A Multiobjective Portfolio Analysis of Dam Removals Addressing Dam Safety, Fish Populations, and Cost

Pearl Q. Zheng[1] and Benjamin F. Hobbs, M. ASCE[2]

Abstract. Decisions concerning dam removal or retention are challenging because they involve tradeoffs, diverse stakeholders, and increasing public safety concerns. A multiobjective portfolio optimization approach, implemented as an integer linear program (ILP), identifies efficient portfolios of dam removals in terms of the objectives of public safety, fish population health, and cost. The ILP integrates judgments by dam safety experts with results of ecosystems simulation and statistical analysis of empirical data, to explore tradeoffs among the three objectives when choosing a portfolio of dams to be removed in multiple watersheds.

We apply the methodology to a case study including 139 dams in ten watersheds of the Lake Erie basin. We find significant tradeoffs between maximizing fish population health and minimizing safety risks under a given budget, with different dams recommended for removal in each case. Also, how dam safety risk is quantified in the ILP affects the selected set and therefore would deserve further research. Overall, the multiobjective portfolio analysis approach provides a simple, flexible, and useful tool to policy makers to explore the nature and magnitude of tradeoffs to screen potential dam removal projects.

CE Database subject headings: Multiple objective analysis; Decision support systems; Optimization models; Dam safety.

Author keywords: Multiobjective portfolio analysis; Dam removal; Tradeoff analysis; Cost-benefit analysis; Dam safety risk assessment.

----

1. Senior Analyst, Abt Associates Inc., 4550 Montgomery Avenue, Suite 800 North, Bethesda, MD 20814 (corresponding author). E-mail: pearl_zheng@abtassoc.com
2. Theodore K. and Kay W. Schad Professor of Environmental Management, Department of Geography & Environmental Engineering and Director, Environment, Energy, Sustainability & Health Institute, Johns Hopkins University, Baltimore, MD 21218. E-mail: bhobbs@jhu.edu

Introduction

Public concern about the adverse impacts of aging and abandoned dams on the physical, chemical, and biological characteristics of rivers, together with the safety risks and economic burdens they impose, has led to a growing call to remove dams (Pejchar and Warner 2001; Poff and Hart 2002). As a result, 888 dams (mostly small) have been removed nationwide, primarily to restore fish habitat and to ensure public safety (Pohl 2002; American Rivers 2010). This activity has accelerated, with over 450 removals since 1999 (American Rivers 2010).

Despite this recent acceleration in removals, decisions on dam removal or retention are complex and sometimes controversial due to the presence of conflicting objectives, diverse stakeholders, and increasing public safety concerns. Dam removal is not always a win-win situation that benefits all interests. It involves numerous social, economic, and ecological tradeoffs and uncertain consequences. In some cases, dams are kept because of their historic value and important functions (e.g., water supply) (The Heinz Center 2002). In other cases, dams serve as barriers to migration of pest or invasive species (e.g., sea lamprey [*Petromyzon marinus*] in the Great Lakes) (Sullivan et al. 2003). Thus, removing dams without proper safeguards may damage ecosystems. While case studies have shown that removing certain small dams costs less than repairing them, removing larger ones is still controversial because of significant costs and uncertain impacts on downstream geomorphic and ecological processes (Poff and Hart 2002). In addition, stakeholders rarely reach consensus concerning the relative priority of conflicting removal objectives (Bowman et al. 2002; The Heinz Center 2002).

Meanwhile, structural deterioration, reservoir sedimentation, or simply changes in society's needs cause dams to outlive their intended purpose, and many currently have no official use (Pohl 2002; The Heinz Center 2002). As the number of deficient dams grows and downstream urban development increases, safety concerns have grown. Often, studies addressing dam safety concentrate on identifying failure mode(s) using geotechnical or hydrological analysis (e.g., Gross and Moglen 2007; Xu and Zhang 2009). However, because dams may serve multiple purposes or their removal may have many types of impacts, dam risk management should consider a wide range of abandonment, repair, and removal options and their associated trade-offs (Brown 1989; Haimes et al. 1992; Keisler and Linkov 2010; Karvetski et al. 2011). An important question is: “how safe is safe enough?” Without constant repair and maintenance, failure risks grow over time, increasing danger to lives and property (Stanley and Doyle 2003). Where the benefits of a dam are marginal, repair and maintenance may simply cost more than removal, even when considering the value of any services the dam provides (The Heinz Center 2002).

Dam removal, on one hand, eliminates the risk of failure and may enhance habitat; on the other hand, costs are incurred, including the expense of removal and possibly replacement of lost services. With many candidate dams in the same basin, the cumulative cost might be unaffordable, so it is desirable to systematically assess which subset of removals best achieves society’s objectives. However, dam removal studies usually focus on single dams and on a subset of habitat recovery, fish population, cost, and risk objectives. Dam removal is rarely framed as a portfolio problem considering cumulative impacts on all objectives (The Heinz Center 2002; Whitelaw and MacMullan 2002; for exceptions, see Kuby et al. 2005; Zheng et al. 2009; Kemp and O' Hanley 2010), although consideration of project portfolios is common elsewhere in water planning ()(e.g., Levner et al. 2008; Kasprzyk et al. 2009; Karvetski et al. 2011).

In contrast, the multiobjective portfolio analysis (MPA) approach used in this paper employs formal decision analysis methods (multicriteria value functions and multiobjective programming) to consider all these objectives. The MPA approach explicitly emphasizes important tradeoffs and stakeholder involvement, and can systematically assess and incorporate relevant expert knowledge through elicitations of probability judgments and weights to be applied to different objectives (Clemen 1996; Hobbs and Meier 2000); thus it has the potential to facilitate informed dam removal decisions (Corsair et al. 2009; Zheng 2009; Kemp and O' Hanley 2010). The MPA approach has been applied to dam safety risk management and dam removal decision-making. Andersen et al. (2001) used a multiobjective risk indexing tool to prioritize ten dams in Massachusetts according to their physical condition for future maintenance and repair actions. Kuby et al. (2005) developed a multiobjective optimization model that considered tradeoffs between salmon passage and dam services (e.g., hydropower generation) for dams in a single watershed in Oregon. Zheng et al. (2009) developed a mixed integer linear program model that analyzed removal costs and ecological benefits in ten watersheds in the Lake Erie basin.

None of these previous portfolio studies addressed safety risks as well as ecological and costs of dam removal. This paper extends the model of Zheng et al. (2009), which focused on linkages between fish riparian habitats and the downstream lake ecosystem, to incorporate a third objective – public safety. Here, we develop an MPA framework (Fig. 1) that combines optimization, ecological models, removal costs, a survey of dam safety officials, and data on dam age, condition, and nearby populations to analyze the benefits and costs of removing dams on tributaries to downstream lake ecosystems. Dam removal is considered here not only as a habitat and ecosystem restoration tool, but also as a public safety management option. An integer linear program (ILP) model is formulated to select candidate dams for removal. Our contributions include: 1) development of a dam safety risk assessment tool that has broad applicability; 2) the elicitation and application of value judgments from dam safety experts; and 3) the generation of a range of efficient alternative portfolios in terms of the three objectives.

This paper proceeds as follows. The next section describes the MPA framework and ILP, with subsections defining the decision variables and objectives, presenting the model formulation, and estimating model coefficients. Subsequent sections apply the framework and ILP to the case study, including data sources, results, and discussion. The last section presents conclusions.

Methodology

Multiobjective Portfolio Analysis Framework

Fig. 1 presents an overview of the MPA framework used here. The figure shows major components of our model and their relationships. The framework consists of a MPA optimization model (ILP), two cost regression models, three ecological models, and a dam safety assessment model. Arrows in Fig. 1 indicate not only linkages among dam removal decisions and different models, but also their corresponding consequences. We consider three principal consequences of removing dams: fish riparian habitat improvements, dam removal costs, and dam failure risk reduction. Each consequence is measured by a corresponding model as shown in Fig. 1. We then take further steps to link fish habitat changes to the downstream lake response using a Lake Erie ecosystem model. The latter is specific to Lake Erie, while models for assessing dam removal costs and failure risk reductions were developed based on national datasets and are applicable elsewhere. In the end, the framework displays tradeoffs among public safety improvements, lake-wide ecosystem impacts, and financial costs.

As shown in Fig. 1, fish riparian habitat models calculate potential habitat changes for two important fish species: desirable native walleye (*Sander vitreus*) and undesirable invasive sea lamprey. Adults of both species leave Lake Erie in spring and migrate up tributary streams to spawn (Bolsenga and Herdendorf 1993). Walleye populations (the top predator and main fishery species in Lake Erie) would benefit from dam removals if suitable walleye spawning habitat exists upstream of those dams. However, dam removal may also provide access to favorable spawning and nursery habitat for sea lamprey, a large stress on the Lake Erie fish community.

