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Optimizing multiple dam removals under multiple objectives: Linking tributary habitat and the Lake Erie ecosystem

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[1] A model is proposed for optimizing the net benefits of removing multiple dams in U.S. watersheds of Lake Erie by quantifying impacts upon social, ecological, and economic objectives of importance to managers and stakeholders. Explicit consideration is given to the linkages between newly accessible tributary habitat and the lake's ecosystem. The model is a mixed integer linear program (MILP) that selects a portfolio of potential dam removals that could achieve the best possible value of a weighted sum of the objective(s), while still satisfying the constraints. Using response functions extracted from the Lake Erie Ecological Model and an empirical cost model, the MILP accounts for ecological and economic effects of habitat changes for both desirable native walleye and undesirable sea lamprey. The solutions show the effect on removal decisions of alternative prioritizations among cost and environmental objectives and the resulting trade-offs among those objectives. The MILP can be used as a screening model to identify portfolios of dam removals that are potentially cost-effective enhancements of habitat and the Lake Erie ecosystem; subsequent site-specific studies would be needed prior to actually removing dams.

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1. Introduction

[2] The most productive and biologically diverse of the Great Lakes, Lake Erie is also the most densely populated and severely perturbed lake of the five [*Burns*, 1985; *Bolsenga and Herdendorf*, 1993]. The drastic degradation of the Lake's ecosystem is the result of natural and cultural stresses [*Leach*, 1999]. Among many stressors that have contributed to this decline, loss of fish habitat caused by damming of streams and other causes plays a critical role [*Regier and Hartman*, 1973; *Koonce et al.*, 1996; *Hayes*, 1999].

[3] Restoration efforts such as nutrient control and fishery management have been undertaken in Lake Erie over the past few decades and have achieved some success. However, the subsequent recovery of key native fish populations (e.g., walleye (*Sander vitreus*)) has slowed recently. Habitat limitations, in particular for spawning and nursery habitat in nearshore areas and tributaries, have been hypothesized as possible limitations to fishery recovery [*Koonce et al.*, 1996; *Hayes and Petrusso*, 1998; *Hayes*, 1999; *Ryan et al.*, 2003].

[4] Here we consider the benefits and costs of habitat restoration through removing dams in U.S. watersheds of Lake Erie that prevent access to historic fish habitat and may no longer serve their original economic purpose. Actions to restore lost or damaged historic habitat can improve fish survival and reproduction [*Geiling et al.*, 1996]. Dam removal has recently drawn substantial attention from ecosystem managers as a practical river and habitat restoration tool [*Bednarek*, 2001; *Poff and Hart*, 2002; *Doyle et al.*, 2003]. Nationwide, over 200 dams have been removed since the year 2000 [*American Rivers*, 2007]. *Pohl* [2002] summarized the primary reasons for dismantling dams. These include: restore species and/or habitat (39%), safety (34%), economics (18%), and failure (5%). Previous removals have shown that restorations of unregulated flow regimes in watersheds have increased biotic diversity [*Shuman*, 1995; *Heinz Center*, 2002].

[5] In the Lake Erie basin, at least 27 dams have already been demolished for reasons such as habitat improvement and removal of public safety hazards (based on data provided by R. Archer, Division of Water, Ohio Department of Natural Resources, 2006). Data available from the Lake Erie Dam Database (C. Geddes, Institute for Fisheries Research, University of Michigan, personal communication, 2006) indicate that more than two thousand dams are located in the U.S. watersheds of Lake Erie. Many are small and were built more than half a century ago. Some are out of service and impose not only adverse ecological impacts but also economic burdens on society. Some have deteriorated and face a significant risk of failure. Because many dams are candidates for removal and because the effects of removing one dam can depend on whether others have been removed (e.g., due to upstream-downstream relationships), efficient decision making requires simultaneous consideration of all removal possibilities as a portfolio problem.

[6] However, dam removal decisions are difficult due to multiple objectives and diverse stakeholders. Removal of tributary dams in the Lake Erie basin involves many trade-offs. On the one hand, removal improves habitat for certain native fish species (e.g., walleye). On the other hand, it

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involves significant costs as well as expansion of habitat for exotic species (especially sea lamprey (*Petromyzon marinus*)), and possibly negative ecological consequences resulting from ecological interactions (e.g., walleye predation on other fish species). In general, there is no consensus among stakeholders about the relative priority to be accorded to economic, ecological, and social objectives [*Bowman et al.*, 2002; *Heinz Center*, 2002]. To address these concerns, this study models the benefits and costs of removing multiple dams, and uses a multiobjective optimization model to identify distinct efficient portfolios and trade-offs among different objectives. We account for possible changes in the ecological health of the lake by explicitly linking effects of dam removal upon tributary habitat and the resulting impacts upon Lake Erie ecosystem structure and function. However, because of uncertainty in model parameters, further site-specific study must be carried out to verify costs and habitat improvements at particular dam sites prior to any actual removals.

[7] In section 2 of this paper, we briefly review the literature related to dam removal decisions and multiobjective analysis (MA). Section 3 describes the numeric models we use and linkages among those models. A model formulated as a mixed integer linear program (MILP) (section 3.2) is proposed to select candidate dams for removal. The objective function of the MILP is a multicriteria value analysis (MVA) model (section 3.1) that combines several ecosystem objectives addressing lake-wide and community-based ecological effects of habitat changes following dam removal. Fish riparian habitat models (section 3.3.1) based on the Habitat Suitability Index (HSI) concept and Geographical Information System (GIS) data are used to quantify the habitat changes for both desirable native walleye and undesirable invasive sea lamprey of Lake Erie. The Lake Erie Ecological Model (LEEM) (section 3.3.2) is then used to link ecosystem objectives to habitat decisions (section 3.3.3). Functions describing the costs of dam removal and sea lamprey treatment control are estimated by regression analysis (section 3.4). Section 4 presents results of a case study using 139 dams in ten U.S. watersheds in Lake Erie. Finally, we offer some conclusions in section 5.

2. Multiobjective Analysis of Dam Removal Decisions

[8] Our review of the literature of dam removal reveals several trends. First, the recent acceleration of dam removal projects reflects problems with aging and substandard dams, and growing public and government interest in restoring rivers and fish tributary habitat [*Pejchar and Warner*, 2001; *Stanley and Doyle*, 2003; *Wohl et al.*, 2005]. Second, dam removal is not always beneficial. While hundreds of dams have been removed, it does not mean that most dams should be torn down [*Pizzuto*, 2002; *William*, 2003]. Many continue to serve important functions such as flood control, water supply, and hydropower generation. Replacing these services could be very costly or infeasible. In some cases, dams are retained because they represent a significant aspect of the community's history or serve as barriers that repel exotic species (e.g., sea lamprey barrier in the Great Lakes regions) [*Sullivan et al.*, 2003]. While the pervasive assumption is that removing small dams is usually financially efficient and has minimal impacts on geomorphic and ecological processes, removing larger dams is usually controversial since they involve large costs and uncertainties [*Poff and Hart*, 2002]. Third, dam removal decisions are considered mostly on a dam-by-dam basis but rarely on a portfolio basis [*Heinz Center*, 2002; *Kuby et al.*, 2005]. Fourth, few dam removal decisions have been based on a formal benefit-cost or decision analysis with respect to effects on fish community in downstream ecosystems [*Whitelaw and MacMullan*, 2002]. Instead, habitat recovery is commonly used in previous removal studies as a proxy for ecological benefits. But habitat increases do not necessarily enhance populations of target species because of complex life histories and other ecological limitations (e.g., habitat bottlenecks at other life stages or available prey for adults) [*Morrison*, 2001; *Corsair et al.*, 2009]. Overall, a lack of systematic analysis of dam removal decision making may result in vague or incomplete statement of the goals of ecosystem restoration as well as decisions that are ineffective at addressing those goals [*Bednarek*, 2001; *Doyle et al.*, 2003].

[9] Use of formal systems analysis methods, in particular multiobjective analysis (MA), could improve dam removal decision making [*Heinz Center*, 2002; *Price*, 2004]. Benefits of MA include increased transparency and explicit recognition of trade-offs [*Keeney and Raiffa*, 1976; *Cohon*, 1978]. More specifically, the use of MA in restoration can quantify noneconomic objectives (e.g., habitat and ecosystem restoration), facilitate consistent valuation (in eliciting expert judgments and decision maker preferences), communicate important trade-offs (e.g., economic costs versus ecological benefits), and facilitate negotiation by helping stakeholders to focus on ultimate objectives [*Corsair et al.*, 2009].

