Uncertainty and Fishery Management in the North American Great Lakes: Lessons from Applications of Decision Analysis

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Abstract.—Many fishery management decisions continue to be guided by science only through "best guess" interpretation of assessment information and deterministic models of fisheries and food webs; until very recently this was true of nearly all fishery management in the Great Lakes. However, fishery management decisions can be improved by formally considering uncertainty when evaluating management options; practical tools for doing this have become increasingly available. Accounting for uncertainty is important because acting as though the best guess is true may be substantially suboptimal if this leads to poor performance for other, less likely, but still plausible "states of the world." For a variety of critical Great Lakes fishery management issues, including determining appropriate investments in sea lamprey *Petromyzon marinus* control, setting suitable levels of salmonine stocking, and establishing percid harvest policies, we have considered the importance of explicitly incorporating uncertainty. In each case, we worked closely with fishery managers to conduct a decision analysis of management options they identified, using contemporary statistical methods to formally assess uncertainty about key fishery parameters and stochastic simulation to compare management options. These decision analyses were used by fishery managers to develop policies that more objectively account for uncertainty and to garner support from stakeholders and policy makers. The approach shows considerable promise for future fishery management in the Great Lakes, but will face substantial challenges as managers seek to more effectively involve stakeholders throughout the process, foster the requisite technical expertise within their agencies, and communicate the results of highly technical analyses to both stakeholders and decision makers. Three important aspects of salmon Arctic-Yukon-Kuskokwim region management for which a decision analysis approach would be particularly valuable are (1) the evaluation of different options for assessment sampling of returning adult salmon, used to determine whether escapement targets are being met; (2) strategies for in-season management of salmon harvest; and (3) setting annual escapement goals for individual stocks.

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Introduction

Wise fishery management requires effective consideration of uncertainty as decisions are made (Walters 1986; Lane and Stephenson 1998). Even so, the types of uncertainty considered, and how uncertainty is used in the management process, can vary greatly. Contemporary stock assessment methods emphasize the derivation of statistically valid estimates of stock size and harvest, for which not only point estimates but also measures of uncertainty can be obtained (e.g., Quinn and Deriso 1999). This approach enables fishery managers to see a range of possible interpretations. In some cases, the uncertainty has been translated into a harvest range or interval of other management actions that are plausibly consistent with established policy. Unfortunately, the policy itself is often based on equilibrium calculations from a deterministic model with an assumption of perfect knowledge of system dynamics (see Quinn and Deriso 1999; Chapter 11). Usually managers recognize that such analyses ignore important aspects of real fisheries, and then take precautions for this uncertainty by adopting a "conservative" approach.

Here we argue for an alternative approach, whereby fishery policies are developed in the context of the critical uncertainties connecting management actions and outcomes of interest, whether those uncertainties are in stock assessments, or in system dynamics. Known as Decision Analysis, this approach is a well-established method of structured decision making drawn from business (Clemen and Reilly 2001). Formal quantitative decision analysis has been used for a growing number of fishery management issues worldwide (Butterworth et al. 1997; Sainsbury et al. 1997; Peters and Marmorek 2001; Punt et al. 2002). These decision analyses explicitly consider how various types of uncertainty affect the ranking of alternative management

actions in terms of their expected success at achieving management objectives. Because uncertainty in dynamic processes and in assessment affects how different management options perform relative to one another, the optimal choice can differ when one accounts for uncertainty. Specifically, failing to account for uncertainty may lead to decisions with a probability of undesirable outcomes high enough to be unacceptably risky from a public policy perspective.

In the North American Great Lakes, fishery management has been largely guided by science that has focused on the most likely consequence of management actions—that is, decisions generally have not considered uncertainty, except subjectively wherein some measure of caution has been introduced ad hoc. The three main management activities carried out by fishery management agencies around the Great Lakes are (1) sea lamprey *Petromyzon marinus* control; (2) stocking of fish; and (3) controls or regulations of harvest. Sea lamprey control decisions are governed by point estimates of sea lamprey populations in streams where lampricides are applied (Christie et al. 2003), or deterministic models of the forecasted effect of policy decisions (Schleen et al. 2003). Fish stocking rates are adjusted in an effort to ensure that predator demand does not exceed best estimates of prey fish production (Jones et al. 1993), in part based on deterministic models of bioenergetics, predator–prey interactions, and prey recruitment dynamics (e.g., Stewart and Ibarra 1991; Jones et al. 1993). Actual management decisions have integrated model-based inferences with concerns about uncertain dynamics, but in an ad hoc fashion.