Specifically, we use riparian habitat suitability index (HSI) models (McMahon et al. 1984) to quantify the extent to which walleye spawning and sea lamprey nursery habitats increase after dam removals (discussed in detail in Corsair et al. 2009). Walleye habitat changes are transferred into walleye young-of-the year (juveniles), which are then input into the Lake Erie Ecological Model (LEEM) (Koonce et al. 1999). LEEM describes the population dynamics of 17 species that comprise the fish community of Lake Erie. It is used here to simulate lake-wide and community-based ecological effects of riparian walleye habitat changes. Since LEEM does not model sea lamprey, we translate sea lamprey habitat changes into the required application of lampricides that target the larvae of lampreys in river systems before they migrate downstream to Lake Erie. We then input estimated treatment chemicals in a control cost model. Both that model and a dam removal cost model, were based on linear regression analysis of historical data (documented in Zheng et al. 2009). Finally, the dam safety assessment model provides an index of risk based on dam age, condition, and possible failure consequences. It is developed based on a survey of dam safety professionals and a national dam database.

With inputs from the ecological, cost regression, and safety models, the ILP generates distinct efficient portfolios of candidate dams for removal that embody trade-offs among safety, economic, and ecological objectives. Here, the term "distinct efficient portfolio" (also called "noninferior", "non-dominated", or "Pareto optimal") means that there exists no other single portfolio that yields an improvement in one objective without causing a degradation in at least one other objective (Cohon 1978).

The ILP generates tradeoffs by the constraint method of multiobjective programming

(Cohon 1978). In particular, fish population health (z_1) is maximized subject to constraints on public safety (z_2) and economic cost (z_3). Decision variables indicate which dams are removed, while constraints capture logical relationships among the variables and objectives.

Decision Variables

The ILP includes two decision variables that separately account for whether removals affect fish population health (by restoring fish access to the lake) and affect dam safety (which does not require such ecological connection to the lake). The first decision variable, d_j^{eco}, is a zero-one variable associated with the ecological objective z_1 and the economic objective z_3. d_j^{eco} equals zero if the decision is to retain dam *j* or if the decision is to remove dam *j* for solely safety reasons with no positive ecological effects are expected. In contrast, d_j^{eco} equals one if the decision is to remove dam *j* which results in positive ecological effects, namely making more walleye habitat accessible to fish migrating from downstream Lake Erie. Due to river network connections, the outcome $d_j^{eco}=1$ occurs only if all dams downstream of dam *j* are also removed.

The second decision variable, d_j^{safety}, also a zero-one variable, is associated with the safety objective z_2. d_j^{safety} equals zero if dam *j* is retained, and equals one if the dam is removed, which *may* reduce a potential dam failure hazard. Because not all dams in questions are hazardous (e.g., having high failure risks and/or posing significant hazards to life and property if failure occurs), only if dam *j* is identified as hazardous does the outcome, $d_j^{safety}=1$ bring improve public safety (indicated by $RISK_j > 0$, which is its coefficient in the risk objective z_2). Unlike the case with d_j^{eco}, this outcome does not depend on the removal of downstream dams.

Here, we have simplified the decision to just two options: remove or retain. However, in the real world, other options such as repairs or upgrading are possible; additional zero-one decision variables could account for such options. For instance, safety repairs without a fish ladder is one option (giving no access to upstream habitats), while an upgrade with a ladder would be another. The resulting model would be larger, and data on repair and upgrade costs would be required.

Objectives

Formulations of the fish population health (z_1) and economic cost (z_3) objectives are based on Zheng et al. (2009), and so are only briefly reviewed here. This paper emphasizes the development of the new objective, safety z_2.

Fish population health (z_1) is estimated by a multicriteria fish population health index [Eq. (1)] that is based on LEEM simulations. The index is a weighted sum of improvements in the scores of eight ecological criteria (i=1,…,8) resulting from connecting upstream walleye spawning habitat to Lake Erie. The criteria are walleye-percid biomass ratio, piscivore-planktivore biomass ratio, total fish community productivity, native species-total species biomass ratio, lake-wide annual average walleye biomass, lake-wide annual average biomass of walleye sport harvest, lake-wide annual average biomass of commercial yellow perch harvest, and lake-wide annual average biomass of commercial smelt harvest biomass. (They are the same ecological criteria used in Corsair et al. (2009) and Zheng et al. (2009), where the assumptions and methods are documented.) These eight criteria were developed in two workshops (Kim et al. 2003) attended by biologists and ecosystem managers from U.S. and Canadian resource management agencies. Collectively, they measure the fundamental objective of restoring the Lake Erie ecosystem.

$$z_1 = \sum_{i=1}^{8} W_i E_i \left(\sum_{j \in J} V_j^{walleye} \Delta YOY_j^{walleye} d_j^{eco} \right) \qquad (1)$$

where W_i is the importance weight for ecological criterion i (i=1,…,8); E_i is the ecological response coefficient for i defining the steady-state average response of that criterion to a unit increase in walleye recruitment; J is a set of indices j for candidates dams that are candidates for removal; $V_j^{walleye}$ is the subjective probability of an increase in walleye recruitment as the result of removing dam j, depending on the watershed in which dam j is located; and $\Delta YOY_j^{walleye}$ is the estimated additional walleye young-of-year (YOY) recruitment (number of walleye YOY) resulting from removing dam j, if recruitment indeed increases. Overall, Eq. (1) expresses downstream ecosystem response as a linear function of additional walleye YOY resulting from the dam removals, and is derived from Eqs. (2), (5), and (6) in Zheng et al. (2009).

Risk reduction (z_2) is assessed by a multicriteria dam safety risk reduction index ($RISK_j$) that prioritizes possible risk reduction associated with dams posing hazard potential to downstream communities and the environment [Eq. (2)]. The $RISK_j$ includes three dam safety criteria, namely, dam age, safety inspection record, and hazard potential classification that have been prioritized based on a survey of dam safety officials. Collectively, they represent a quantitative measure of the safety objective for reducing dam failure risk; further details are given below.

$$z_2 = \sum_{j \in J} RISK_j d_j^{safety} / \sum_{j \in J} RISK_j \qquad (2)$$

Finally, economic costs (z_3) are calculated by combining the results (in \$M) from two regression models (documented in Zheng et al. 2009) [Eq. (3)]. Those models determine cost coefficients for removal cost C_j^{dam} and lamprey control $C_j^{lamprey}$ as functions of dam characteristics (length, height, and construction) and amount of lamprey habitat opened up, respectively.

$$z_3 = \sum_{j \in J} \left(C_j^{dam} d_j^{safety} + V_j^{lamprey} C_j^{lamprey} d_j^{eco} \right) \qquad (3)$$

C_j^{dam} (present worth \$M) is the dam removal cost coefficient representing not only expenditures for removing dam j but also the value of lost services (e.g., water supply and flood control);

$V_j^{lamprey}$ is a biologist's subjective probability of an increase in sea lamprey recruitment as the result of removing dam *j*, depending on the watershed in which dam *j* is located; and $C_j^{lamprey}$ (present worth $M) is the sea lamprey control cost made necessary by removing dam *j*, which is incurred only if all dams downstream of dam *j* are also removed.

Model Formulation

To generate an efficient portfolio, the ILP maximizes the ecological objective z_1 [Eq. (1)] while simultaneously constraining z_2 [Eq. (2)] to be no less than a minimum allowable risk reduction goal (*G*, in fraction of total risk) and z_3 [Eq. (3)] to no more than a budget cap (*B*, in $M). By varying *G* and *B* in Eqs. (5) and (6), respectively, the ILP generates a range of alternative portfolios that describe tradeoffs among the objectives. The model formulation is:

$$\text{Maximize} \quad z_1 \tag{4}$$

$$\text{subject to:} \quad z_2 \geq G \tag{5}$$

$$z_3 \leq B \tag{6}$$

$$d_j^{eco} \leq d_j^{safety} \qquad \forall\, j \in J \tag{7}$$

$$d_n^{eco} \leq d_j^{eco} \qquad \forall\, j \in J,\, n \in J^j \tag{8}$$

$$d_j^{eco}, d_j^{safety} \in 0,1 \qquad \forall\, j \in J \tag{9}$$

Eqs. (7) and (8) define the logical relationship between d_j^{safety} and d_j^{eco}, enforcing the logic that dam safety risk reduction does not require removal of downstream dams, but ecological enhancement does. Eq. (7) states that hazardous dams can be removed solely for safety reasons regardless of ecological conditions. Because of Eq. (7) only three types of removal decisions are possible: 1) dam *j* is removed for solely safety benefits (d_j^{safety}=1 and d_j^{eco}=0); 2) dam *j* is removed for solely ecological benefits (d_j^{safety}=1, d_j^{eco}=1, and $RISK_j$ =0); and 3) dam j is removed for both safety and ecological benefits (d_j^{safety}=1, d_j^{eco}=1, and $RISK_j$ >0). Eq. (8), on the other hand, enforces the logic of accessibility of river habitat to spawning fish migrating from the lake (Kuby et al. 2005). Eq. (7) states that no dam can be removed for ecological reasons unless the dam immediately downstream of it (if any) is also removed.

In addition, an important assumption of our ILP is that any particular dam removal results in a net ecological improvement, or at least cannot worsen z_1. If there is a dam whose removal would lower the net ecological benefit in z_1, then it would be optimal for the model to erroneously set d_j^{eco} to zero, even if downstream dams are removed and the dam has been removed for safety reasons (d_j^{safety}=1). This does not occur under our assumed coefficient values.