[10] MA has long been applied to ecological management, especially conservation issues [e.g., *Williams et al.*, 2005], fisheries [e.g., *Alexander et al.*, 2006], and forestry [e.g., *Mendoza and Martins*, 2006]. In the case of Lake Erie, *Anderson et al.* [2001] used MA to evaluate phosphorus targets for the lake. MA is also used by *Kim et al.* [2003] to address lower trophic level uncertainties in Lake Erie and value of ecological research. *Haeseker et al.* [2007] used MA to assist the Great Lake Fishery Commission with sea lamprey control decisions in the St. Marys River. However, in contrast to the rich range of other ecological applications, the use of MA to evaluate dam removal decisions is relatively infrequent. For removal of single dams, MA is applied by *Corsair et al.* [2009] for a proposed removal decision on a large dam in the Sandusky River in Ohio. For multiple dam removals, *Peters and Marmorek* [2001] applied MA to evaluate chinook salmon (*Oncorhynchus tshawytscha*) recovery actions that include drawdowns of four dams on the lower Snake River. *O'Hanley and Tomberlin* [2005] used integer programming techniques to optimize repair or removal decisions on small fish passage barriers including dams. The most directly relevant research was done by *Kuby et al.* [2005]. They developed a multidam removal model that considered trade-offs between increased salmon passage with decreased hydropower and water storage in one watershed, the Willamette River basin. We extend the model of *Kuby et al.* [2005] by quantifying costs of dam removal, by considering multiple species and watersheds, by modeling the linkages between habitat change and ecosystem response, and finally by quantifying tradeoffs between ecosystem response and dam removal costs.

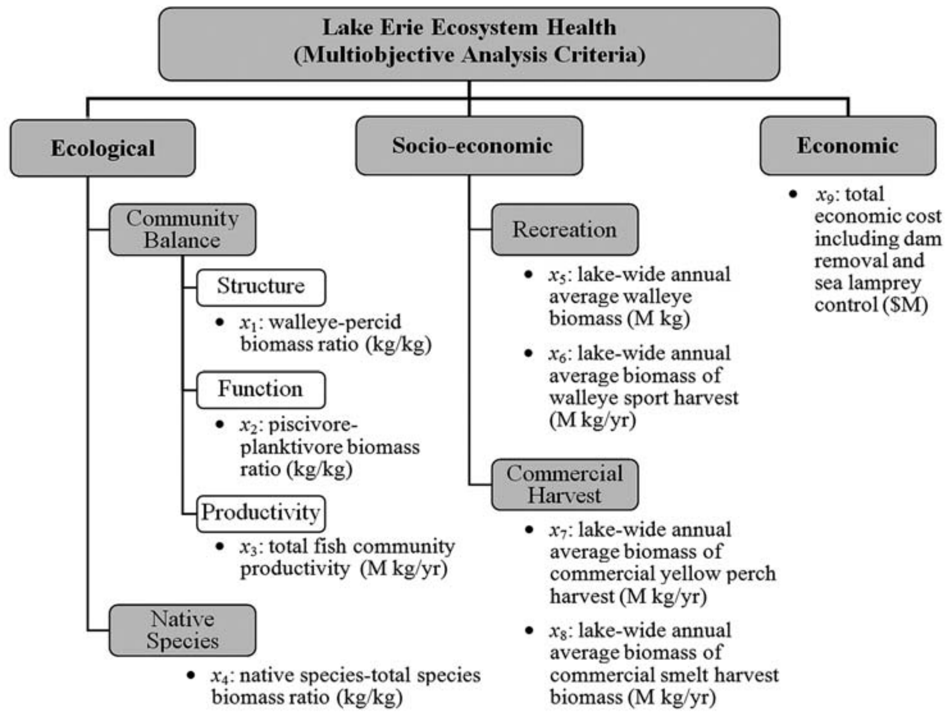

Figure 1. Objective hierarchy and criteria for the Lake Erie multidam removal MA. (Based upon *Corsair et al.* [2009] with kind permission from Springer and *Kim et al.* [2003] with kind permission from Taylor and Francis.) (Here x_1–x_8 are fish community criteria estimated by LEEM simulations. They include characteristics that are not only ecological (e.g., community balance and native species), but also socioeconomic (e.g., recreation and commercial harvest).)

[11] Multicriteria value analysis (MVA) and multiobjective programming (MP) are two commonly used MA methods. MVA emphasizes the capture of user value judgments concerning multiple objectives in the form of single criterion value functions and weights [*Keeney and Raiffa*, 1976]. The resulting multicriteria value functions can be used to rank alternatives. MVA can facilitate involvement of diverse stakeholders by helping them to articulate and apply their priorities, and communicate the reasons why different parties make different recommendations [*Belton and Stewart*, 2002]. In contrast, MP focuses on describing trade-offs among alternatives rather than representing value judgments, and emphasizes constrained optimization with two or more objective functions. It is a specific form of mathematical programming whose solutions are members of the efficient set; an alternative is "efficient" if no other feasible solution exists that is just as good in all objectives and strictly better in at least one [*Cohon*, 1978]. Here, we apply MVA (section 3.1) to quantify ecological objectives within an optimization model, a form of MP (section 3.2), which we then use to describe trade-offs between an aggregate ecological objective and cost for multidam removal decisions in the U.S. watersheds of Lake Erie.

3. Model Formulations and Coefficient Estimation

3.1. Multicriteria Value Analysis Model

[12] We quantify ecological benefits by MVA. MVA assumes that it is possible to define and model someone's preferences by first disaggregating preferences concerning individual criteria and then synthesizing overall values [*Belton and Stewart*, 2002]. There are various forms of MVA; we adopt the additive value model, a form widely used in practice [*Anderson and Hobbs*, 2002]

$$V(x_1, \cdots, x_I) = \sum_{i=1}^{I} W_i V_i(x_i), \qquad (1)$$

where x_i is the ith criterion, a quantitative index of the performance of an alternative on a particular objective (e.g., Lake Erie walleye population); I is the number of criteria; $V()$ is the overall value of an alternative as a function of the values of the I criteria; W_i is the importance weight with respect to criterion i; and $V_i(x_i)$ is the single criterion value function for x_i, which describes the relative desirability of different levels of the criterion. In general, the criterion weights (W_i) are elicited from the user and represent their relative willingness to trade-off the criteria [*Keeney*, 1992]. The sum of weights is arbitrarily set to one. The value functions ($V_i(x_i)$) are arbitrarily scaled from zero (least preferred level) to one (most preferred level).

[13] We use equation (1) to define an aggregate measure of ecological health of Lake Erie, which we then trade off against cost. "Health" is defined broadly as being associated with various social, ecological, and economic objectives of importance to ecosystem managers and stakeholders. Figure 1 displays nine criteria (x_i, i = 1, …, 9) defined in this study, grouped into three general objectives: ecological, socioeconomic, and economic. Criteria x_1 to x_8 are fish community structure, function, and use indicators, which are used in the aggregate measure of health. Together with cost criterion x_9, these nine criteria can be viewed as

quantitative interpretations of the fundamental objectives for restoring the Lake Erie ecosystem.

[14] Criteria x_1 to x_8 are included because they have been adopted in previous MVA studies addressing other decision problems related to Lake Erie ecosystem modeling and management [*Anderson et al.*, 2001; *Anderson and Hobbs*, 2002; *Kim et al.*, 2003; *Corsair et al.*, 2009]. In this paper, the values of those criteria for different decisions are estimated through linking the walleye habitat model (section 3.3.1) and a lake-wide ecological model (section 3.3.2) through a representation of walleye young of year (YOY) survival and impulse response functions (section 3.3.3). (YOY refers to fish that are less than two years old.) The economic objective is implemented by criterion x_9, the combined cost for dam removal and sea lamprey control. Its value as a function of the decision variables is estimated through regression analysis (section 3.4).