Where allowable harvests are set (either for commercial fisheries or a combined recreational and commercial fishery), they have generally been based on a "fixed" target fishing mortality rate or fixed total mortality rate (where both sea lamprey and fishing are acknowledged as important temporally varying

mortality rates subject to management). Fixed target mortality rates have either been based on staying below levels of mortality that have produced population collapses in other systems (e.g., lake trout and lake whitefish; Healey 1978; TTWG 1984), or on standard reference points such as $F_{0.1}$ (Deriso 1987) which is used as a surrogate for F_{MSY}. (e.g., Lake Erie walleye—see case study 3 below).

In recent years, Great Lakes fishery managers have become interested in applying techniques for assessing the risk of management strategies and more formally accounting for that risk in their decisions. Two factors have contributed to this growing interest. First, Great Lakes fishery managers have noted the growing number of examples from marine fisheries of both applications of uncertainty-sensitive approaches to policy analysis (Sainsbury et al. 1997; Peterman et al. 1998), and cases where collapses of important fisheries have, in part, been attributed to inadequate attention to uncertainty (Walters and Maguire 1996). Second, recent experience reveals that the success of sea lamprey control (Jones et al. 2003), and salmonine stocking (Hansen and Holey 2002; Szalai 2003) can depend on highly uncertain recruitment. Similarly, Lake Erie fishery managers noted several years of poor walleye *Sander vitreus* recruitment during the 1990s that elevated concerns about harvest strategies. Increased interest led to the application of decision analysis to each issue, with the goal of providing managers with a more objective means of accounting for uncertainty when decisions are made. Our objectives for this paper are to describe our experiences with each of these applications of decision analysis, reflect on their consequences for management, and draw conclusions about the broader implications of our experience for fisheries management in other systems including the salmon fisheries of the Arctic-Yukon-Kuskokwim (AYK) region.

The applications of decision analysis described in this paper closely follow the meth-odology outlined by Peterman and Anderson (1999), as summarized in Table 1. Specifically, in each case we worked interactively with stakeholders, including decision makers, subject matter experts, managers, and, in one case, nongovernment stakeholders, to define the problem by identifying management objectives, options, and critical uncertainties. Through a series of analytical steps, we assessed the structure and magnitude of key uncertainties and developed a system model that allowed us to forecast the outcome of alternative management options while explicitly accounting for this uncertainty. The model was used to rank management options in terms of their performance at achieving management objectives; we used sensitivity analysis to assess whether our ranking conclusions were strongly influenced by our assumptions. Our process involved interactions with the stakeholders at the beginning (problem definition), middle (model development and refinement), and end (evaluation and sensitivity analysis) of the project, ensuring that they retained a sense of ownership of the analysis. This process mirrors the analytical-deliberative process advocated by the U.S. National Research Council Committee on Risk Characterization in their 1996 report (Stern and Fineburg 1996).

Case study 1: Sea Lamprey Control in the St. Marys River

The invasion of the parasitic sea lamprey and its devastating effects on Great Lakes fish stocks has been well documented (e.g., Smith and Tibbles 1980). Sea lamprey control in the Great Lakes has continued since the 1950s when the Great Lakes Fishery Commission (GLFC) was formed by treaty between Canada and the United States (Christie and Goddard 2003). Since the late 1950s sea lampreys have been controlled by killing larval sea lamprey with TFM, the liquid lampricide 4-ni-

TABLE 1. The steps to a typical decision analysis (after Peterman and Anderson 1999).