Model Coefficients

The ILP contains several economic, ecological, and dam safety risk coefficients. Estimates of all economic (C_j^{dam} and $C_j^{lamprey}$) and ecological ($V_j^{lamprey}$, $V_j^{walleye}$, W_i, and $\Delta YOY_j^{walleye}$) coefficients are from Zheng et al. (2009). The ecological response coefficient (E_i) is derived based on Eqs. (1), (2), (5), and (6) in that paper. In general, economic coefficients are derived from regression analyses based on historical data. Ecological coefficients, on the other hands, are estimated from expert judgments by biologists and LEEM simulations. Here, we use the revised values listed in Table 2 of Zheng et al. (2009) for the importance weight (W_i). In this paper, we focus on the derivation of the new objective z_2.

Dam Safety Risk Index ($RISK_j$). Risk has two components: the likelihood and consequences of failure (Hartford and Baecher 2004). $RISK_j$ covers both. ‘Failure’ is defined as a rapid release of the entire contents of the reservoir due to loss of integrity of the dam structure. We conducted a survey among dam safety professionals to estimate $RISK_j$ in Eq. (2). The product of $RISK_j$ and d_j^{safety} in Eq. (2) represents the risk reduction from removing dam *j*, so higher values of $RISK_j$ indicate that the removal is more desirable from a public safety perspective.

Safety Criteria Selection and Scaling. One important step in defining $RISK_j$ is to identify constituent criteria ($S_{m,j}$) that gauge its likelihood and consequence components. We use three (m=1,…,3) important and readily obtained criteria: dam age ($S_{1,j}$), safety inspection record ($S_{2,j}$), and hazard potential classification ($S_{3,j}$). The first criterion ($S_{1,j}$) is based on the year in which a dam was built or most recently subjected to major repairs. The second criterion ($S_{2,j}$) indicates a dam's physical condition based on the most recent safety inspection. $S_{2,j}$ is an ordinal criterion having five categories, four of which are naturally ordered: unsatisfactory, poor, fair, satisfactory and not rated. Definitions of these record rating categories are obtained from the "*National Dam Safety Board of Review—National Inventory of Dams Assessment of Inspection Field*" (Mark Ogden, Division of Water, Ohio Dept. of Natural Resources, personal communication, April 22, 2009). The third criterion ($S_{3,j}$) represents the possible consequence of failure, such as loss of human life, property damage and other economic loss, and environmental impact (Federal Emergency Management Agency (FEMA) 2004). $S_{3,j}$ is also ordinal with three ordered categories: high, significant, and low. Definitions of these classifications are given by FEMA (2004).

The logic we used to select our safety criteria is straightforward. Aging dams (indicated by $S_{1,j}$) will increase the likelihood of the dam's purpose being outlived, being of substandard design, and of deterioration. Evident deficiencies are indicated by $S_{2,j}$.(not all dams are inspected and have records of $S_{2,j}$, thus it is important to include $S_{1,j}$). Historically, dams that failed usually had some deficiencies that made them more vulnerable to failure under extreme circumstances such as large floods (Robert and Pare 1995). Once a dam fails, its consequences depend in part on the presence of vulnerable property, populations, or ecosystems downstream (indicated by $S_{3,j}$). Thus, these criteria cover the two components of risk: $S_{1,j}$ and $S_{2,j}$ address the likelihood of dam failure, while $S_{3,j}$ is an index of the consequences of failure. They are selected also because they are characterized for most dams in the National Inventory of Dams (NID).

To map each of the three risk criteria to a quantitative 0-1 scale (where zero means no risk and one means highest risk), we create a relative risk value function ($R_m^{dam}(\ )$) for each. For $S_{1,j}$, we assume that $R_1^{dam}(\ )$ equals 1 for dams that are over 200 years old and zero for dams less than 50 years old; for ages between 50 and 200, $R_1^{dam}(\ )$ is obtained by linear interpolation. The lower bound (50 years old) reflects the fact that due to gradual structure deterioration and reservoir sedimentation, the average functional life span of most U.S. dams is approximately 50 years (Bowman et al. 2002; The Heinz Center 2002). Therefore, we assume the risk of failure caused by aging to be negligible for dams that were built in the past five decades. For dams that are more than 50 years old, since they may have outlived their designed functional life span, we assume that aging-induced failure is possible and such risk increases linearly with age.

For safety inspection record ($S_{2,j}$) and hazard potential classification ($S_{3,j}$), value functions $R_m^{dam}(\ )$ are based on a survey of seven dam safety professionals from state and federal agencies. We asked the experts to directly rate the relative safety of different criterion categories on a 0-1 scale, where zero represents the least risky case (i.e., $R_2^{dam}(satisfactory)=0$ and $R_3^{dam}(low)=0$) and one represents the most risky case (i.e., $R_2^{dam}(unsatisfactory)=1$ and $R_3^{dam}(high)=1$). Table 1 shows the relative risk values elicited from our survey.

The use of expert surveys to quantify probabilities and relative risk is commonly undertaken in risk analyses when data is lacking but experts possess relative knowledge. There is a large literature on appropriate procedures to elicit such judgments (e.g., Clemen 1996). However, care must be taken because such judgments are subject to well-known cognitive biases (Clemen 1996).

Safety Criteria Aggregation. Another important step in defining $RISK_j$ is to aggregate the selected safety criteria. Given that the product of $RISK_j$ and d_j^{safety} in Eq. (2) represents the reduction in failure risk by removing dam *j*, higher values of $RISK_j$ indicate that the removal is more desirable from a public safety perspective. Here, a $RISK_j$ index with this property is created from the constituent criteria using a multicriteria value (MCV) function. Among possible MCV function forms, we tested two: the additive value function (Keeney and Raiffa 1976), which is widely used in decision analysis, and the Power Law value function (Gum et al. 1976), which can represent risk as the product of likelihood and consequence. The two forms are:

$$\text{Additive: } RISK_j = \sum_{m=1}^{3} P_m\left(R_m^{dam}\left(S_{m,j}\right)\right) \qquad \forall\, j \in J,\ m=1,\ldots,3 \tag{10}$$

$$\text{Power Law: } RISK_j = \prod_{m=1}^{3}\left(R_m^{dam}\left(S_{m,j}\right)\right)^{P_m} \qquad \forall\, j \in J,\ m=1,\ldots,3 \tag{11}$$

where P_m is the relative importance weight for risk reduction criterion $S_{m,j}$ ($0 \le P_m \le 1$ for all *m* and $\sum_{m \in M} P_m = 1$). The weights were obtained by asking the same dam safety professionals to allocate 100 points among the three risk criteria ($S_{m,j}$) according to their relative importance, which is a common means of weight selection (Hobbs and Meier 2000). In our questionnaire, we provided instructions and examples of consistency tests so that the expert could consider the consistency of their weights with their willingness to exchange one criterion for another. Survey results for the relative weights are also presented in Table 1.

Each formulation of $RISK_j$ has advantages. The additive form [Eq. (10)] balances the dam safety risk criteria ($S_{m,j}$) assuming that they are mutually compensatory: a low value of one criterion can be compensated for by a high value of the other(s) (Einhorn 1970; Kozielecki 1981). The strengths of the additive formulation are its simplicity, wide use in practice, and robust results in linear or mildly nonlinear problems (Stewart 1996; Hobbs and Meier 2000).

In dam safety management, however, risk is more often considered as a product of the probability of failure and its consequences, which is a nonlinear relationship. The Power Law formulation [Eq. (11)] is a nonlinear utility model in a multiplicative form. It is a non-compensatory model, where improvement in one criterion cannot compensate for deterioration in another at a constant rate, unlike the additive model (Einhorn 1970). Mathematically, Eq. (11) achieves its maximum value ($RISK_j$=1) when all $R_m^{dam}(\ )$ are maximized ($R_m^{dam}(\ )$=1 for all m), and achieves its minimum value ($RISK_j$=0) if just one or more $R_m^{dam}(\ )$ are zero.

The Power Law favors the most distinctive advantage among criteria values (i.e. "safe" in one criterion $S_{m,j}$, where $R_m^{dam}(\ )$=0), rather than disadvantages (i.e., "unsafe" in another criterion $S_{m',j}$, where $R_{m'}^{dam}(\ )$>0). This makes the Power Law formulation less conservative with respect to dam safety than the additive formulation. That is, if $R_m^{dam}(\ )$ equals 0 for one or more $S_{m,j}$, then overall $RISK_j$ equals 0, meaning no risk to the public. However, in dam safety management, we may not want to consider a dam being safe simply because one criterion has met its "safety" threshold; in that case, the more familiar and widely used additive function may be preferred.

Case Study

Data Sources

Our case study uses the database of dams used in Zheng et al. (2009). The database includes 139 candidate dams located in ten U.S. watersheds of the Lake Erie basin. These dams were selected from data collected from the NID, the U.S. Environmental Protection Agency, and state governments (Zheng et al. 2009).

