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Confronting tipping points: Can multi-objective evolutionary algorithms discover pollution control tradeoffs given environmental thresholds?

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ABSTRACT

This study contributes a stochastic, multi-objective adaptation of the classic environmental economics Lake Problem as a computationally simple but mathematically challenging benchmarking problem. The Lake Problem considers a hypothetical town by a lake, which hopes to maximize its economic benefit without crossing a nonlinear, and potentially irreversible, pollution threshold. Optimization objectives are maximize economic benefit, minimize phosphorus in the lake, maximize the probability of avoiding the pollution threshold, and minimize the probability of drastic phosphorus loading reductions in a given year. Uncertainty is introduced through a stochastic natural phosphorus inflow. We performed comprehensive diagnostics using six algorithms: the Borg multi-objective evolutionary algorithm (MOEA), MOEA/D, epsilon-MOEA, the Non-dominated Sorting Genetic Algorithm II (NSGAII), epsilon-NSGAII, and Generalized Differential Evolution 3 (GDE3) to evaluate their controllability, reliability, efficiency, and effectiveness. Our results show only the self-adaptive search of the Borg MOEA was capable of performing well on this nontrivial benchmarking problem.

1. Introduction

Over the last decade there has been an increased focus on the risks posed by high consequence thresholds or “tipping point” responses across a range of coupled environmental and economic systems (Kwadijk et al., 2010; Walker et al., 2013; Lenton, 2013; Kriegler et al., 2009; Brock, 2006; Keller et al., 2004). Tipping points represent a unique and often challenging class of environmental management problems because they often pose severe nonlinearities, high levels of uncertainty, irreversible consequences, and stakeholder tensions related to conflicting values or objectives. Haimes and Hall (1977) provided one of the first explorations of these issues in the water resources planning and management literature. Their work strongly emphasizes the need for multi-objective analyses that are capable of capturing the sensitivity, stability, and irreversibility of candidate management actions. The core mathematical and decision support challenges that arise when managing environmental tipping points as eloquently framed by Haimes and Hall (1977) remain as grand challenges today (for example, see the discussions in the following reviews: Herman et al. (2015); Walker et al. (2013); Nicklow et al. (2010); Reed et al. (2013); Keller et al. (2008)). The difficulties posed by environmental threshold problems have motivated their use as technical benchmarks when evaluating alternative decision support frameworks (Singh et al., 2015; Lempert and Collins, 2007; Carpenter et al., 1999; Peterson et al., 2003; Kwadijk et al., 2010; Lenton, 2013; Brock, 2006; Hall et al., 2012). One of the most popular tipping point benchmark problems to emerge from the environmental decision-making literature is the Lake Problem (Carpenter et al., 1999; Peterson et al., 2003; Lempert and Collins, 2007). It has a rich conceptualization that allows for a wide range of challenging management and mathematical traits to be

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explored with relatively modest computational demands.

The classical Lake Problem considers a fictional town on a lake seeking to balance competing desires of maximizing its economic productivity resulting in phosphorus pollution and minimizing the negative impacts on the lake's water quality. The current study builds on a specific instance of the Lake Problem where the lake's water quality is strongly impacted by a potentially uncertain threshold that governs transitions between two stable states: (1) an oligotrophic state (in simple terms, mostly unpolluted) or (2) a eutrophic polluted state (Carpenter et al., 1999). The transition from an oligotrophic to a eutrophic state can be rapid once the concentration of phosphorus in a lake reaches a critical threshold. Furthermore, the Lake Problem's simple but challenging system dynamics provide a high degree of flexibility in defining the consequences of crossing the water quality threshold.

In the arguably least challenging situation, the Lake Problem water quality impacts are reversible, meaning that the lake can be restored to an unpolluted state through reductions in phosphorus loading alone. In a more complex situation, the lake can show a hysteresis response, increasing the negative consequences of crossing the threshold, where restoration to an unpolluted state requires drastic reductions in pollution input. The most challenging case of the Lake Problem is defined such that the lake is irreversible, where water quality cannot be restored by a reduction in phosphorus loading alone. Consequently, if the town is situated on an irreversible lake there is an increased concern of crossing the threshold as the lake would then become permanently eutrophic. The Lake Problem's representation of decision making given the potential for crossing an irreversible threshold has made the problem a useful proxy for a broad class of environmental management problems (Brozović and Schlenker, 2011; Carpenter et al., 1999; Lempert and Collins, 2007). Simultaneously, it is useful for methodological benchmarking given its ability to represent tipping points, nonlinearity, and system uncertainties (Carpenter et al., 1999; Singh et al., 2015; Lempert and Collins, 2007; Hadka et al., in press). Past analyses of the Lake Problem have typically approximated the decision making by the town as a single rational actor optimizing one weighted utility objective. This traditional normative economic formulation assumes an *a priori* preferential weighting between the town's economic benefits and the impacts of pollution (Carpenter et al., 1999; Lempert and Collins, 2007; Peterson et al., 2003).