3.2. Multidam Removal Using a Mixed Integer Linear Mathematical Program

[15] A mixed integer linear program (MILP) is developed to select candidate dams for removal that are "efficient" (also called "noninferior," "nondominated, or "Pareto optimal") in the sense that no other single portfolio of removed dams could yield an improvement in one objective without causing a degradation in at least one other objective [*Cohon*, 1978]. A MILP contains both zero-one and continuous decision variables. A zero-one variable represents a decision that is of a yes-or-no nature, such as dam removal. Continuous variables represent social, economic and ecological values brought by removing candidate dams. In this paper, the multidam removal optimization focuses on the following two aggregate objectives: (1) to maximize the multicriteria ecosystem health index defined in equation (1) and (2) to minimize economic costs (x_9) accounting for both dam removal and sea lamprey control cost. The decision variables are which dams to remove from a set of candidate dams within multiple watersheds, considering trade-offs between the two objectives. The MILP maximizes the aggregate index of ecological health (equation (1) as a function of x_1,.., x_8) subject to a budget constraint (upper bound upon x_9). By varying the budget, trade-offs between the ecosystem and cost objectives can be generated by identifying distinct efficient portfolios. The model formulation is

$$\text{Maximize} \quad z_1 = \sum_{i=1}^{8} W_i V_i(x_i) \tag{2}$$

subject to

$$x_9 \leq B, \tag{3}$$

$$x_9 = \sum_{j \in J} \left(C_j^{dam} + V_j^{lamprey} C_j^{lamprey} \right) d_j, \tag{4}$$

$$x_i = X_i^{base} + IR_{x_i} \Delta yoy^{walleye}, \quad i = 1, \ldots, 8, \tag{5}$$

$$\Delta yoy^{walleye} = \sum_{j \in J} V_j^{walleye} \Delta YOY_j^{walleye} d_j, \tag{6}$$

$$d_n \leq d_j \ \forall j \in J, \quad n \in J^j, \tag{7}$$

$$d_j \in \{0, 1\} \ \forall j \in J, \tag{8}$$

where objective function z_1 maximizes the multicriteria value (equation (1)) of the fish community criteria (x_1 to x_8) including their ecological and socioeconomic aspects, and objective function x_9 limits the total economic cost of dam removal decisions to a given a budget B (millions of dollars ($M)) for dam removals.

[16] The MILP has three types of decision variables. x_i is a continuous decision variable defined in equation (1) and Figure 1 as a quantitative measure of the fundamental objective for restoring the Lake Erie ecosystem. d_j is a zero-one decision variable, equaling one if dam j is removed and zero otherwise (as given by *Kuby et al.* [2005]). Here $\Delta yoy^{walleye}$ is a continuous decision variable (number of walleye YOY) that calculates the increase in walleye YOY recruitment from the Lake Erie tributaries as the result of the dam removals.

[17] Turning to the other constraints, (3) uses the constraint method developed by *Cohon* [1978]. By altering the budget constraint B in (3), different solutions can be obtained representing alternative efficient combinations of the cost objective x_9 and ecological objective z_1. Another approach, called the weighting method [*Cohon*, 1978], can be used to generate some of those solutions. It weights the two objectives, maximizing $M \times z_1 - (1 - M) \times x_9$, where M is weight on objective z_1 and ranges from zero to one (as *Kuby et al.* [2005] have done). The two methods are compared by *Cohon* [1978], who points out that both methods can generate the same optimal solutions if the optimization problem is convex. An advantage of the weighting method is that it turns a multiobjective problem into a "single" objective problem without adding new constraints. Also, given two or more points in the noninferior set, the weighting method can also find additional noninferior points that dominate some convex combinations of those points. The main advantage of using the constraint method is that when decision variables are integers (or the problem is otherwise nonconvex), it can obtain noninferior solutions in nonconvex portions of the feasible region; these are called "weakly noninferior solutions." The weighting method cannot generate such points, and so the constraint method can provide a fuller portrayal of the trade-offs between the ecological and cost objectives. Constraint (4) calculates economic cost including dam removal and sea lamprey control expenses. Constraints (5) and (6) link decision variables d_j and x_i through $\Delta yoy^{walleye}$. With two types of index sets, constraint (7) enforces the logic of habitat accessibility in a stream network by allowing no dam to be removed unless the dam immediately downstream of it (if any) is also removed, where J denotes the index set of candidates dams for removal and J^j denotes the set of indices n for dams that are directly upstream of dam j. This type of constraint was used by *Kuby et al.* [2005]. Constraint (8) defines d_j as a zero-one variable.

[18] The basic structure of our model is based on the model of *Kuby et al.* [2005]. Both models use binary variables to represent dam removals; both use two objectives that are linear in the dam removal variables (an ecologic objective and a cost objective); and both account for upstream/downstream accessibility relationships among removed dams when considering benefits. However, our model extends the approach of Kuby et al. in several important ways. Our ecological benefit is based on an ecosystem simulation model (rather than the fraction of watershed made accessible used by Kuby et al.) and our cost function is based on an empirical

relationship between dam characteristics and removal cost (rather than the weighted sum of storage capacity and hydropower capacity used by Kuby et al.) as well as the expense of exotic species control. The estimation of ecological benefit in our model involves quantification of habitat across several basins for both desirable native and undesirable exotic species, simulation of the resulting ecosystem response, and then weighting the various ecological health indices based upon judgments by fisheries experts. A final difference in the modeling approaches is that we use the constraint method of multiobjective optimization rather than the weighting method of multiobjective optimization so that the nonconvex portions of the noninferior set can be described.

[19] The MILP contains several economic and ecological coefficients. W_i, $V_i(x_i)$, $V_j^{walleye}$, $V_j^{lamprey}$, $\Delta YOY_j^{walleye}$, X_i^{base}, and IR_{x_i} are ecological coefficients, where W_i and $V_i(x_i)$ are the criterion weight and value function for x_i ($i = 1, \ldots, 8$), respectively (see section 3.1); $V_j^{walleye}$ ($V_j^{lamprey}$) is a subjective probability of an increase in walleye (sea lamprey) recruitment as the result of removing dam j, depending on the basin in which dam j is located; $\Delta YOY_j^{walleye}$ is the estimated additional walleye recruitment resulting from removing dam j, if recruitment indeed increases; X_i^{base} is the average value of criterion i for all of Lake Erie in a steady state base case (i.e., no dam removal and therefore no change in walleye YOY recruitment), as estimated by LEEM (see section 3.3.2); and IR_{x_i} is the impulse response function coefficient for ecological criterion i from LEEM that describes the change in x_i given a unit change in walleye YOY recruitment. Turning to the two economic coefficients, C_j^{dam} is the dam removal cost ($M) representing not just expenditures for removing dam j but also the value of lost services. Meanwhile, $C_j^{lamprey}$ is the cost of lampricide for sea lamprey control ($M) made necessary by the removal of dam j. We discuss the estimation of these ecological and economic coefficients in sections 3.3 and 3.4, respectively.

3.3. Estimation of Ecological Coefficients

[20] Ecological coefficients of the model were assessed by reviewing the literature, eliciting expert judgment, developing fish habitat models, and linking the habitat model to the ecological model. Criteria weights (W_i) and single criterion value functions ($V_i(x_i)$) in equation (1) are based upon two workshops held in Cleveland, Ohio [*Anderson and Hobbs*, 2002; *Kim et al.*, 2003], where fishery managers and biological researchers from the U.S. and Canadian resource management agencies specified the most and least desirable criterion values for a set of ten criteria including these eight criteria (x_1–x_8), as well as their weights (Table 2). For simplicity, we assume that the single criterion value functions are linear in x_i. To make the analysis nontrivial, the original values of the three criterion weights (W_4, W_5, and W_6) that are related to walleye criteria (x_4, x_5 and x_6) are multiplied by three and then all weights are renormalized to sum to one (Table 2), so more aggregate weight are assigned to the walleye. This is done because the original weights result in the trivial decision of no dam removal in our model, as the negative ecological consequences of increased walleye habitat (in terms of impacts upon other species) outweighed the positive benefits of more walleye under the original weights. Of course, in an actual application by managers and stakeholders, no such adjustment should be made; we make it here so that we can illustrate the methodology. $V_j^{lamprey}$ and $V_j^{walleye}$ are estimated by a fishery biologist based on historical records (Table 1). $\Delta YOY_j^{walleye}$, X_i^{base} and IR_{x_i} result from modeling exercises, which include an analysis of habitat creation using a fish habitat model that is linked to LEEM.

3.3.1. Fish Riparian Habitat Model

[21] This model is developed based on the Habitat Suitability Index (HSI) concept. HSI "quantifies an organism's life requisites, using the structure, composition and spatial components of habitat" [*Roloff and Kernohan*, 1999]. It is an index ranging from zero to one, from least to most suitable. HSI is commonly used for habitat impact assessments [*Guay et al.*, 2000]. Our HSI calculations evaluate habitat effects for both walleye and sea lamprey, since adults of both species migrate from lake to stream to spawn. A top predator in Lake Erie's food web, and popular with anglers, walleye abundances are good indicators of not only ecological health, but also social benefits (i.e., recreational fishing). Walleye populations are highly variable, and their recruitment depends heavily on spawning success [*Shuter and Koonce*, 1977]. Accordingly, walleye populations would likely benefit from removing dams with suitable upstream spawning habitat [*Hatch et al.*, 1987].