To estimate $RISK_j$, we used dam ages ($S_{1,j}$) and hazard potential classifications ($S_{3,j}$) in the NID (U.S. Army Corps of Engineers (USACE) 2006). We obtained dam safety inspection records ($S_{2,j}$) from relevant state dam safety agencies (personal communications, Alon Dominitz, Bur. of Program Resources & Flood Protection, NY State Dept. of Environmental Conservation, April 20, 2009; Mark Ogden, Div. of Water, Ohio Dept. of Natural Resources, April 22, 2009; Dennis Dickey, Div. of Dam Safety, Pennsylvania Dept. of Environmental Protection, April 28, 2009; Byron Lane, Geological and Land Div., Michigan Dept. of Environmental Quality, April 30, 2009; Kenneth Smith, Div. of Water, Indiana Dept. of Natural Resources, May 6, 2009).

Estimates of $RISK_j$

In the case study, $RISK_j$ is assumed to be nonzero only for relatively large dams, assuming that failures of low head dams would have relatively negligible consequences. We use 3 meters (10 feet) of dam height as a cutoff criterion.

We apply Eqs. (10) and (11) to calculate $RISK_j$. According to Eq. (10), the additive formulation, among 139 candidate dams, 35 relatively large dams involve varying degrees of potential failure risks to the pubic ($RISK_j > 0$); the remaining dams are either low head dams or have a zero value for all three risk criteria ($R_m^{dam}(\ ) = 0$ for all m), and so their overall $RISK_j$ is zero by Eq. (10). In contrast, according to Eq. (11), the Power Law formulation, only 17 dams have positive values of all three criteria and so have some potential failure risk ($RISK_j. > 0$).

Model Simulation

We use the Xpress-IVE solver (http://optimization.fico.com/) to solve the ILP. For each of the two risk function formulations [Eqs. (10) and (11)], we vary two parameters in the ILP constraints (5) and (6) to generate alternative non-inferior portfolios: risk reduction goal G ranging from 0 (no removal of any risky dams) to 1 (removals of all risky dams—35 or 17 dams depending on the choice of the risk function form), and budget B ranging from \$55 thousand (the lowest cost for the first removal) to \$49 million (removal of all 139 dams). The resulting range of non-inferior solutions reveals tradeoffs among safety, ecological, and economic objectives.

Results and Discussion

Tables 2 and 3 show selected case study results under the additive and Power Law risk functions, respectively. For ease of interpretation, the values of z_1 and z_2 are scaled to percentages, where 0% is the base case (no dams removed), and 100% is the maximum possible improvement (all dams or all hazardous dams removed, respectively). The results in Tables 2 and 3 show three major trends, discussed below, regarding tradeoffs and the impact of alternative risk indices.

Safety-Ecological-Cost Tradeoffs. The first trend, unsurprisingly, is that higher budgets allow more dams to be removed and more ecological and safety benefits to be obtained. Eventually, all dams under consideration are removed once the budget B exceeds the total cost of removing all 139 dams (\$49M). This is because all candidate dams have some ecological benefits, in terms of walleye habitat improvement, if all dams downstream have also been removed.

The second trend concerns tradeoffs between safety and ecological objectives. Under the same cost budget (B), with varying risk reduction goals (G), there are large shifts in the composition of the dam removal portfolio, and the resulting values of ecological benefits z_1 and risk benefits z_2 change greatly. Especially under lower budgets, a higher risk reduction goal leads to more dams being removed solely for safety benefits (d_j^{safety}=1 and d_j^{eco}=0). For example, Table 2 (additive risk formulation) indicates that when B equals \$5M, the risk reduction goal G can be increased from 10% to 54% (causing the value of the safety objective z_2 to increases from 11%

to 55%), but only by worsening the ecological objective z_1 from 34% to 12%. (Note that the value of z_2 does not usually equal G because the model is an integer program.) The number of hazardous dams removed solely for safety reasons jumps from 2 to 16 and the number of dams removed solely for ecological reasons decreases from 8 to 3. Meanwhile, more hazardous dams are removed (from 3 to 19), and the overall number removals doubles (11 to 22).

These changes indicate that a higher risk reduction goal leads to more small hazardous dams with low removal costs being removed as opposed to a few larger dams that would open up more fish habitats. Because of Eqs. (7) and (8), dams posing a safety risk can be removed without removing any downstream dams, while, in contrast, downstream dams must be removed for fish habitat and ecosystem benefits to be realized. If hazardous dams are located further upstream in the watersheds, it is unlikely to be necessary to control sea lamprey, which, in turn, reduces their estimated removal costs. This enhances the attractiveness of removing certain hazardous dams, all else being equal. Table 3 shows a similar trend for the Power Law form.

The locations of the removed dams in the two solutions just mentioned (additive form, B=\$5M, G=10% and 54%) are plotted in Figs. 2 and 3. The patterns of dam removals differ considerably. When the risk reduction goal is low (G=10%), only two dams are removed solely for safety reasons and most removals occur in the central and western basins, where walleye abundance is higher than in the eastern basin. Under the same budget, a more ambitious risk reduction goal (G=54%) leads to a six-fold increase in the number of hazardous dams being removed, many of which are located well upstream. This increase occurs in all regions.

Fig. 4 shows three selected tradeoff curves among ecological, safety, and economic objectives where the additive formulation is used and G (the risk reduction goal assigned on z_2, the safety objective) is set equal to 25%, 50%, and 75%, respectively. The tradeoff curves associated with different *G* in Fig. 4 diverge notably when the budget is below $30 million. In contrast, the curves converge under a high budget. This is because when the budget is high, most of the hazardous dams have been removed (z_2, the safety objective, is close to 100%). Thus the tradeoff between z_1 and z_2 diminishes regardless of the value of *G*.

Additive vs. Power Law Risk Functions. The third trend is that different risk functions yield different dam removal portfolios. Results presented in Tables 2 and 3 show different portfolios in terms of objective values and numbers of removals. For example, given the same budget (B=$5M) and the same expected ecological benefit (z_1=12.4%), using the additive formulation leads to a 55% risk reduction in the safety objective z_2 and 22 removals; while using the Power Law formulation leads to a 66% risk reduction in z_2 and 15 removals. These solutions are plotted in Fig. 3 (additive form) and Fig. 5 (Power Law) to demonstrate their differences.

Comparing Figs. 3 and 5, we find that the differences occur in seven watersheds (Raisin, Maumee, Sandusky, Black-Rocky, Cuyahoga, Grand, and Ashtabula-Chagrin). In particular, five dams in the Sandusky River basin are chosen to be removed using the additive formulation, whereas only one dam (the Ballville Dam) is selected using the Power Law formulation. A closer observation shows that among the 22 dams selected in Fig. 3 and the 15 selected in Fig. 5, eleven dams are chosen in both cases (two nonhazardous dams removed for z_1, seven hazardous dams removed for z_2, and two hazardous dams for both z_1 and z_2). The remaining selections differ. Eleven dams are selected to be removed under the additive formulation but retained under the Power Law formulation. Similarly, the Power Law removes four dams that are kept under the additive formulation. In addition, we find that the dams chosen by the Power Law are individually more expensive to remove and are riskier in terms of the Power Law formulation (but less risky in terms of the additive form) than the dams chosen by the additive form.

In order to further compare the overall effect of different risk models on portfolio composition, Fig. 6 plots tradeoff curves between the ecological objective z_1 and two different forms of z_2 (the additive and the Power Law) under three different budget levels: $5 million, $15 million, and $30 million. In Fig. 6, portfolios chosen using the Power Law method are dominated by portfolios chosen by the additive method. The two sets diverge sharply when the safety objective is pushed up to the 40-80% range. This means that using the Power Law value function formulation would yield appreciably different portfolios of dams to be removed and kept than if the additive function form is used instead. Note that only through careful questioning can one determine which form (additive, Power Law, or other) best represents decision maker preferences (Keeney and Raiffa 1976). Lacking such information, we can only highlight differences in the solutions selected by each form for consideration by managers and stakeholders.

Conclusions

The ILP model provides a useful screening tool for policy makers to explore the nature and magnitude of trade-offs when considering portfolios of potential dam removal projects. Given limited funding, users can explore how different prioritizations affect the portfolio of selected dams, and its public safety and ecosystem enhancement performance. A huge set of alternative portfolios ($3^{139} \approx 2 \times 10^{66}$ in the case study) can be considered. These results can inform stakeholders and aid negotiations by making clear what is at stake in the decision.

Our results also indicate that the particular form of the value function for dam safety can affect the optimum portfolio of removals. Here, we contrast the two methods (additive and Power Law) to emphasis that in dam removal, not only risk matters, but so does its definition. Despite their differences, both the additive and the Power Law-based indices can be used to characterize potential dam failure risks. The indices are parameterized using survey data from dam safety professionals and available data from the NID and dam inspection records. This approach can be readily applied elsewhere to help safety officials to prioritize dams for removal.