More recently, Singh et al. (2015) analyzed a multi-objective extension of the Lake Problem. In their extension, Singh et al. (2015) broaden the formulation to represent and analyze the tradeoffs among diverse stakeholder objectives (or values) representing near term versus long term economic benefits, an environmental regulatory perspective seeking to maximize water quality, and a reliability-based engineering perspective that seeks to minimize the probability of tipping the lake into an irreversible eutrophic state. This work illustrates how framing the problem as a maximization of expected utility (MEU) alone can lead to myopia and increase the risks of crossing the threshold response (Carpenter et al., 1999; Peterson et al., 2003; Lempert and Collins, 2007).

Utility function formulations can prioritize economic benefits over other potential objectives, including environmental concerns. In systems confronting environmental thresholds, an *a priori* preferential weighting of economic benefits in utility functions may bias optimal policies to delay environmental management actions and increase the risks for an irreversible collapse in environmental quality (Admiraal et al., 2013; Peterson et al., 2003; Keller et al., 2004; McInerney et al., 2012). These prior studies explore the following concerns that emerge when using MEU to select environmental policies: (1) the MEU approach faces severe challenges in representing complex group or stakeholder preferences; (2) it is often difficult to understand the ecological and ethical ramifications of how MEU rankings value environmental systems; and (3) the MEU approach implicitly assumes that system dynamics and uncertainties are well characterized. Alternatively, Singh et al. (2015) illustrate the potential for multi-objective formulations to overcome the myopia of MEU formulations (Brill et al., 1990) by providing a far more diverse suite of management alternatives that explicitly compose the optimal trade-offs between economic and environmental objectives. This result reflects insights from a growing number of applications employing *a posteriori* multi-objective decision support, where decision makers explore key system tradeoffs before they have to express a preference for desired actions (Cohon and Marks, 1975; Coello Coello, 2007; Nicklow et al., 2010; Reed et al., 2013; Maier et al., 2014).

A core requirement of the *a posteriori* multi-objective approach to managing environmental tipping points is the availability of solution techniques that are able to effectively approximate complex multi-objective tradeoffs (or Pareto fronts). Examples ranging from local management of landscape nutrient pollution (Brozović and Schlenker, 2011; Carpenter et al., 1999; Lempert and Collins, 2007; Peterson et al., 2003) to the impacts of crossing global climate change thresholds (Keller et al., 2004; Kriegler et al., 2009; Kwadijk et al., 2010), all demonstrate a strong tension or conflict between a range of economic, environmental, and inter-generational objectives or values. More formally, the solutions that define the Pareto optimal set (Cohon and Marks, 1975; Pareto, 1896) for management applications can only be improved in one objective's performance by degrading their performance in one or more of the remaining objectives (i.e., the performance conflicts that yield tradeoffs). Plotting the Pareto optimal set of solutions in an application's objective space yields the Pareto front. Over the last 20 years, multi-objective evolutionary algorithms (MOEAs) have emerged as the dominant solution technique for supporting complex *a posteriori* multi-objective decision support (Coello Coello, 2007; Reed et al., 2013; Maier et al., 2014; Nicklow et al., 2010). Despite their rapidly growing popularity and broad application, Reed et al. (2013) have shown that stochastic many-objective (i.e., 3 to 10 objectives) risk-based planning applications with severe constraints can lead to search failures in a majority of currently available MOEAs.

This study builds off of the foundational MOEA benchmarking framework developed by Hadka and Reed (2012b) as well as the specific insights for environmental and water resources provided by Reed et al. (2013) to demonstrate the value of our proposed many-objective version of the Lake Problem as a highly challenging benchmarking application. The contributed version of the Lake Problem is a high dimensional real-valued control problem (i.e., 100 decision variables) with significant performance constraints, stochastic uncertainty in natural phosphorus loading, and an irreversible environmental threshold. The problem combines the complexities of managing nonlinear tipping points and high-dimensional stochastic multi-objective control optimization to yield a benchmarking application that can pose severe challenges to modern solution techniques (see the reviews by Castelletti et al. (2008); Reed et al. (2013); Walker et al. (2013)). Building on the recent quantitative MOEA benchmarking and review by Reed et al. (2013), the Lake Problem benchmark problem and diagnostic assessment contributed in this study: (1)