[22] But as a side effect, dam removal also may provide access to spawning and nursery habitat for sea lamprey, which could negatively impact the Lake Erie fish community. Sea lamprey are eel-like fish that attach themselves to game fish, such as lake trout (*Salvelinus namaycush*) and whitefish (*Coregonus clupeaformis*), and drain blood from them, often killing the host [*Bolsenga and Herdendorf*, 1993]. After spreading into Lake Erie in 1921, sea lamprey moved rapidly to the other Great Lakes, and some fisheries (e.g., lake trout) were devastated during the time of highest sea lamprey abundance [*Sullivan et al.*, 2003; Great Lakes Fishery Commission (GLFC), Sea lamprey: A Great Lakes invader, fact sheet 3, 2 pp., Ann Arbor, Michigan, 2000, available at http://www.seagrant.umn.edu/downloads/x106.pdf]. Thus, we consider increases in sea lamprey habitat to be undesirable. Unlike adult walleye, adult sea lamprey die after spawning, and larvae sea lamprey, called "ammocoetes," live in the bottom of the stream for several years (typically 3 to 17 years) before swimming to lakes as parasitic adults [*Bolsenga and Herdendorf*, 1993; *Sullivan et al.*, 2003]. Suitability of ammocoetes nursery habitat is considered more critical than spawning in this paper.

[23] The HSI calculations here focus on physical habitat factors (i.e., stream depth, velocity and substrate). There are many ways to estimate HSI. Most generally, HSI for a riparian system is calculated as a function of stream characteristics based on fish habitat preferences [*Minns et al.*, 1996; *Minns and Bakelaar*, 1999]. The relevant characteristics and preferences depend on fish species and life stage. For example, adult walleye prefer to spawn on a coarse substrate [*Lowie et al.*, 2001]. In contrast, ammocoetes prefer to live in a fine substrate for several years [*Sullivan et al.*, 2003]. In this paper, the expressions used for the amount of HSI-weighted walleye and sea lamprey habitat made available by removing dam j are

$$H_{j,s}^{walleye} = \sum_{k \in K^j} HSI_k^{walleye} A_{k,s} \ \forall j \in J, \quad s \in S \tag{9}$$

$$H_j^{lamprey} = \sum_{k \in K^j} HSI_k^{lamprey} \ \ L_k \ \forall j \in J, \tag{10}$$

Table 1. Summary of Weighted Potential Habitats and Costs

Watershed Name	Drainage Area (km^2)	Recruitment Likelihood: Walleye, $V_j^{walleye}$ (%)	Recruitment Likelihood: Lamprey, $V_j^{lamprey}$ (%)	Candidate Dams for Removal	Suitable Habitat: Walleye, $H_j^{walleye}$ (km^2)	Suitable Habitat: Lamprey, $H_j^{lamprey}$ (km)	Potential Habitat: Walleye, $H_j^{walleye} \times V_j^{walleye}$ (km^2)	Potential Habitat: Lamprey, $H_j^{lamprey} \times V_j^{lamprey}$ (km)	Cost: TFM, $C_j^{lamprey}$ ($M)	Cost: Removal, C_j^{dam} ($M)
Raisin	2817	10	100	16	8.34	37.98	0.83	37.98	1.31	4.10
Maumee[a]	12156	100	100	35	11.74	284.40	11.74	284.40	9.80	7.76
Cedar-Portage	2532	100	100	1	0.01	0.27	0.01	0.27	0.01	1.65
Black-Rocky	2328	5	0	23	5.78	31.62	0.29	0.00	0.00	2.76
Cuyahoga	2074	40	50	6	7.33	40.10	2.93	20.05	0.69	1.99
Ashtabula-Chagrin	1658	5	100	6	1.55	9.92	0.08	9.92	0.34	1.55
Grand	1842	40	100	8	7.90	32.12	3.16	32.12	1.11	1.69
Cattaraugus	1423	5	0	4	2.42	12.30	0.12	0.00	0.00	1.60
Buffalo-Eighteen-Mile	1930	5	0	24	2.86	23.77	0.14	0.00	0.00	5.15
Sandusky	4729	100	100	16	13.65	98.25	13.65	98.25	3.39	4.21
Total				139	61.59	570.74	32.96	483.00	16.64	32.45

[a]Maumee watershed includes Lower Maumee, Tiffin, Upper Maumee, Auglaize, and Blanchard subwatersheds.

where S denotes the set of indices s for substrate types including rubble, cobble, gravel, sand and mud detritus; K^j denotes the index set of river reaches k that lie between dam j and dam $n \in J^j$; $H_{j,s}^{walleye}$ is the area-weighted suitable stream habitat (km^2) for walleye spawning created by removing dam j that contains the sth type of substrate; $HSI_k^{walleye}$ is the value of HSI based just on depth and velocity for reach k for walleye spawning (sediment's effect on habitat is considered later); $A_{k,s}$ is the area (km^2) of sth type of substrate in reach k; $H_j^{lamprey}$ is the length-weighted suitable stream habitat (km) for ammocoetes nursery created by removal of dam j; $HSI_k^{lamprey}$ is the value of HSI for reach k for ammocoetes nursery; and L_k is the length (km) of reach k. Different units for $H_{j,s}^{walleye}$ and $H_j^{lamprey}$ reflect that habitat area is relevant for walleye YOY survival, while stream length is what matters for the cost of lamprey control.

[24] The most common expression for HSI calculations is [*McMahon et al.*, 1984; *Leclerc et al.*, 1996; *Minns and Bakelaar*, 1999]

$$HSI_k^f = \prod_{c=1}^{C} \left(HSI_{c,k}^f \right)^{\frac{1}{C}} \; \forall \quad k \in K^j, \tag{11}$$

where c is a category of stream characteristics (e.g., stream depth or velocity); C is the number of characteristics; f stands for fish species (walleye or sea lamprey); and $HSI_{c,k}^f$ is the value of HSI for the cth kind of steam characteristic in the kth stream reach, depending on fish species f.

[25] For walleye spawning, we consider two stream characteristics (C = 2): stream velocity, and channel depth [*McMahon et al.*, 1984; *Mion et al.*, 1998; *Lowie et al.*, 2001]. Substrate type, also an important characteristic, is addressed instead when calculating egg production (equation (12) below). For ammocoetes nursery habitat, only the substrate type (C = 1) matters [*Bolsenga and Herdendorf*, 1993; *Sullivan et al.*, 2003; GLFC, fact sheet, 2000]. Equation (11) assumes that the overall HSI_j^f is a function of the product of the characteristics, which allows the characteristics to be both substitutes (if all characteristics are positive, more of one can substitute for less of another) and complements (if one is zero, then overall suitability is zero) [*Jones et al.*, 2003; *Corsair et al.*, 2009]. The value of $HSI_{c,k}^f$ is obtained by constructing a preference curve for the cth stream characteristic that ranges from zero to one. They represent degrees of preference (from the least to the most suitable physical conditions) by the fish species for stream characteristics [*Guay et al.*, 2000]. We based preference curves on a review of the literature on walleye and sea lamprey life cycles and habitat requirements [*McMahon et al.*, 1984; *Lowie et al.*, 2001; *Jones et al.*, 2003; *Sullivan et al.*, 2003; *Cheng et al.*, 2006; GLFC, fact sheet, 2000]. Stream velocities are obtained from streamflow data (1996–2006) available at United States Geological Survey (USGS) gaging stations, and are quantified for the monthly mean flow rate of March, during the walleye spawning season in the Lake Erie basin [*Bolsenga and Herdendorf*, 1993; *Mion et al.*, 1998; *Jones et al.*, 2003]. Stream channel substrate compositions are calculated using regional pebble count data (P. Whiting, Case Western Reserve University, unpublished data, 2003).

The reach areas ($A_{k,s}$) and lengths (L_k) are calculated using GIS data [*Neeson et al.*, 2008].

3.3.2. Lake Erie Ecological Model

[26] LEEM was developed to address the dropping populations of major fish species, as well as some key factors affecting the Lake Erie ecosystem [*Koonce et al.*, 1999]. It is a community-based simulation model that describes the interactive effects of the decline of phosphorus loadings, contamination by toxic substances, invasion of zebra mussels, and fish harvest policy on the Lake Erie ecosystem. The model simulates 17 species that represent the fish community of Lake Erie through predator-prey relationships constrained by energy flow and nutrient availability [*Koonce et al.*, 1999; *Locci and Koonce*, 1999].

[27] LEEM has been applied to previous studies of Lake Erie management [e.g., *Anderson et al.*, 2001; *Kim et al.*, 2003; *Corsair et al.*, 2009]. Here, we use LEEM to quantify how dam removal affects lake-wide fish community criteria (x_1 to x_8). Since it is difficult to extrapolate from habitat improvement to ecosystem changes, stream restoration studies rarely quantify fish community effects. Instead, habitat enhancement is usually used as a proxy for ecosystem restoration. However, temporal and spatial variability in tributary habitat and the presence of other bottlenecks (e.g., low survival rate at early life stage, or lack of available prey or habitat for adults) mean that fish production may not respond proportionally to habitat additions from dam removals. Linking removal decisions explicitly to ecological community criteria can offer more meaningful insights concerning the benefits of habitat restoration.