Our model has limitations. First, actual removal decisions requires subsequent site-specific study, as, for instance, our cost and safety estimates are based on national data bases that may not be accurate characterizations of local conditions. Second, we assume dam failure risks are independent to each other, which may not hold in some cases, as, for instance, the failure risk at a downstream dam depends on the condition of upstream dams, while the presence of a down-stream dam could protect populations further downstream from the consequences of an upstream dam failure. Third, the current risk indices are only broadly indicative of dam safety risks, and do not explicitly quantify the probability of dam failure and its precise consequences. The prob-ability of failure could be estimated from models (e.g., estimating the frequency of floods that exceed spillway capacity) or expert judgment. Consequences could be presented as populations that could be exposed to the resulting flood wave. Another limitation is that the ecological mod-el assumes steady state conditions in calculating the impact of increased walleye recruitment. Future work could explicitly characterize uncertainties in these impacts and, in a two-stage (Bayesian) model consider how subsequent site-specific investigation might alter removal deci-sions and their consequences. For example, detailed study might show that the actual cost for removing particular dams will be much larger than considered in the ILP, and this would likely affect the final choice of dams to remove.

Acknowledgements. This study was supported by the National Center for Earth-surface Dy-namics (a NSF Science and Technology Center), the Public Safety Canada Research Fellowship in honor of Stuart Nesbitt White, and the Daniel McGillis Development and Dissemination Grant Program at Abt Associates Inc. The writers thank the experts listed in the paper who provided data and the dam safety professionals who participated in our survey. We also thank B. Rhodes, E. Post, I. Morin, J. Klerman, and S. Kennedy at Abt Associates Inc. for helpful comments.

References

American Rivers (2010). "Dam slated for removal in 2010." *American Rivers*, Washington, D. C.

Anderson, R. M., Hobbs, B. F., Koonce, J. F., and Locci, A. B. (2001). "Using decision analysis to choose phosphorus targets for Lake Erie." *Environ. Manage.* 27(2), 235–252.

Bolsenga, S. J., and Herdendorf, C. E. (1993). "Lake Erie and Lake St. Clair handbook." Wayne State University Press, Detroit, MI.

Bowman, M., Higgs, S., Maclin, E., McClain, S., Sicchio, M., Souers, A., Johnson, S., and Graber, B. (2002). "Exploring dam removal: A decision-making guide." *American Rivers and Trout Unlimited*, Washington D. C. and Madison, WI.

Brown, C. A. (1989). "Managing conflict over a dam safety problem." *Managing water-related conflicts: The engineer's role*, W. J. Viessman and E. T. Smerdon, eds, ASCE, New York.

Clemen, R. T. (1996). "Making hard decisions: An introduction to decision analysis." Duxbury Press, Pacific Grove, CA.

Cohon, J. L. (1978). "Multiobjective programming and planning." Dover Publications, Mineola, NY.

Corsair, H. J., Ruch, J. B., Zheng, P. Q., Hobbs, B. F., and Koonce, J. F. (2009). "Multicriteria decision analysis of stream restoration: Potential and examples." *Group Decis. Negot.* 18(4), 387-417.

Einhorn, H. J. (1970). "The use of nonlinear, noncompensatory models in decision making." *PsyB* 73, 221-230.

Federal Emergency Management Agency (FEMA) (2004). "Federal guidelines for dam safety: Hazard potential classification system for dams." *FEMA 333*, Washington D. C.

Gross, E. J., and Moglen, G. E. (2007). "Estimating the hydrological influence of Maryland State dams using GIS and the HEC-1 model." *J. Hydrol. Eng.* 12(6), 690-693.

Gum, R. L., Roefs, T. G., and Kimball, D. B. (1976). "Quantifying societal foals - Development of a weighting methodology." *Water Resour. Res.* 12(4), 617-622.

Haimes, Y. Y., Lambert, J. H., and Li, D. (1992). "Risk of extreme events in a multiobjective framework." *Water Resour. Bull.* 28(1), 201-209.

Hartford, D. N. D., and Baecher, G. B., eds. (2004). "Risk and uncertainty in dam safety." Thomas Telford Books, Bodmin, UK.

Hobbs, B. F., and Meier, P. (2000). "Energy decision and the environment: A guide to the use of multicriteria methods." Kluwer Academic Publishers, Norwell, MA.

Karvetski, C. W., Lambert, J. H., Keisler, J. M., and Linkov, I. I. (2011). "Integration of decision analysis and scenario planning: Application to coastal engineering and climate change." *IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Human* 41(1), 63 -73.

Kasprzyk, J. R., Reed, P. M., Kirsch, B. R., and Characklis, G. W. (2009). "Managing population and drought risks using many-objective water portfolio planning under uncertainty." *Water Resour. Res.* 45(W12401), 18 pp.

Keeney, R. L., and Raiffa, H. (1976). "Decisions with multiple objectives: Preferences and value tradeoffs." John Wiley & Sons, Inc., New York, NY.

Keisler, J. M., and Linkov, I. I. 2010. Managing a portfolio of risks. In *Wiley Encyclopedia of Operations Research and Management Science*. http://onlinelibrary.wiley.com/doi/10.1002/9780470400531.eorms0488/full.

Kemp, P. S., and O' Hanley, J. R. (2010). "Procedures for evaluating and prioritising the removal of fish passage barriers: A synthesis." *Fisheries Management and Ecology* 17, 297-322.

Kim, J. B., Hobbs, B. F., and Koonce, J. F. (2003). "Multicriteria Bayesian analysis of lower trophic level uncertainties and value of research in Lake Erie." *Hum. Ecol. Risk Assess.* 9(4), 1023–1057.

Koonce, J. F., Locci, A. B., and Knight, R. L. (1999). "Contributions of fishery management to changes in walleye and yellow perch populations of Lake Erie." *Great Lakes fisheries policy and management: A binational perspective*, W. W. Taylor and C. P. Ferreri, eds, Michigan State University Press, East Lansing, MI.

Kozielecki, J. (1981). "Psychological decision theory." D. Reidel Publishing Company, Boston, MA.

Kuby, M. J., Fagan, W. F., ReVelle, C. S., and Graf, W. L. (2005). "A multiobjective optimization model for dam removal: an example trading off salmon passage with hydropower and water storage in the Willamette basin." *Adv. Water Resour.* 28(8), 845–855.

Levner, E., Ganoulis, J., Alcaide López de Pablo, D., and Linkov, I. I. (2008). "Sustainable management of water resources and minimization of environmental Risks: A multi-portfolio optimization model." *Real-time and deliberative decision making: Application to emerging stressors*, I. I. Linkov, E. Ferguson and V. S. Magar, eds, Springer, Dordrecht, The Netherlands.

McMahon, T. E., Terrell, J. W., and Nelson, P. C. (1984). "Habitat suitability information: Walleye." *Division of Ecological Services, U.S. Fish and Wildlife Service, Department of the Interior*, Washington, D. C.

Pejchar, L., and Warner, K. (2001). "A river might run through it again: Criteria for consideration of dam removal and interim lessons from California." *Environ. Manage.* 28(5), 561–575.

Poff, N. L., and Hart, D. D. (2002). "How dams vary and why it matters for the emerging science of dam removal." *Bioscience* 52(8), 659–668.

Pohl, M. M. (2002). "Bringing down our dams: Trends in American dam removal rationales." *J. Am. Water Resour. Assoc.* 38(6), 1511–1519.

Robert, B., and Pare, J. J. (1995). "Failure of the dam at Lake Beloeil - Causes and consequences." *Can. J. Civ. Eng.* 22(3), 506-513.

Stanley, E. H., and Doyle, M. W. (2003). "Trading off: the ecological removal effects of dam." *Front. Ecol. Environ.* 1(1), 15–22.

Stewart, T. J. (1996). "Robustness of additive value function method in MCDM." *J. Multicriteria Decis. Anal.* 5, 301-309.

Sullivan, W. P., Christie, G. C., Cornelius, F. C., Fodale, M. F., Johnson, D. A., Koonce, J. F., Larson, G. L., McDonald, R. B., Mullett, K. M., Murray, C. K., and Ryan, P. A. (2003). "The sea lamprey in Lake Erie: a case history." *J. Great Lakes Res.* 29(Suppl 1), 615–636.

The Heinz Center (2002). "Dam removal: Science and decision making." The H. John Heinz III Center for Science, Economics and the Environment, Washington, D. C.

U.S. Army Corps of Engineers (USACE) (2006). "National inventory of dams (NID)." <http://crunch.tec.army.mil/nid/webpages/nid.cfm> (May 25, 2006).

Whitelaw, E., and MacMullan, E. (2002). "A framework for estimating the costs and benefits of dam removal " *BioScience* 52(8), 724–730

Xu, Y., and Zhang, L. M. (2009). "Breaching parameters for earth and rockfill dams." *J. Geotech. Geoenviron.* 135(12), 1957-1970.

Zheng, P. Q. 2009. "Multiobjective decision analysis and risk analysis of multi-dam removal: Optimizing dam failure risk, removal cost, and ecosystem benefit." Ph.D. thesis, Johns Hopkins University, Baltimore, MD.

Zheng, P. Q., Hobbs, B. F., and Koonce, J. F. (2009). "Optimizing multiple dam removals under multiple objectives: Linking tributary habitat and the Lake Erie ecosystem." *Water Resour. Res.* 45,(W12417), 14 pp.