Step	Task
1	Define management options
2	Define management objectives
3	Identify critical uncertainties (alternative states of nature)
4	Assign probabilities to alternative states of nature
5	Develop a model to forecast outcomes of management options, in terms of performance meeting management objectives
6	Rank management options in terms of their performance
7	Conduct a sensitivity analysis

tro-3-(trifluoromethyl) phenol, before they become parasites and migrate to the lakes to feed on large-bodied fishes, such as lake trout *Salvelinus namaycush*. This chemical control program reduced sea lamprey populations to 10% of precontrol levels (e.g., Heinrich et al. 2003; Lavis et al. 2003a). Other controls are being used to a lesser extent, including low-head barrier dams to prevent sea lamprey access to spawning habitats (Lavis et al. 2003b), traps to remove migrating adult sea lampreys as they enter rivers to spawn (Mullett et al. 2003), and the release of sterilized male sea lampreys into spawning habitats to compete with unsterilized males (Twohey et al. 2003). The GLFC has stated that they seek to increase the use of these alternative methods in the future, and thereby reduce reliance on chemical control (GLFC 2001).

The St. Marys River connects Lake Superior to Lake Huron (Figure 1), and unlike other Great Lakes streams that contain substantial larval sea lamprey populations, has too large a flow to treat with TFM at a reasonable cost. Increasing recruitment of sea lampreys from the St. Marys River led to a large increase in the abundance of sea lampreys in Lake Huron during the 1990s. Consequent-ly, the GLFC sponsored the development of a strategy for integrated pest control of sea lampreys in this large river. In 1997, the strategy was adopted and included three tactics: use of an alternative chemical method (Bayluscide[1]) that enabled selective application of lampricide to 981 ha of larval sea lamprey habitat, deployment of traps to capture adult sea lampreys, and releases of chemically sterilized male sea lampreys into spawning areas (Schleen et al. 2003). Of these three tactics, the chemical control component was by far the most expensive.

The decision to adopt this three-pronged strategy was based on deterministic models presented to the GLFC that forecasted the effects of various management options on Lake Huron sea lamprey and lake trout populations along with a cost–benefit analysis of those management options (Schleen et al. 2003). However, the strategy was not designed as, nor was intended to be, a long-term strategy;

[1]Bayluscide is the commercial name for 2',5-dichloro-4'-nitrosalicylanilide, also known as niclosamide. Development of a granular formulation enabled the use of this lampricide for application to specific patches of larval habitat rather than to the entire river, as is required for conventional lampricide applications.
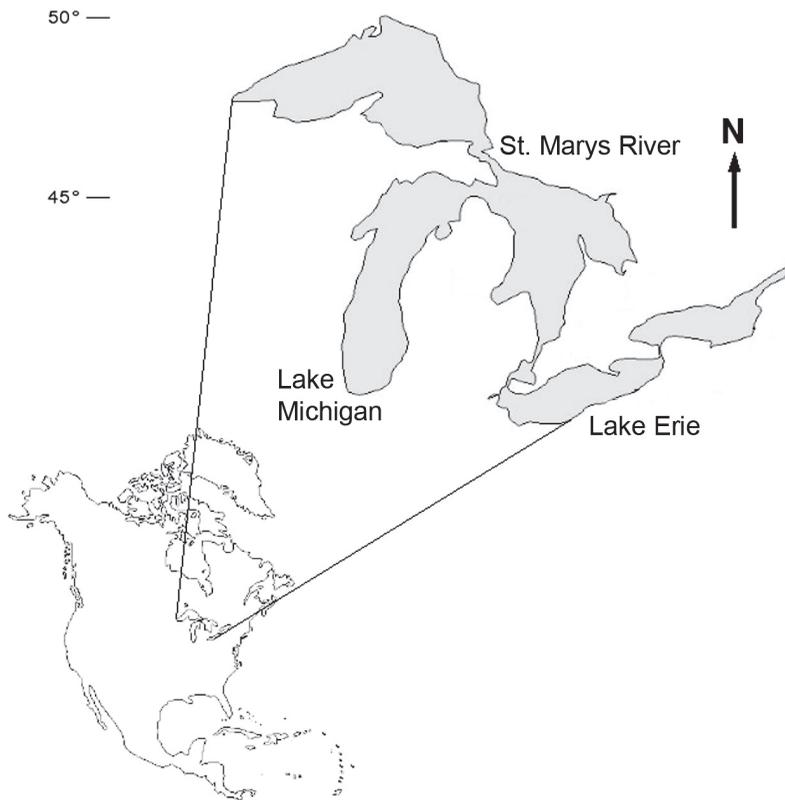
FIGURE 1. Map of the North American Great Lakes, showing the locations of the three case studies discussed in the paper: St. Marys River (sea lamprey control); Lake Michigan (salmonine stocking); and Lake Erie (walleye exploitation).