3.3.3. Habitat and Ecological Model Linkages

[28] The following two steps are involved in linking habitat and the lake community: (1) convert walleye spawning habitat changes ($H_j^{walleye}$) into changes in walleye YOY recruitment ($\Delta YOY_j^{walleye}$) and (2) translate the cumulative changes in walleye YOY recruitment ($\Delta yoy^{walleye}$) from multiple subbasins into corresponding lake-wide ecosystem responses. A similar approach was used by *Corsair et al.* [2009] in their model which considered removing a single dam.

[29] To convert $H_j^{walleye}$ into $\Delta YOY_j^{walleye}$, changes in egg production need to be calculated. We do this by first defining

$$EP_j = \sum_{s \in S} CC_s H_{j,s}^{walleye} \ \forall \ j \ \in J, \qquad (12)$$

where EP_j represents the egg production (number of eggs) by removing dam j; and CC_s is the maximum egg carrying capacity (number of eggs per km^2) for the sth kind of substrate. The values of EP_j are the expected number of eggs that will be produced by removing dam j but none of the dams further upstream, assuming that adult walleye can reach that location. The values of CC_s are obtained from *Jones et al.* [2003].

[30] Egg mortality in rivers is high due to vulnerability to substrate condition, streamflow, and predation [*Jones et al.*, 2003; *Cheng et al.*, 2006]. Surviving eggs then hatch, and the larvae are transported downstream [*Mion et al.*, 1998]. Stream velocity, temperature, and distance are important at this stage. Larvae that survive to reach Lake Erie nearshore nursery habitat become subject to predation [*Knight*, 1997]. Existing studies give insufficient information about survival rates at each life stage. We use the below overall survival relationship from egg production to YOY recruitment based on a calibrated value used in previous LEEM studies

$$\Delta YOY_j^{walleye} = 0.000074 EP_j \ \ \forall \ \ j \in J. \qquad (13)$$

[31] Through the MILP's constraint (6), $\Delta yoy^{walleye}$, the increase in walleye YOY recruitment from removing multiple dams is calculated. Then, to link $\Delta yoy^{walleye}$ with the ecological criteria x_1,.., x_8, we assume that the ecosystem response to changes in walleye YOY recruitment is locally linear. We therefore estimate impulse response (IR) functions for each LEEM based criterion (x_i). An IR function is defined as the system response to an impulse or a "shock" as a function of time since the impulse. It can be derived from any model that is sufficient linear and time invariant [*Nir and Lewis*, 1975]. The linearity assumption is justified by the small change in tributary spawned YOY relative to lake-wide walleye YOY. By the use of IR functions, we connect the changes in tributary spawned walleye YOY recruitment and the lake-wide community effects. Specifically, IR coefficients (IR_{x_i}) are estimated by running LEEM twice; first as a steady state base case (this yields X_i^{base}), and second with an impulse input of additional walleye YOY during a single year. Dividing the changes in the output variables x_i by the impulse input yields the IR function coefficients (IR_{x_i}). Multiplying these IR_{x_i} by $\Delta yoy^{walleye}$ in constraint (5) yields the changes in the ecological criteria. Through the MILP objective (2), lake-wide fish community effects are valued using the multicriteria value function.

3.4. Estimation of Economic Coefficients

[32] Economic coefficients are empirically estimated. In particular, C_j^{dam} is obtained by a regression model that accounts for dam size, type and purpose. $C_j^{lamprey}$ is calculated as a function of habitat changes resulting from the sea lamprey habitat model ($H_j^{lamprey}$).

3.4.1. Estimation of Dam Removal Cost Coefficients

[33] The removal cost regression model estimates cost as a function of dam size (height and length), type (such as earth or concrete), and purpose (such as water supply, hydropower generation, and flood control). Information of over 600 documented dam removals in the U.S. was collected [*Maclin and Sicchio*, 1999; *ICF Consulting*, 2005; *American Rivers*, 2007], of which 117 records had usable values of all variables required for the regression. These selected data show that larger dams significantly increase removal costs (Figure 2). The data also indicate that other parameters may contribute to removal costs as well. First, different dam types require different removal methods. Explosives and heavy equipment (e.g., hydraulic hammer) are often used to remove concrete dams. Removals of earthen dams, on the other hand, usually require only bulldozers, and so are less expensive [*Maclin and Sicchio*, 1999]. Second, removal costs also include the value of lost services. The expense of replacing water supply, irrigation, hydropower generation, or even recreational use can be very high. Thus, dam purpose is expected to be an important predictor of dam removal cost. The inventory lists 11 dam types and 11 dam purposes. For the regression, these dam types and purposes are each classified into two categories.

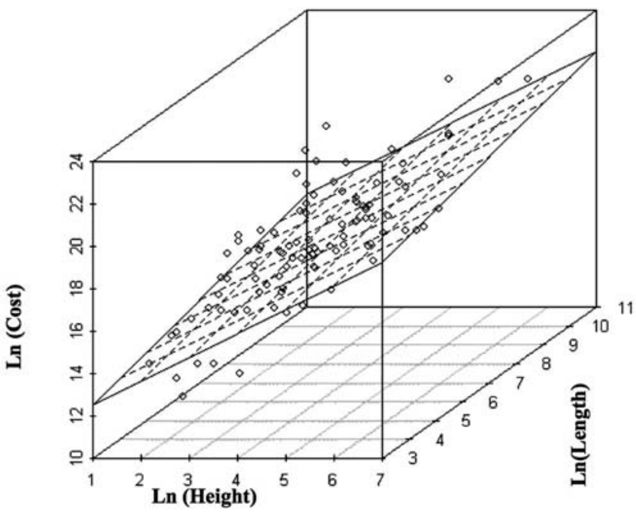

Figure 2. Scatterplot of dam removal cost (2006 dollars) versus dam height (ft, 3.28 ft = 1 m) and length (ft) (log transformed).

Dam types include earthen and nonearthen. Nonearthen types include concrete, gravity, rockfill, buttress, stone, timber crib, masonry, arch, multiarch, and others. Two dam purpose categories are defined as "important" or "less important." Important purposes include irrigation, hydropower, flood control and storm water management, navigation, and water supply. Less important purposes include recreation, fire protection, fish and wildlife pond, debris control, tailings, and no current purpose.

[34] We perform a multivariate linear regression to quantify the relationship between removal costs (the dependent variable) and those independent variables. After various statistical tests to ensure model quality and robustness, the following is adopted as the cost model (R^2 = 0.60):

$$\ln\left(C_j^{dam}\right) = \underbrace{7.79}_{(\text{S.E.}=0.52)} + \overbrace{\underbrace{0.80}_{(0.14)}\left(\ln\left(Height_j\right)\right) + \underbrace{0.33}_{(0.11)}\left(\ln\left(Length_j\right)\right)}^{\text{DamSize}} + \overbrace{\underbrace{1.49}_{(0.26)}\left(FuncW_j\right)}^{\text{DamPurpose}} - \overbrace{\underbrace{0.44}_{(0.22)}\left(TypeE_j\right)}^{\text{DamType}}, \quad (14)$$

where SE stands for standard error of each estimated model coefficient; $Height_j$ is the structural height (feet) for dam j; $Length_j$ is the length (feet) for dam j; $FuncW_j$ is the purpose dummy variable (1 signifies that dam j currently serves an important purpose); and $TypeE_j$ is the type dummy (1 means that dam j is earthen). Dummy variables are 0–1 variables that are widely employed in regression models to quantify a qualitative feature [*Kutner et al.*, 2005]. Costs used in the analysis are escalated to year 2006 dollars, and are the total removal project costs including engineering consulting, permitting, and removal.

[35] Equation (14) shows that (1) dam height contributes much more to removal costs than dam length; (2) removing a dam that currently serves an important purpose adds additional costs; (3) earthen dams are cheaper to remove; and (4) costs due to lost dam services (indicated by $FuncW_j$) have a proportionally greater effect than the ability to use a low cost removal method (indicated by $TypeE_j$). Using regression results in equation (14) and input data for Lake Erie dams, it is possible to estimate the removal costs of each structure considered.

[36] The removal cost model (14) has limitations because some important factors, such as dam maintenance costs, safety hazards, and recreation benefits, are not included in the data set. Thus, the MILP must be viewed as a screening model for identifying candidates for removal, which would then be subjected to more site-specific study before finalizing removal decisions.