Table 1. Risk-based Dam Safety Survey Results -- Single Criterion Value Functions and Importance Weights

Risk Criterion ($S_{m,j}$)	Category	Value Function $R_m^{dam}(\ )$		Relative Weight P_m	
		Mean	SD	Mean	SD
Dam Age				31	11
Safety Inspection Record	Unsatisfactory (pre-assigned)	1		56	17
	Poor	0.8	0.14		
	Fair	0.54	0.15		
	Not Rated	0.43	0.23		
	Satisfactory (pre-assigned)	0			
Hazard Potential	High (pre-assigned)	1		13	7
	Significant	0.56	0.14		
	Low (pre-assigned)	0			

Note: SD = Standard Deviation. All materials related to our survey (e.g., selection of the officials, survey questionnaire, and official approval from the Institutional Review Board to conduct the survey) can be found in Zheng (2009).

Table 2. Selected Results Using the Additive Value Function Formulation for Risk z_2

Budget	Safety Goal	-------MILP Objectives-----			Dams Removed (#)			
		Ecol.	Safety	Econ.	---------- Removal Reasons ----------------			
B ($M)	G (%)	z_1 (%)	z_2 (%)	z_3 ($K)	E z_1	S z_2	S+E $z_1 + z_2$	Total
5	10[a]	34.12	10.75	4999	8	2	1	11
	30	26.17	30.15	4993	4	6	4	14
	54[b]	12.41	54.59	4973	3	16	3	22
	60	6.10	60.17	4953	3	19	2	24
	90	Infeasible						
15	10	68.34	22.71	14987	23	0	8	31
	30	68.02	30.23	14983	22	2	8	32
	60	63.65	60.65	14997	25	9	12	46
	90	29.72	90.81	14998	5	26	5	36
30	1-38[c]	96.35	38.62	29996	52	0	14	66
	50	95.99	50.10	29990	50	2	16	68
	60	95.52	60.00	29998	52	5	16	73
	90	89.17	90.92	29979	33	13	18	64

Note: Ecol. = ecological objective; Econ. = economic objective; E= dams are removed solely for ecological benefits (d_j^{safety}=1, d_j^{eco}=1, and $RISK_j$=0); S = risk related dams are removed solely for safety benefit (d_j^{safety}=1 and d_j^{eco}=0); and S+E = risk related dams are removed for both safety and ecological benefits (d_j^{safety}=1, d_j^{eco}=1, and $RISK_j$>0).

a. Example used for Fig. 2.

b. Example used for Fig. 3.

c. When budget B equals $30M, dam removal portfolios do not change when G increases from 1% to 38%.

Table 3. Selected Results Using the Power Law Formulation for Risk z_2

Budget	Safety Goal	MILP Objectives			Dams Removed (#)			
		Ecol.	Safety	Econ.	Removal Reasons			
B ($M)	G (%)	z_1 (%)	z_2 (%)	z_3 ($K)	E z_1	S z_2	S+E $z_1 + z_2$	Total
5	10	34.60	13.41	4999	8	0	2	10
	30	32.39	30.63	4980	6	3	2	11
	60	18.76	60.11	4940	6	8	2	16
	66[a]	12.41	66.75	4994	4	9	2	15
	90	-------------Infeasible-------------						
15	10	68.34	19.25	14987	28	0	3	31
	30	68.08	30.23	14995	27	1	4	32
	60	65.16	61.80	14941	22	6	5	33
	90	54.99	90.419	14979.4	19	12	3	34
30	1-32[b]	96.35	33.00	29996	61	0	5	66
	50	95.99	50.22	29989	61	2	6	69
	60	95.80	60.18	29996	57	1	9	67
	90	92.36	90.98	29999	45	7	8	60

a. Example used for Fig. 5.

b. When budget B equals $30M, dam removal portfolios do not change when G increases from 1% to 32%.

Fig. 1. Multiobjective portfolio analysis framework for dam removal in the Lake Erie Basin

Fig. 2. MILP results-example 1 (additive formulation): Locations of 11 removals under a $5M budget and with a low risk reduction goal (G = 10%), achieving an ecological benefit of 34.1%

Fig. 3. MILP results-example 2 (additive formulations): locations of 22 removals under a $5M budget and high risk reduction goal (*G* = 54 %), achieving an ecological benefit of 12.4%

Fig. 4. 3-Dimensional Tradeoff Curves among the Ecological, Safety, and Economic Objectives

Fig. 5. MILP results-example 3 (Power Law formulation): locations of 15 removals under a $5M budget and high risk reduction goal (*G* = 66%) to achieve ecological benefit of 12.4%

Fig. 6. Comparison of the additive and the Power Law formulations

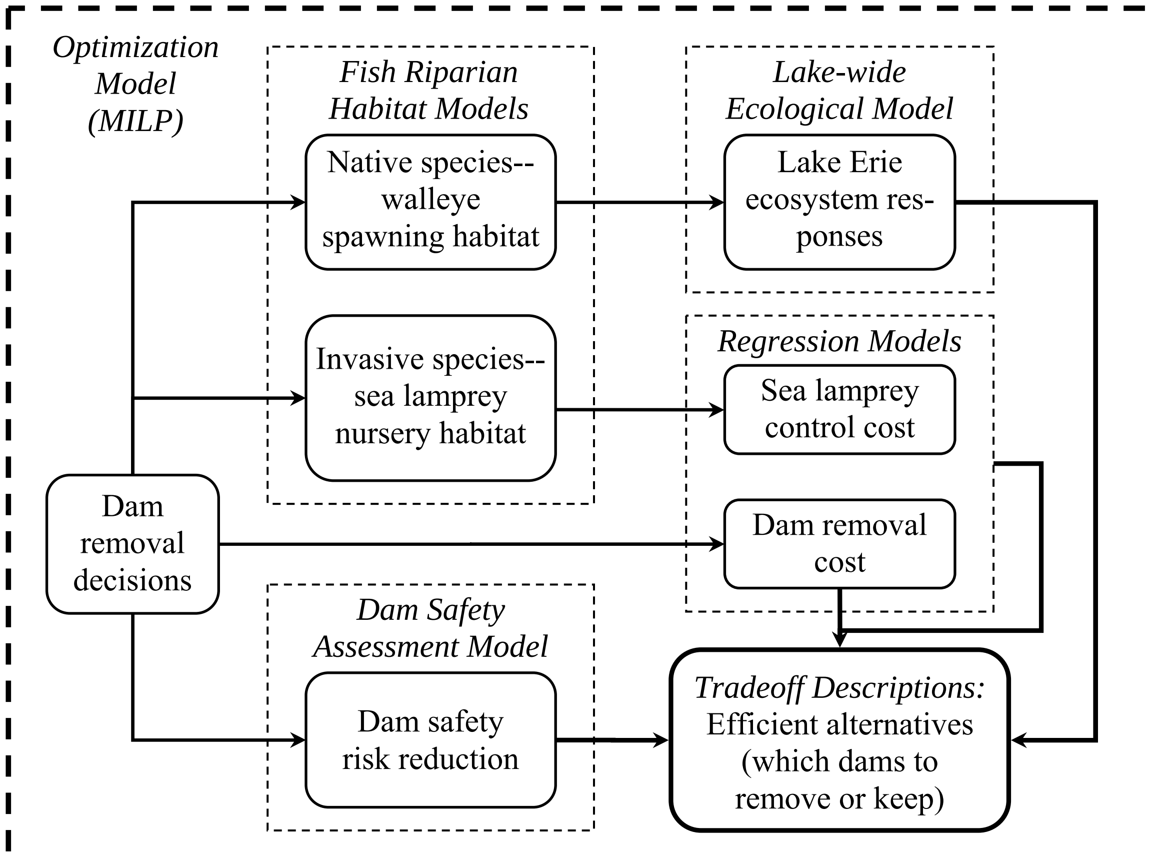

Fig. 1. Multiobjective portfolio analysis framework for dam removal in the Lake Erie Basin

