounded to the nearest thousand.

Variable	Benefit	Cost	BCR
Maximum	64,349,000	645,799,000	8.84
75^{th} Quartile	177,000	968,000	0.24
Median	58,000	243,000	0.07
25^{th} Quartile	22,000	82,000	0.02
Minimum	2000	1000	0.00
Mean	360,000	2,322,000	0.27
Standard Deviation	2,297,000	20,666,000	0.62

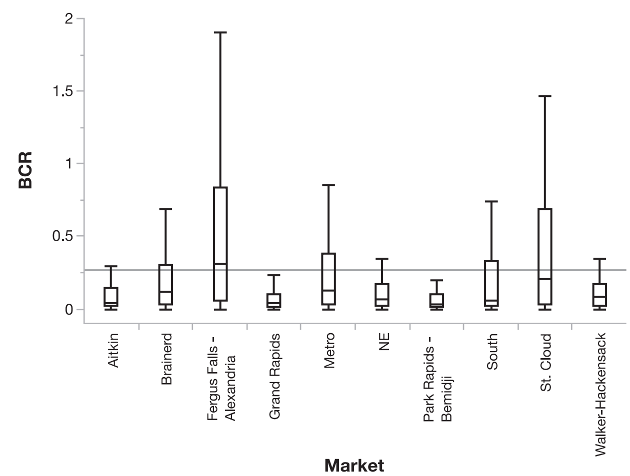

Figure 5. Box plots of benefit:cost ratio (BCR) for lakes grouped by real estate market. The box is the interquartile range. The vertical endpoints are not longer than 1.5 times the interquartile range, and the line within the box is the median. The horizontal line is the mean for all lakes. NE = Northeast.

Falls–Alexandria market, followed by the St. Cloud, Metro, and Brainerd markets (Fig. 5, Table 5). Lakes in the Fergus Falls–Alexandria market generally had lower costs given their watersheds had a greater proportion of land in agricultural use, and they had a substantial number of lakes estimated to be responsive to a 5% TP reduction. Lakes in the St. Cloud, Metro, and Brainerd markets, with their higher land value, generally had high benefits as measured in increased land value with TP reduction. The top BCR lakes were clustered around Fergus Falls, west and south of Minneapolis, in north-central Minnesota, and scattered throughout the northeast.

Some priority lakes based on this analysis that were not a high priority based on LPSS include Lake Minnetonka (Metro market), Black Duck Lake (Northeast market), and Washington Lake (South market). Lake Minnetonka is a large, high land value lake on the outskirts of Minneapolis; it was predicted that restoration efforts that reduced TP loading by 5% may increase total land value by $64 million. Black Duck Lake is a minimally developed lake in the northern part of the state. While the benefits of protecting Black

Table 5. For the top 20 BCR lakes by location, total benefit, total cost, and median BCR for management activities that assumed a TP loading reduction of 5%.

Location	Total Benefit ($)	Total Cost ($)	Median BCR (range)
Ecoregion			
Northern Lakes and Forests	27,111,000	10,506,000	0.96 (0.69–5.23)
North Central Hardwood Forests	81,920,000	11,790,000	3.26 (2.32–8.84)
Western Corn Belt Plains	2,155,000	8,515,000	0.03 (0.01–0.46)
Real Estate Market			
Aitkin	6,589,000	14,116,000	0.18 (0.09–1.09)
Brainerd	27,394,000	11,989,000	0.69 (0.50–5.23)
Fergus Falls – Alexandria	22,666,000	4,322,000	2.30 (1.20–8.84)
Grand Rapids	12,327,000	10,759,000	0.24 (0.17–0.78)
Metro	86,481,000	15,833,000	1.57 (0.85–5.35)
Northeast	7,112,000	6,517,000	0.48 (0.32–0.91)
Park Rapids – Bemidji	8,081,000	13,101,000	0.17 (0.11–3.10)
South	4,127,000	2,892,000	0.44 (0.24–2.49)
St. Cloud	8,766,000	2,444,000	1.18 (06.5–5.56)
Walker-Hackensack	36,913,000	85,828,103	0.25 (0.16–0.69)