3.4.2. Lampricide Cost Estimation

[37] The sea lamprey is one of the few aquatic invasive species that is being successfully controlled in the Great Lake region [*Sullivan et al.*, 2003]. Ongoing control efforts have resulted in an estimated 90 percent reduction of their populations (GLFC, fact sheet, 2000). Currently, the most effective lamprey control measure is to regularly apply lampricides to tributaries infested with larvae sea lamprey (ammocoetes) in order to eliminate them at the most vulnerable life stage [*Sullivan et al.*, 2003]. Hence, we assume here that any newly accessible nursery habitat following dam removals will be treated with lampricide, and that this control will be 100% effective. We do not consider less commonly used controls, such as sea lamprey barrier, trapping, and the sterile male release. This allows us to quantify potential lamprey invasion as the additional cost of lampricide treatment.

[38] Our approach is to estimate control cost as a function of ammocoetes nursery habitat length ($H_j^{lamprey}$). An advantage of monetizing the lamprey objective is that it can then be combined with dam removal cost in the MILP. TFM (3-trifluoromethyl-4-nitrophenol) is an effective lampricide that targets larval lamprey. Its cost of purchase and application is \$227/kg (2006 dollars) [*Koonce et al.*, 1993]. Because of the duration of the larval stage, the TFM treatment cycle is typically 3 to 5 years [*Sullivan et al.*, 2003]. A regression analysis based on published data [*Sullivan et al.*, 2003] indicates a linear relationship (R^2 = 0.83) between TFM usage (kg/treatment cycle) and treated stream length (km). With this relationship and the unit cost of TFM use, lamprey control cost (present value, in \$M) is approximated as

$$C_j^{lamprey} = \left(\frac{C^{TFM}\,TFM}{1 + \frac{1}{(1+r)^m}} \times 10^{-6}\right) H_j^{lamprey}, \quad (15)$$

where TFM is the estimated regression coefficient (31.56 kg/km) that converts stream length to TFM usage per treatment cycle; C^{TFM} is the unit cost of TFM application (\$227/kg); m is the length of the average TFM treatment cycle (4 years); and r is the interest rate (6%/yr) used to calculate the present value of $C_j^{lamprey}$.

4. Case Study

[39] The Lake Erie Dam Database was created by the Institute for Fisheries Research in University of Michigan and Michigan Department of Natural Resources for the Lake Erie GIS Project (C. Geddes, Institute for Fisheries

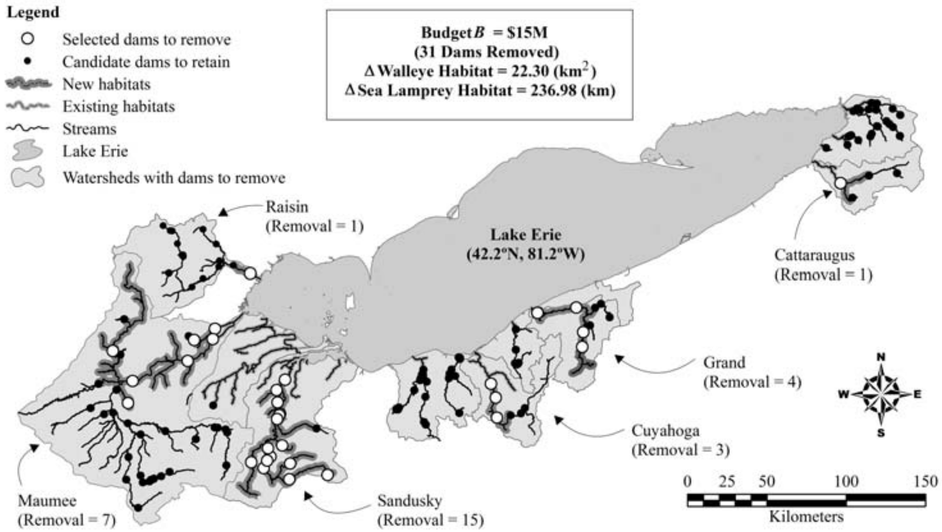

Figure 3. MILP results example 1; locations of 31 removals under a \$15M budget. (Dam removal sites shown here are selected when a high weight is given to enhance native species abundance and walleye fishery for recreation. Results should be interpreted considering uncertainty in model parameters, such as errors in removal cost estimates. Site-specific study must be carried out before finalizing any dam removal plans.)

Research, University of Michigan, personal communication, 2006). The database draws upon multiple sources including the National Inventory of Dams (NID), U.S. Environmental Protection Agency (EPA), and state governments. It contains information on 2176 dams in the Lake Erie basin, including dams in Michigan, Ohio, New York, Pennsylvania, and Indiana. The Ohio Department of Natural Resources maintains a GIS database of 5975 dams including 300 low-head dams (both existing and removed) in the State of Ohio (R. Archer, Division of Water, Ohio Department of Natural Resources, personal communication, 2006). Information available from both databases includes physical, geographical, and management data. We use this information and available GIS data of the Lake Erie river systems (created from hydrological Digital Line Graph (DLG) data supplied by USGS) to select dams that are candidates for removal. We narrow the list of candidates to 139 dams located in ten watersheds by making three assumptions. First, we exclude watersheds whose habitat might involve too long a migration distance (greater than 250 km) to the river mouth to support successful walleye YOY recruitment. Second, reaches with a bankfull width less than 20 m are considered to be too small to be viable for walleye and sea lamprey habitat, thus dams located in these reaches are not considered. Third, dams in watersheds identified by the fishery expert with a 100% likelihood of potential sea lamprey recruitment success ($V_j^{lamprey}$ = 100%) but a 0% likelihood of potential walleye recruitment success ($V_j^{walleye}$ = 0%) after dam removals are also excluded. Figure 3 shows the locations of the candidate dams and their watersheds.

[40] The expected removal cost (present worth) if all 139 dams were to be removed would be about \$32M. The corresponding sea lamprey control cost would be \$17M (present value). Thus, we consider budget amounts ranging up to the sum of these values. Table 1 summarizes, for each watershed, the recruitment likelihood probabilities ($V_j^{walleye}$ and $V_j^{lamprey}$), numbers of dams that are subject to removal, weighted suitable habitats ($H_j^{walleye}$ and $H_j^{lamprey}$) calculated by Fish Riparian Habitat Model (FRHM) for both walleye and sea lamprey if all those dams were removed, expected habitat accounting for the probability of successful recruitment ($V_j^{walleye} \times H_j^{walleye}$ nd $V_j^{lamprey} \times H_j^{lamprey}$), and costs including sea lamprey control cost ($C_j^{lamprey}$) and dam removal cost (C_j^{dam}).

[41] The input data shown in Table 1 indicates that removing all candidate dams in the Sandusky River basin leads to the most walleye habitat creation among the 10 watersheds, while removing all candidate dams in the Maumee River basin provides the most newly accessible habitat for sea lamprey. Note that in some watersheds, such as Ashtabula-Chagrin and Black-Rocky, suitable habitats calculated by FRHM for either walleye alone or both species are reduced remarkably after multiplying by the relevant recruitment probabilities.

[42] We considered budget caps B ranging from zero to \$50 million in the MILP. The cap is increased by \$50,000 in each model run until it has reached the maximum value. This process reveals the trade-offs between the ecological and economic objectives. Table 2 shows selected results. The values of the ecological objective z_1 (equation (2)) are rescaled to percentages, where 0% represents the base case (no removal), and 100% represents the maximum increase (all removals) in multicriteria ecosystem health index across solutions.

[43] In general, Table 2 shows that as B increases, the number of dams removed increases, as well as the values of habitat creation and the two objective functions (z_1 and x_9). However, the results also reveal that increases in expenditures do not proportionally increase dam removals or improve ecosystem health. For instance, spending \$5 million leads to nine removals that free up about 11 km^2 of suitable walleye habitat ($\Delta H^{walleye}$), yielding a 35%

Table 2. Selected Results for Multidam Removal Case Study[a]

Variable, Definition	MVA Criteria Weight, W_i		Base Case, $B = 0$, $R = 0$		Optimization Results							
					$B = 5$, $R = 9$		$B = 15$, $R = 31$		$B = 30$, $R = 66$		$B = 45$, $R = 130$	
	Original	Revised	X_i^{base}(× 10)	$V_i(X_i^{base})$ (× 10^2)	Δx_i (× 10)	$\Delta V(x_i)$ (× 10^2)	Δx_i (× 10)	$\Delta V(x_i)$ (× 10^2)	Δx_i (× 10)	$V(x_i)$ (× 10^2)	Δx_i (× 10^2)	$V(x_i)$ (× 10^2)
LEEM-Based Criteria (x_1–x_8)												
x_1, walleye/percid (kg/kg)	0.11	0.05	4.75	41.26	1.06	−24.84	2.05	−48.23	2.89	−68.03	3.00	−70.55
x_2, piscivore/planktivore (kg/kg)	0.11	0.05	0.44	97.97	0.07	−1.19	0.14	−2.31	0.19	−3.26	0.20	−3.38
x_3, total productivity (M kg/y)	0.12	0.06	7246.77	100.00	−1071.44	−15.88	−2080.50	−30.84	−2934.59	−43.50	−3043.26	−45.11
x_4, native/total (kg/kg)	0.13	0.18	4.07	44.64	0.10	1.68	0.19	3.27	0.27	4.61	0.28	4.78
x_5, walleye biomass (M kg)	0.20	0.29	153.02	20.29	35.44	6.87	68.83	13.34	97.08	18.82	100.67	19.52
x_6, walleye fishery (M kg/y)	0.22	0.32	33.02	36.51	7.60	9.13	14.75	17.74	20.81	25.02	21.58	25.94
x_7, yellow perch fishery (M kg/y)	0.07	0.03	61.80	100.00	−13.42	−22.64	−26.06	−43.96	−36.76	−62.00	−38.13	−64.30
x_8, smelt fishery (M kg/y)	0.04	0.02	78.44	21.89	−7.00	−4.83	−13.58	−9.37	−19.16	−13.22	−19.87	−13.71