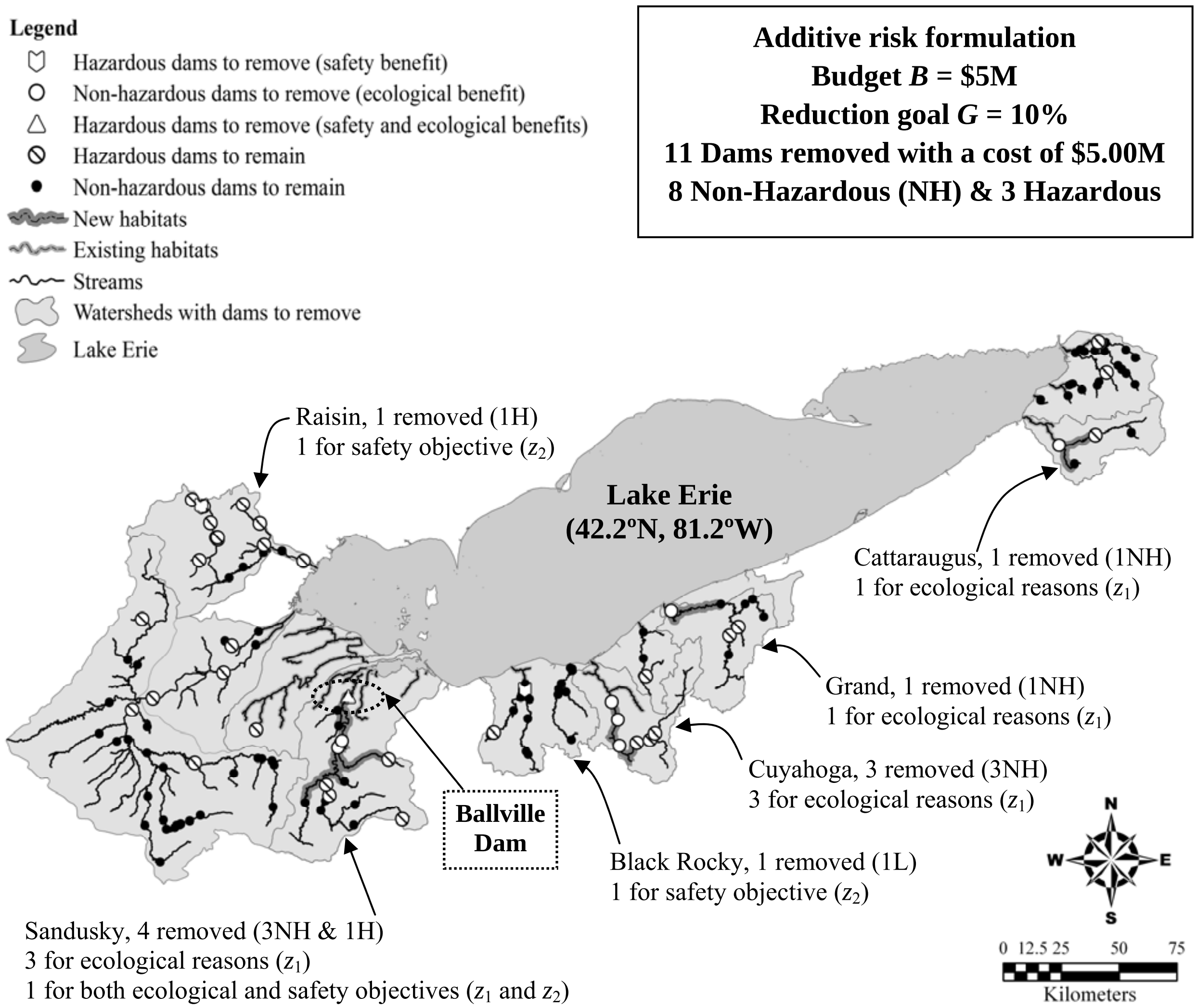

Fig. 2. MILP results-example 1 (additive formulation): Locations of 11 removals under a $5M budget and with a low risk reduction goal (G = 10%), achieving an ecological benefit of 34.1% (Note: NH = non-hazardous dams that are not classified by the NID as presenting hazard potential to downstream population and environment; H = High hazard potential; S = Significant hazard potential; and L = Low hazard potential)

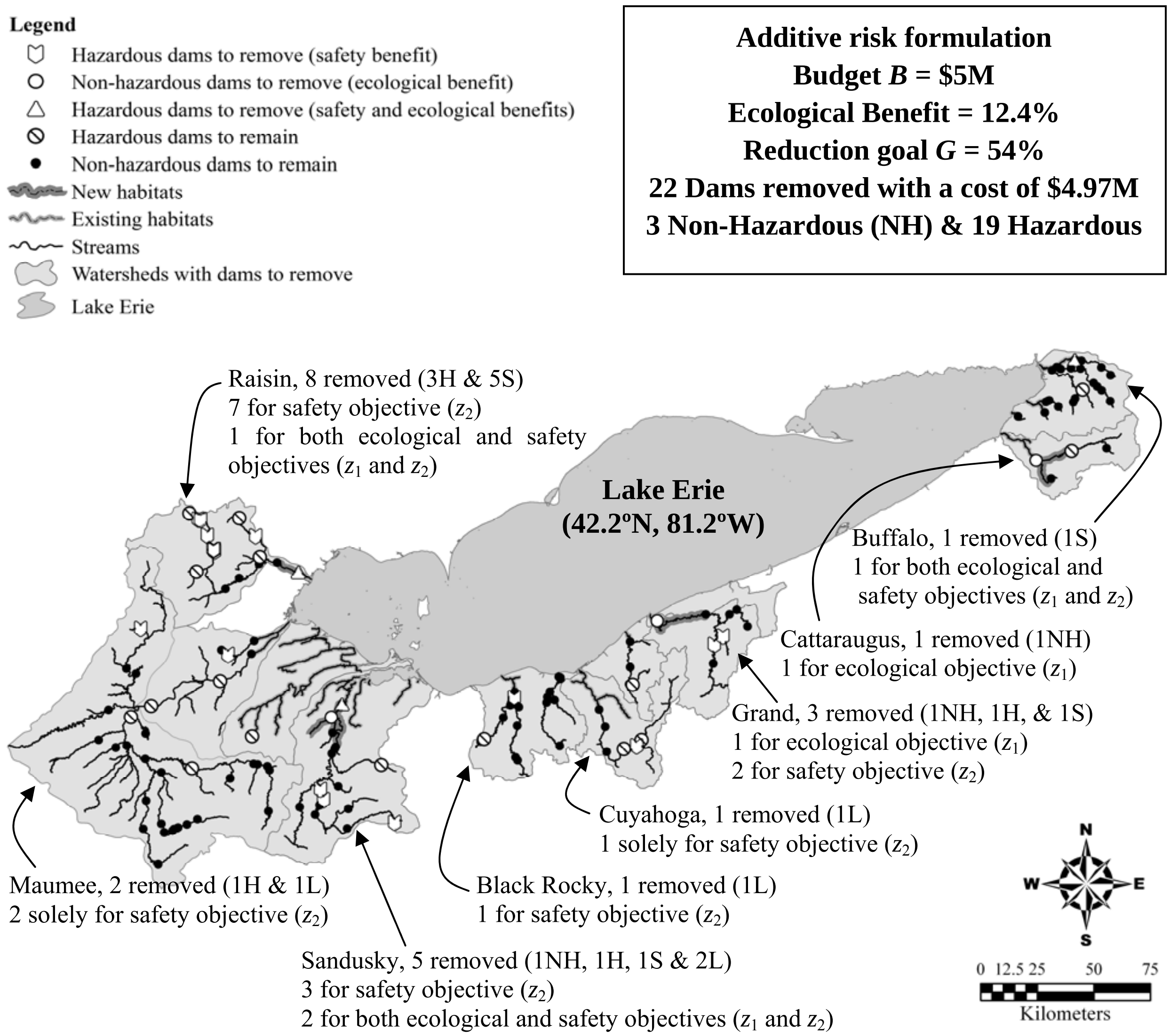

Fig. 3. MILP results-example 2 (additive formulations): locations of 22 removals under a \$5M budget and high risk reduction goal (G = 54 %), achieving an ecological benefit of 12.4%