Duck Lake were modest ($250,000), the cost of protection was low ($160,000). Protecting Black Duck Lake's shorelands, 39% of which were in private ownership, via conservation easements may provide a good return on investment. Lastly, Washington Lake is a highly developed, southern lake near the city of Mankato; it is a popular lake for water recreation. Washington Lake's watershed is dominated by cultivated agricultural land use. If low-cost agricultural practices could be effectively implemented to reduce TP load to the lake, then those efforts may produce sufficient water quality benefits to increase total shoreland value.

Several types of lakes had high mean BCR. Large lakes (>500 ha) had significantly higher mean BCR than small lakes (Mann–Whitney test, $P < 0.0001$). High land value lakes, where the total shoreland value was greater than $48 million (the 90th percentile, $n = 113$ lakes) had significantly higher mean BCR than lakes with lower total value shorelands (Mann–Whitney test, $P < 0.0001$). Lakes of Biological Significance (LOBS) had significantly higher mean BCR than lakes that were not (Mann–Whitney test, $P = 0.0431$). Lakes that were estimated to be highly vulnerable to additional TP loading (lakes with a TP loading sensitivity index, S, greater than the 90th percentile, $n = 113$ lakes) had significantly higher mean BCR than those that were less sensitive (Mann–Whitney test, $P < 0.0001$).

Two classes of lakes had low mean BCR. First, lakes with high predicted TP load to TP load threshold ratios (ratios between 0.75 and 1.0, $n = 131$ lakes) had lower mean BCR than other lakes (Mann–Whitney test, $P < 0.0066$). These lakes, which may have higher probability of tipping into recreational use impairment, generally had higher protection or restoration costs. Second, and related, the mean BCR for lakes listed as recreational use impaired was significantly lower than unimpaired lakes (Mann–Whitney test, $P < 0.0001$). The mean BCR for impaired lakes was 0.14 ($n = 208$ lakes) compared to 0.30 for unimpaired lakes ($n = 919$ lakes). If restoration efforts focused on impaired lakes, prioritizing those lakes ranked by BCR, then restoration for the top 100 ranked lakes would have a cumulative cost of $80 million and a cumulative benefit of $34 million in total land value increase. For the same $80 million, selecting any high BCR ranked lake in the state without regard to impairment status, protection and restoration activities could be conducted on 198 lakes (versus 100) and the benefit would be $209 million (versus $34 million). Prioritizing for impaired lakes resulted in a 49% reduction in the number of lakes and 84% loss in benefits. Prioritizing without regard to impairment status was predicted to have a 6 times greater return on investment than focusing on impaired lakes with high BCR. Only a few impaired lakes would be targeted for restoration with the any-lake BCR prioritization approach (i.e., only the highest BCR impaired lakes would be included for restoration with such a prioritization).

Comparison of prioritizations

The values-based model (LPSS) and BCR prioritizations shared many lakes in their respective top 100 ranked lakes and these 2 prioritizations were moderately correlated (Fig. 6; for values $r^2 = 0.45$; for their ranks $r^2 = 0.43$). Sixty-nine lakes scored in the top 100 ranked lakes for both LPSS and BCR, and most of these lakes are located in the ecological transition zone from Detroit Lakes southeast to Minneapolis (Fig. 7). Sixty-one lakes were in the top ranked lakes for the LPSS prioritization that were not in the top ranked lakes for BCR (61/130 = 47%; the total lakes summed to more than 100 in the LPSS priority score due to ties). Thirty-one lakes were in the top ranked lakes for the BCR prioritization that were not in the top ranked lakes for LPSS (31%; no ties in the BCR).