Variable, Definition	Base Case, $B = 0$, $R = 0$	Optimization Results			
		$B = 5$, $R = 9$	$B = 15$, $R = 31$	$B = 30$, $R = 66$	$B = 45$, $R = 130$
Habitat Change					
$\Delta H^{walleye}$, walleye (km^2)	0	11.05	22.30	31.74	32.93
$\Delta H^{lamprey}$, sea lamprey (km)	0	54.16	236.98	434.21	482.73
Objective Value					
x_9, economic objective ($M)	0	4.96	14.94	30.00	44.95
z_1, ecological objective (%)	0	35.18	68.31	96.35	99.92

[a]B is the budget cap ($M) and R is the number of dams removed.

increase in multicriteria ecosystem health index (z_1). If six times as much is spent ($30 million), more than seven times as many removals are made (66 in total), but less than three times as much walleye habitat is made accessible (32 km^2), and the multicriteria ecosystem health index roughly triples (to 96% of the maximum). Such nonlinearities demonstrate the complexity of dam removal decisions.

[44] Table 2 also lists changes in LEEM based criteria (Δx_1,.., Δx_8) and changes in corresponding value functions ($\Delta V_1(x_1)$, …, $\Delta V_8(x_8)$) from the base case. These demonstrate important trade-offs among the ecological and socioeconomic objectives. For instance, dam removals deteriorate fish community balance criteria in terms of structure and function (x_1 and x_2, respectively, where higher values are less preferred). Further, they also harm fish community productivity (x_3) and other important commercial fisheries (x_7 and x_8) because of increased competition and predation from enhanced walleye recruitment. On the other hand, native fish biomass as a fraction of the total (x_4), walleye population (x_5), and sport harvest (x_6) all improve. Dam removal is not an unambiguous enhancement for the Lake Erie ecosystem. The trade-offs in dam removal interact with other management policies in complex ways. Competing decisions in such cases hinge on value judgments concerning the importance of fish community balance, enhancement of fisheries, and preservation of other ecological services affected by dam removals. These decisions are also appropriate for multiobjective analysis, but are beyond the scope of this paper.

[45] A closer look at each efficient portfolio reveals that most removals are relatively small dams that currently have little purpose. They are also more likely to be close to the river mouth; block long stretches of walleye habitat; and less likely to open up significant lamprey habitat. Figure 3 shows one of the MILP solutions with 31 removals for a $15 million budget. Solid black points are candidate dams left in place. Solid white points are dams selected by MILP for removal, and wide lines are reaches of newly accessible habitat. Most removals are in the western basin of Lake Erie, where walleye abundance is higher than the central and eastern basins. As shown in Figure 3, 15 out of 16 candidate dams are selected for removal in the Sandusky River basin, which is world famous for walleye runs. Removing these 15 dams would open up more than 13 km^2 of walleye habitat (41% of the total lake-wide potential habitat and 99% of the total potential habitat in the Sandusky River basin), but only 94 km of lamprey habitat (20% of the lake-wide potential habitat and 96% of that in the Sandusky River basin). The only dam that the MILP decides to keep in that basin has a much higher potential sea lamprey habitat than walleye habitat and the second highest removal cost among 16 candidate dams in the Sandusky River basin.

[46] Figure 4 summarizes the model solutions as a trade-off curve between z_1 and x_9 (Figure 4a), along with the number of dam removals (Figure 4b). Figure 4a confirms that the relationship between multicriteria ecosystem health index (z_1) and economic cost (x_9) is nondecreasing (as

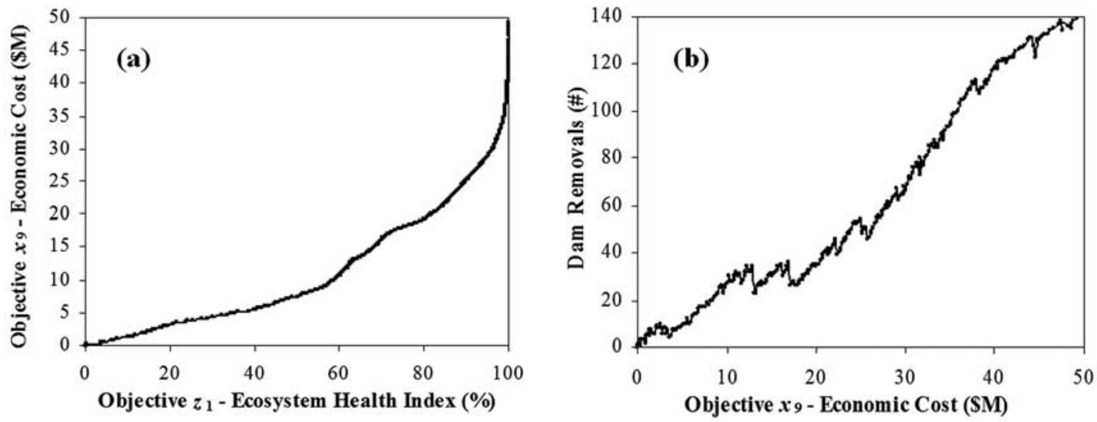

Figure 4. MILP model results. (a) Trade-offs between multicriteria ecosystem health index z_1 and cost x_9 and (b) number of dam removals as a function of cost x_9. (Objective z_1, an aggregate index of ecological health, is the weighted sum of criteria value functions from x_1 to x_8.)

expected, since a greater budget constraint on x_9 cannot worsen the MILP's objective z_1). However, the trade-off curve is generally, but not always, convex, indicating a decreasing marginal value of budget dollars, in terms of improvements in the multicriteria ecosystem health index (nonconvexities are possible because of the model's integer variables). In contrast, Figure 4b shows that the number of removals does not increase monotonically with x_9. This is because removal of a single large dam can be as or more effective as taking out several small ones. Steep drops in Figure 4b indicate that an increased budget allows substitution of one or a few large dam removals for several small dam removals.

[47] To demonstrate that weights assigned to different objectives can lead to different removal decisions, we conduct a sensitivity analysis by adding a new objective (z_3) in objective function (2) to minimize the potential for sea lamprey population increases. The lamprey objective (z_3) is the percentage of all potential ammocoetes habitat created from removing selected dams relative to the total habitat that would be opened up if all dams were removed. (The percentage is used so that the upper bound is 100%, similar in scale to the upper bound of z_1.) This objective can be of interest if the effectiveness of sea lamprey treatment is not 100% and there is concern about potential ammocoetes habitat. Using the weighting method [*Cohon*, 1978], we revise the objective function (2) of the MILP model as

$$\text{Maximize} \quad z_1' = (1 - WL)z_1 - WLz_3 = (1 - WL)z_1 - WL\left(\frac{\sum_{j\in J} V_j^{lamprey} H_j^{lamprey} d_j}{\sum_{j\in J} V_j^{lamprey} H_j^{lamprey}}\right), \tag{16}$$

where WL is the weight on the sea lamprey invasion objective and ranges from zero to one. When WL is zero, (16) reduces to (2). When WL is one, the optimal value of (16) is zero and no dams are removed (all d_j are zeroes). Under a fixed budget of $15 million, we run the revised MILP model using different values of WL.