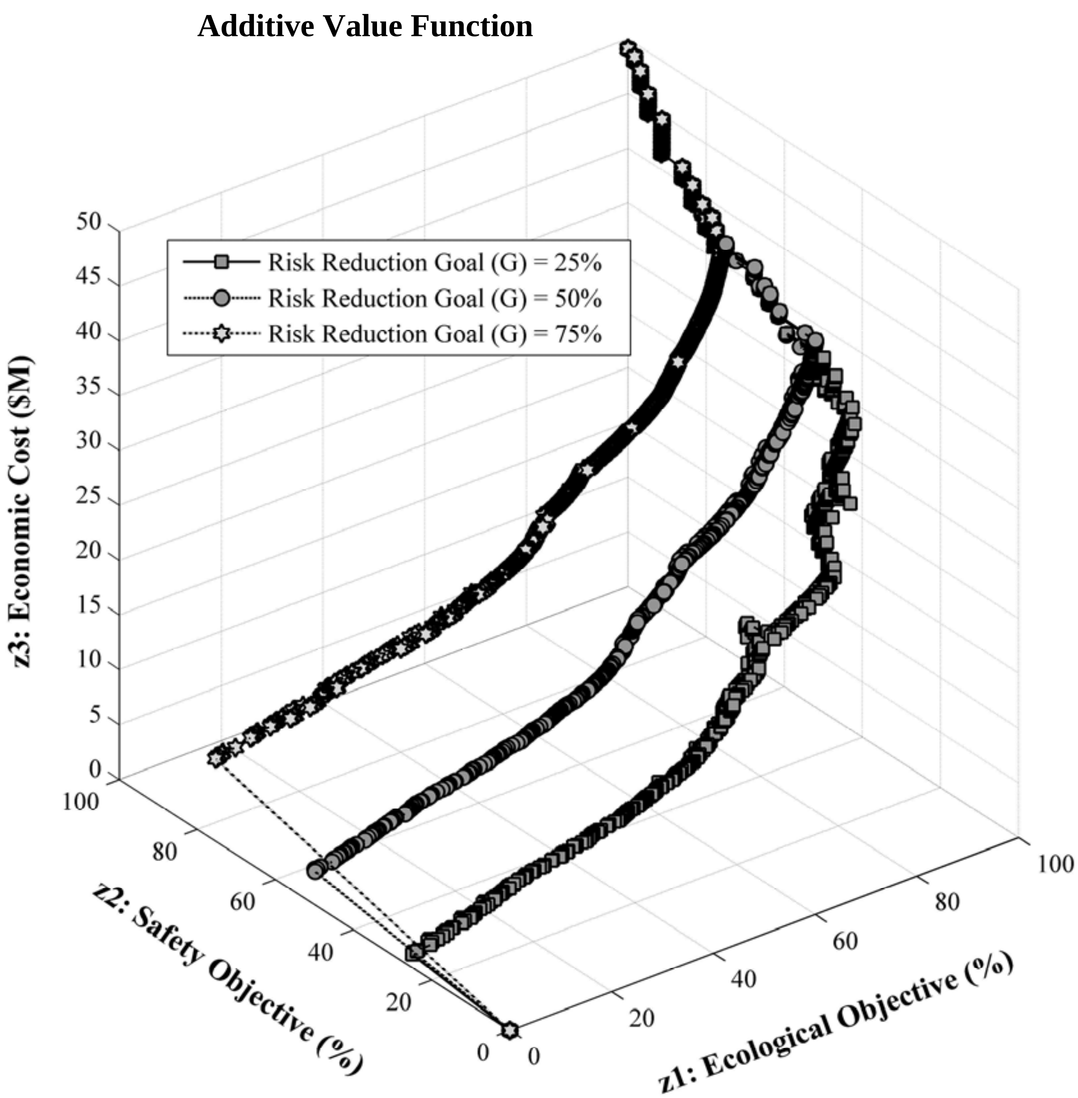

Fig. 4. 3-Dimensional Tradeoff Curves among the Ecological, Safety, and Economic Objectives (Note: : using the additive risk function, and *G* = 25%, 50%, and 75%)

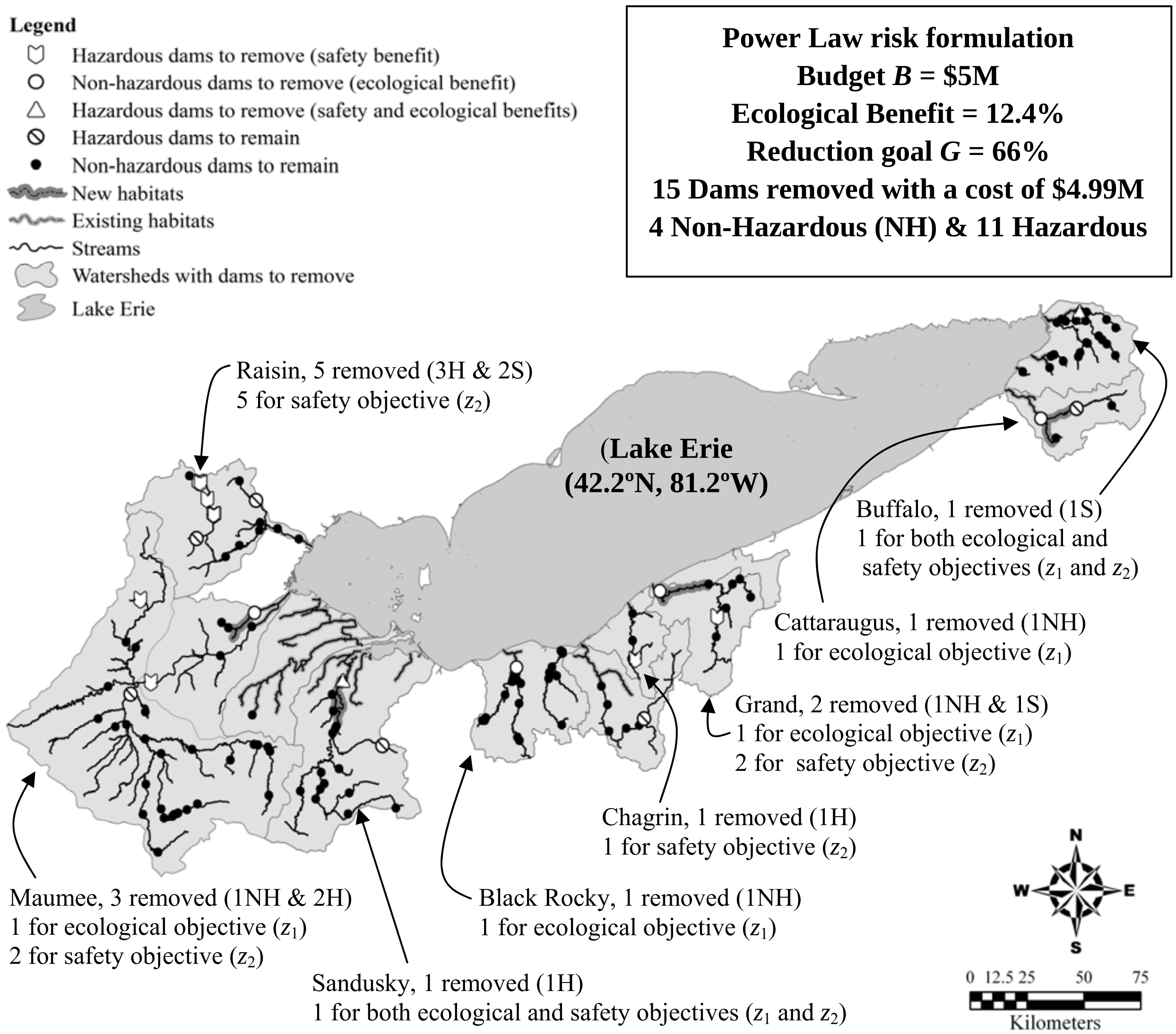

Fig. 5. MILP results-example 3 (Power Law formulation): locations of 15 removals under a $5M budget and high risk reduction goal (G = 66%) to achieve ecological benefit of 12.4%

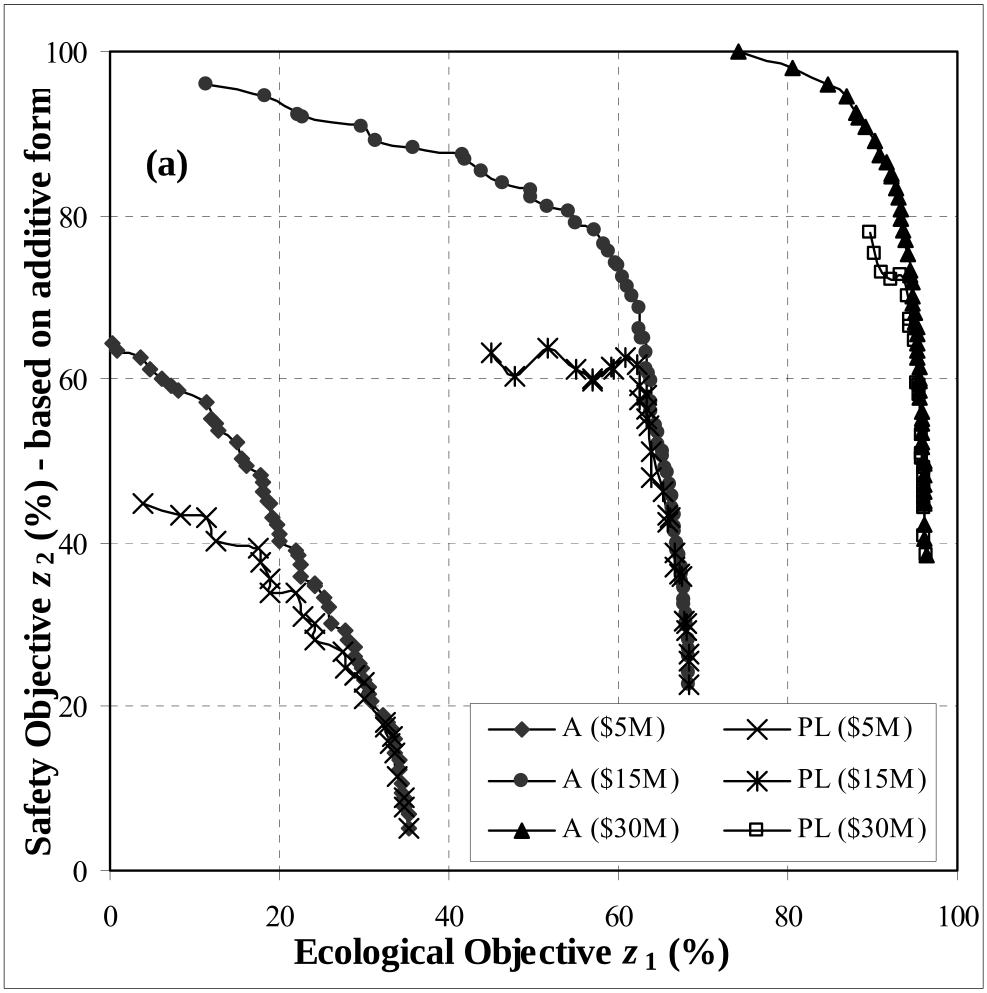

Fig. 6. Comparison of the additive and the Power Law formulations (Note: The resulting risk objective z_2 are shown for both the additive and the Power Law solutions; in the case of the additive solution, these z_2 values are reported directly from MILP simulations, but for the Power Law solution, the resulting z_2 shown here are calculated using the additive form. Detailed procedures see Zheng (2009))