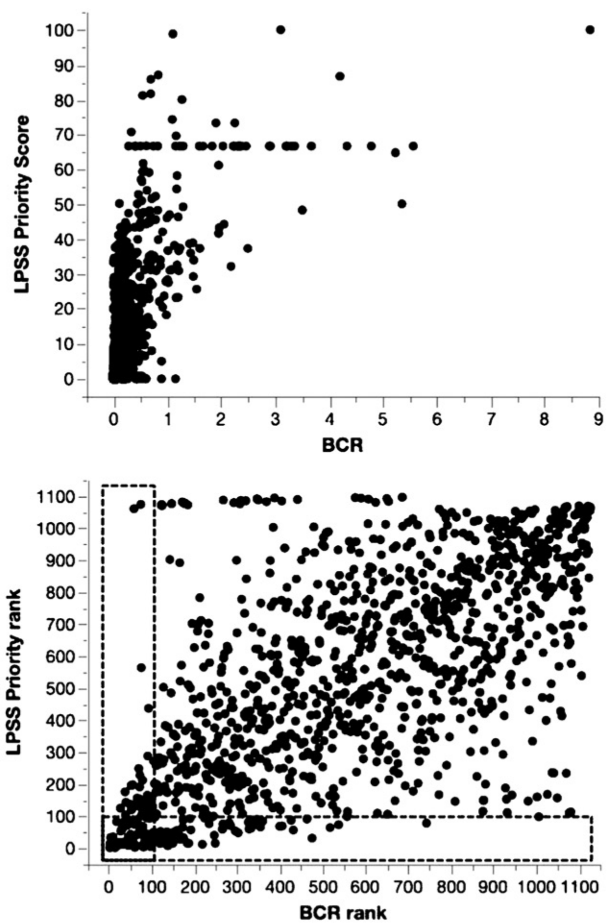

Figure 6. The benefit:cost ratio (BCR) for lakes plotted against the lake phosphorus sensitivity significance (LPSS) priority score (upper panel; $r^2 = 0.45$), and the BCR rank plotted against the LPSS priority rank (lower panel; $r^2 = 0.43$). The dashed boxes show the top 100 ranked lakes for BCR and LPSS.

Notably, several of these lakes were minimally disturbed lakes in forested watersheds, and these lakes had very low LPSS priority scores and ranks because their risk of becoming impaired was low (those lakes are visible in Fig. 6, lower panel, as a line of points in the upper left).

LPSS and BCR priorities also differed in regard to high land value lakes—high land value lakes generally had lower LPSS priorities than comparable BCR ranked lakes. If protection and restoration efforts focused on the top 100 LPSS lakes, the cumulative cost was \$30 million and the cumulative benefit was \$124 million. For the same \$30 million cost, selecting lakes just by BCR would get 77 lakes with a cumulative benefit of \$143 million (a 15% increase in benefits). If protection and restoration just focused on the top 100 BCR lakes the cumulative cost was \$36 million and the cumulative benefit was \$154 million (compared to the LPSS prioritization, a 20% increase in cost with a 24% increase in benefits).

From a statewide perspective, lake protection and restoration priorities vary spatially based on the different prioritization approaches (Fig. 8). LPSS and BCR priorities both focus on lakes