[48] Table 3 shows selected results and indicates that optimal dam removal decisions depend on the relative weight assigned to the lamprey objective. When WL increases from zero to 0.4, under the same budget constraint, ecological health z_1 declines and less lamprey habitat z_3 is opened up. With $WL = 0$, we obtain the same solution as in the original model with a $15 million budget. At the highest weight ($WL = 0.4$), zero additional lamprey habitat is made accessible. Table 3 reveals that numbers of dams removed increase when more weight is assigned to sea lamprey invasion. This is because that if people are more concerned about sea lamprey invasion than walleye improvement, dams associated with no or little potential ammocoetes habitat are more favored. In this case, dams identified by the fishery expert as having zero recruitment likelihood probability ($V_j^{lamprey} = 0$) will be removed first. Since these dams are in no danger of sea lamprey infection, no treatment costs are involved; and, all else being equal, those dams are less expensive to remove. This results in an increased number of removals. However, more removals do not lead to an improvement in the ecosystem heath index z_1. For example, when WL increases from zero to 0.4, we no longer face the threat of sea lamprey invasion ($z_3 = 0$); however, the improvement in z_1 caused by additional walleye spawning habitat has decreased from over 68% to less than 2% (a reduction of almost 2 orders of magnitude).

[49] In sum, this sensitivity analysis indicates that value judgments matter—different weights assigned to walleye and sea lamprey impacts alter dam removal recommendations. Figure 5 highlights this impact of value judgments by

Table 3. Selected Results for Revised MILP Model[a]

Weight on Sea Lamprey Invasion, WL	Objective Value: Ecosystem Health, z_1 (%)	Economic Cost, x_9 ($M)	Sea Lamprey Invasion z_3[b] (%)	Number of Dams Removed, R
0	68.31	14.94	49.06 (236.98)	31
0.1	47.25	14.90	15.36 (74.18)	61
0.2	15.35	12.02	2.03 (9.83)	56
0.3	6.28	10.06	0.50 (2.41)	53
≥0.4	1.76	9.50	0 (0)	51

[a] B = $15M and $WL \in [0,1]$.
[b] Values in parentheses are in km.

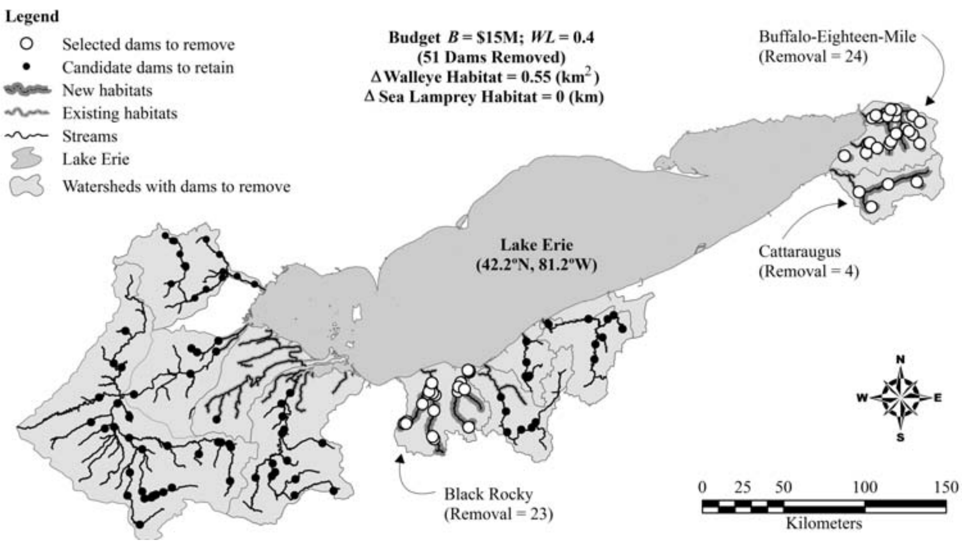

Figure 5. MILP results example 2; locations of 51 removals under a \$15M budget and with $WL = 0.4$. (Dam removal sites shown here are selected when a high weight is given to prevent sea lamprey invasion.)

showing one of the MILP solutions with $WL = 0.4$. In this case, 51 dams are removed; and unlike Figure 3, most removals are in the eastern and central basin of Lake Erie, where sea lamprey invasions are considered unlikely.

5. Conclusions

[50] A mixed integer linear program is developed to calculate trade-offs between an aggregated ecosystem health index and economic costs when choosing a portfolio of dams to remove as a habitat restoration strategy in the Lake Erie basin. Because dam removal is a lumpy (0–1) decision, and because of the benefits of removing a particular dam depends on which other dams have been removed, a multi-dam and multiwatershed approach is necessary to optimize the linked network of dams, rivers, and lake as an integrated system. The MILP explores interactions among dam removal, habitat restoration, exotic species invasion and control, and lake-wide fish community responses. Our MILP uses fundamental objectives (e.g., fish community balance and commercial harvest) that people ultimately value to represent ecological impacts of dam removal decisions rather than so-called "means" or intermediate objectives (i.e., amounts of habitat that would be made accessible) that are more commonly used in dam removal studies. As illustrated in our Lake Erie basin case study, the ecological effects of dam removal can be ambiguous, with some ecological criteria deteriorating in response to additional habitat creation due to complex community effects (e.g., conflicts between walleye recruitment and total fish community productivity). This points out the importance of coupling ecosystem and decision models so that the ultimate ecological effects of dam removal can be better understood when choosing which dams to remove. Additionally, the MILP allows priorities from decision makers and stakeholders to be operationalized and translated into recommendations on dam removal projects, while implicitly considering the huge number of potential alternative portfolios of dam removals (as many as 2^{139} in our case study). The multiobjective formulation yields optimal trade-off curves instead of a single optimal solution; such curves can inform negotiations among managers and stakeholders.

[51] In summary, the model can help identify portfolios of dam removals that cost effectively enhance habitat and the Lake Erie ecosystem. However, there are many uncertainties in the economic and ecological parameters of the model; these mean that the model must be used only in a screening mode, and further site-specific study is needed to finalize dam removal plans. In general, the science of evaluating ecological effects of dam removal remains at a learning stage because of the relatively limited history of dam removal, insufficient empirical data, and the complexity of river processes [*Hart et al.*, 2002; *Pohl*, 2002; *Doyle et al.*, 2003]. Therefore, dam removal decisions involve not only numerous trade-offs but also many large uncertainties. Future work should emphasize the development of probabilistic MILPs using methods such as multistage mathematical programming [*Wagner*, 1975] to address the uncertainties in the economic, hydrological, and ecological processes involved in dam removal decisions.

Notation

$A_{k,s}$ area of sth type of substrate in reach k, km^2.

B budget cap, \$M.

C_j^{dam} dam removal cost coefficient representing not only expenditures for removing dam j but also the value of lost services, \$M.

$C_j^{lamprey}$ lampricide cost for lamprey control made necessary by the removal of dam j, \$M.

C^{TFM} unit cost of TFM application, \$227/kg.

CC_s maximum egg carrying capacity for the sth kind of substrate, number of eggs/km^2.

EP_j egg production by removing dam j, number of eggs.

$H_j^{lamprey}$ length-weighted suitable stream habitat for ammocoetes created by removing dam j, km.

$H_{j,s}^{walleye}$ area-weighted suitable stream habitat for walleye spawning created by removing dam j that contains the sth type of substrate for the kth stream reach in set K^j, km^2.

$HSI_k^{lamprey}$ value of HSI for reach k for ammocoetes nursery in set K^j, dimensionless.

$HSI_k^{walleye}$ value of HSI for reach k for walleye spawning in set K^j, dimensionless.

$HSI_{c,k}^f$ value of HSI for the cth kind of steam characteristic in the kth stream reach, depending on fish species f, dimensionless.

IR_{x_i} impulse response function coefficient for each ecological criterion i from LEEM, describing the change in x_i given a unit change in walleye recruitment, $i = 1, \ldots, 8$.

J set of indices j for candidates dams that are subject to removal.

J^j set of indices n for dams that are directly upstream of dam j.

K^j index set of river reaches k that lie between dam j and dams n belonging to J^j.

L_k stream length of reach k in set K^j, km.

M weight on weight on objective z_1, $M \in [0,1]$.

n length of the average TFM treatment cycle, 4 years.

r interest rate used to calculate the present value of $C_j^{lamprey}$, 6%/yr.

S set of indices s for substrate types, $S = \{s|s =$ rubble, cobble, gravel, sand/mud detritus$\}$.

TFM estimated regression coefficient that converts stream length to TFM usage per treatment cycle, 31.56 kg/km.

$V_j^{lamprey}$ subjective probability of an increase in sea lamprey recruitment as the result of removing dam j, depending on the basin that dam j is located.

$V_j^{walleye}$ subjective probability of an increase in or walleye recruitment as the result of removing dam j, depending on the basin that dam j is located.

w_i importance weight for criterion i, $i = 1, \ldots, 8$.

WL weight on sea lamprey invasion objective, $WL \in [0,1]$.

X_i^{base} average value of criterion i for all of Lake Erie in a steady state base case as estimated by LEEM, $i = 1, \ldots, 8$.

$\Delta YOY_j^{walleye}$ estimated additional walleye YOY recruitment (number of walleye YOY) resulting from removing dam j, if recruitment indeed increases.

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