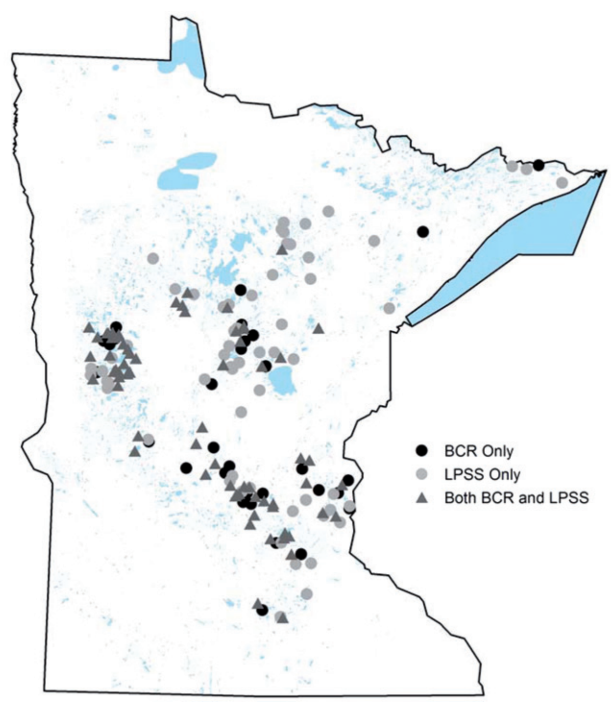

Figure 7. The top 100 ranked lakes by benefit:cost ratio (BCR) and lake phosphorus sensitivity significance (LPSS). Multiple lakes scored in the top 100 for both BCR and LPSS (triangles), N = 69 lakes.

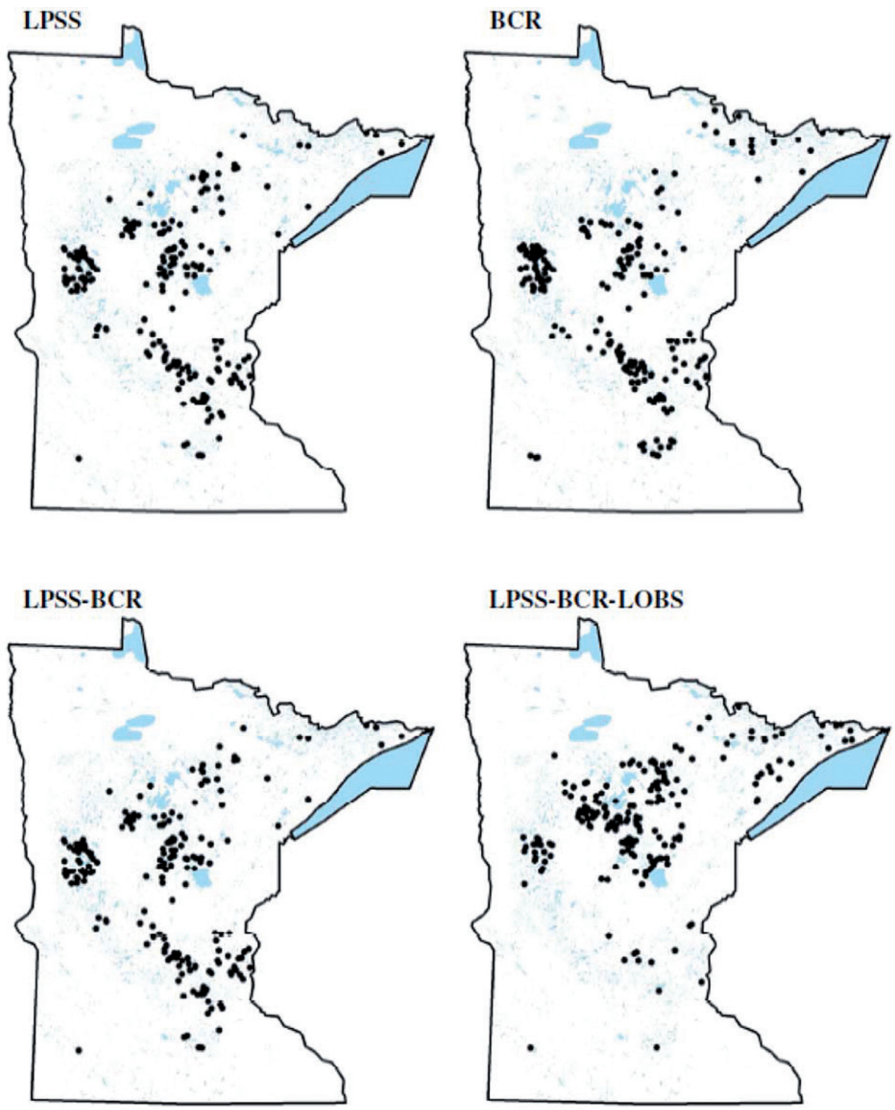

Figure 8. The top 200 ranked lakes by lake phosphorus sensitivity significance (LPSS) priority score, benefit:cost ratio (BCR), 2-dimensional BCR–LPSS feature prioritization, and 3-dimensional BCR–LPSS–Lakes of Biological Significance (LOBS) feature prioritization.

located in the ecological transition zone from Detroit Lakes southeast to Minneapolis and in north-central Minnesota. The top BCR priorities include more lakes in northeastern Minnesota. The 2-dimensional BCR–LPSS prioritization produces a spatial distribution that blends the 2, while the top 3-dimensional BCR–LPSS–LOBS priority lakes tend to be located in north-central and northeast Minnesota, where a large proportion of LOBS lakes exist.

Discussion

The multi-criteria values-based model identified a list of priority lakes based on the objective of identifying high-quality lakes at greatest risk of becoming degraded or further degraded. The results of this approach were moderately correlated with the results of the benefit:cost ratio (BCR) approach. Our analyses indicate that the exclusion of benefits and cost in prioritization would likely result in a modest amount of potential benefit forgone (~20%). In other comparisons, values-based models had higher forgone benefits and higher costs than those based on benefit:cost analyses (Joseph et al. 2009, Pannell and Gibson 2014).

Protection of lakes with mostly undisturbed forested watersheds was estimated to be a cost-effective use of resources. Of the lakes studied, many were sensitive to TP loading and the cost of protection via conservation easement was often lower than the cost of restoration; on average, the conservation easement cost was one-third of that for restoration activities related to stormwater management. While we used conservation easements only for minimally impacted lakes, a protection approach applied more broadly, where feasible, would likely have high BCRs. For example, medium to large parcels on vulnerable lakes would be good opportunities for investment with willing landowners. This approach may also produce other environmental benefits (fish and wildlife habitat, aesthetic, etc.).

A focus just on impaired waters would likely result in considerable forgone benefit (our results suggest a potential benefit forgone at ∼80%). There are benefits of restoring degraded lakes, but there are also shortcomings associated with a dominant focus on this subset of lakes. First, in many impaired waters, TP loading is from non-point sources that have non-regulatory and more challenging source reduction strategies than control of discharges from end-of-pipe (Carpenter et al. 1998). Second, these lakes are often difficult to restore (Carpenter 2005, Cook et al. 2005), and they often require TP load reductions greater than the 5% reduction used in this analysis. Restorations may be hindered by internal TP cycling or the ability to scale non-point pollution controls (Huser et al. 2016). Higher returns of conservation investments may be achieved with a greater share of resources dedicated to protecting and restoring lakes with high resiliency and high benefit:cost ratios.

There are shortcomings to using benefit:cost ratios only. Ackerman and Heinzerling (2002) and Ackerman (2008) made a compelling case that benefit:cost analysis should not be the central method for decision-making; that is, taking action on environmental protection should not be dependent on such analysis. While our results show that the use of BCR would improve return on investment, it is still useful to consider those concerns that are relevant to prioritizing lakes for protection and restoration. First, whereas some costs are often well defined, benefits are hard to define well. For example, we did not include many benefits, such as the presence of unique lake characteristics (cultural, biological, etc.) or the value of recreational activities; these benefits have clear value but were not monetized. Riparian land value was an important factor in the calculation of BCR, and when prioritizing by location, lakes in high-value real estate markets were prioritized over other high-quality lakes in less-valuable markets or those more distant from population centers (Aitkin, Grand Rapids, Northeast, and Walker–Hackensack). The list of priority lakes changed substantially when we included high-quality biological lakes within the prioritization (i.e., more high-quality lakes in less valuable or more-distant real estate markets were included). Second, benefit:cost analyses can lead to troubling tradeoffs that are not addressed. The use of the estimated costs for agricultural and stormwater BMPs assumed no explicit impact to society and the benefits accrued only to those with shoreland property. Third, the technicalities of benefit:cost analysis may lead to biases in the promotion of policies or in the interpretation of the results. For example, many minimally disturbed lakes in forested watersheds had high BCR priorities; however, while some of these lakes would likely benefit with proactive protection via conservation easement, others would not (e.g., they are located in watersheds predominantly in public ownership). In addition, only a few management options were used and their costs had considerable uncertainties and variabilities. Thus, even in efforts to prioritize lakes for protection and restoration it is important that BCR analysis is not the main method for deciding on which lakes to invest greater resources. Incorporation of additional information through a peer-review process may help mitigate some of the shortcomings associated with BCR analysis, and lead to a better priority list (Armsworth et al. 2017).

Peer review is an important process to include in any prioritization. BCR analysis is constrained, and it is necessary to include information not expressed in monetary terms. A deliberative process is necessary when adding in expert judgements (Martin 2012). Adding in expert judgement is important not because funding decisions are inherently subjective, but because there is good information that is not incorporated into even the most thorough and complex values-based model or BCR analysis. Silver (2012) noted that predictions are often improved when the models were supplemented with human judgments that incorporate information not used. In prioritization of lakes, the same can be said—the incorporation of human judgments to alter the prioritization based on information not used in a multi-criteria values-based model or a BCR analysis can produce a better priority list. However, the judgments expressed should be transparent and contestable (Game et al. 2013).

We pose the following recommendations based on our comparisons and understanding of the benefits and shortcomings of different prioritization approaches. First, define a clear objective. A reasonable one for Minnesota might be "*focus on high-quality, high-value lakes that provide the greatest return on investment*." The objective should include the diverse aspects of lakes. High-quality would refer primarily to water quality, but include biological character, cultural importance, and other attributes that are measured or subjectively assessed. High-value would relate to economic factors including shoreland property value, recreational use values, and other attributes that might be priceless. Greatest return on investment would relate to phosphorus-loading resilience and economic considerations. For example, Keeler et al. (2015) found that lake recreational value, as assessed by lake visitation, was a function of lake size, water clarity, boat access, and near-lake human population size. They also determined that people traveled farther to recreate on clearer lakes.

Second, develop one or more multi-criteria values-based models that reasonably capture all or a portion of the defined objective function. An alternative values-based model, with an objective function of "*focusing on high-quality, high-value lakes that likely provide the greatest return on investment*," is:

$$Priority\ Score_2 = S^a \times A^b \times (D + 0.01)^c$$

where the multipliers are the TP loading sensitivity index (S), lake surface area (A, acres), and the proportion of the lake's immediate catchment in disturbed land cover (D), and a, b, and c are multiplier weights. This values-based model is better correlated with the BCR ($r^2 = 0.71$, power-law function, vs. $r^2 = 0.45$) than the original values-based model which had the objective of "focusing on high-quality lakes at greatest risk of becoming impaired or further degraded."

Third, use benefit:cost analysis to re-sort an initial priority list of lakes from the values-based models. For example, take the top lakes from the values-based model and re-prioritize based on benefit:cost analysis. What lakes are likely to provide higher benefit per cost of investment? Essentially, benefit:cost analysis becomes more of a cost-effectiveness analysis. In the absence of a formal cost-effectiveness analysis the following guidelines could be used: (1) give higher priority to large lakes; (2) give higher priority to lakes that are sensitive to changes in TP loading; (3) give higher priority to lakes that can be protected with cost-effective strategies (e.g., forested watershed lakes that can be protected with proactive shoreland conservation easements); and (4) give higher priority to developed lakes in or close to large cities as they have high social values. Finally, make the draft priority list available for peer review. Reviewers will bring information and insights not included in the analyses, and help make the priority list even more defensible and practical.

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