its objective was to substantially reduce the St. Marys River sea lamprey population in the short term. This control program was judged necessary in 1997 because of perceived large, but un-quantified, uncertainty about how effective the less costly control actions (trapping and sterile male releases) would be if implemented alone. However, an expensive long-term control strategy that relied heavily on chemical methods would re-direct limited funds from controlling other sea lamprey-producing rivers in the Great Lakes basin. Consequently, the GLFC was challenged with developing a feasible long-term strategy to maintain cost-effective control in the St. Marys River. Recognizing the need for a

long-term approach that better reflected uncertainty, the GLFC invited us to apply decision analysis. Our analysis began in 1999 and continued for 3 years. Punctuated by three workshops involving scientists, managers, and decision makers, we developed and evaluated the decision analysis, and then presented and discussed our findings with the GLFC on four occasions during 2001–2002.

At the initial workshop, we identified levels of each of the three management tactics (trapping, sterile male release, and chemical control) that were to be considered. The performance measures were to be the forecasted future abundance of parasitic sea lampreys in Lake Huron, the frequency of outcomes with

parasitic sea lamprey abundance that exceeded a target level, and the net economic benefit of the option[2] (Table 2). The key uncertainties to be included were demographic processes (particularly recruitment dynamics) in the sea lamprey population, and implementation uncertainty for each control tactic (Table 2).

The first workshop was followed by a thorough investigation of these sources of uncertainty, and the development of a stochastic model to forecast future Lake Huron parasitic sea lamprey abundance, conditional on a particular set of management tactics being employed (Haeseker 2001). The demographic analysis was completed using an inverse population modeling approach similar to statistical catch-at-age analysis (Fournier and Archibald 1982) allowing us to quantify the uncertainty associated with sea lamprey population dynamics (Haeseker et al. 2003). Implementation uncertainty for trapping and sterile male releases was quantified by examining empirical data on past inter-annual variation of each tactic's effectiveness. Implementation uncertainty for chemical control was quantified by examining inter-annual variation in the distribution of larval sea lampreys in the area targeted for chemical control (Haeseker 2001), and assuming that future decisions about where to direct future chemical treatment would be based on historical larval distribution patterns derived from a single, exhaustive survey conducted during the mid-1990s—annual distributional surveys for larval sea lampreys in the St. Marys River would be prohibitively expensive.

At a second workshop attended primarily by technical experts, both the uncertainty analysis and the forecasting model were presented and criticized. The workshop led to further refinements of the model.

At the third workshop, and at several follow-on meetings with sea lamprey program staff, we developed a specific set of management options to consider (Table 3), and used the forecasting model to compare their expected performance at achieving management objectives. Our analysis revealed that the highest ranking management options included increased trapping and sterile male releases, and moderate amounts of chemical control (Table 3, Option 8). Rankings were similar for all three performance measures. A sensitivity analysis revealed that these rankings were also robust to two key assumptions, one about sources of sea lamprey to Lake Huron other than the St. Marys River, and a second about the economic benefit of reduced sea lamprey abundance. During winter 2002/2003, the GLFC adopted a control strategy similar to our highest ranking option; this strategy has continued since 2003.

Before our decision analysis, key GLFC commissioners and staff, as well as the lead author of this paper, were skeptical about the potential of trapping and sterile male releases as control options, believing that these methods would be rendered ineffective by large density-independent recruitment variation (Jones et al. 2003). By explicitly accounting for uncertainty, especially concerning sea lamprey demographics, we demonstrated that enhancing these methods had a high probability of contributing substantially to future suppression of sea lampreys in the St. Marys River. Without our modeling results, the GLFC likely would not have funded enhanced trapping and sterile male releases, principally because of a qualitative impression of the risks (i.e., likelihood of failure) associated with these methods.

In this decision analysis, accounting for uncertainty did not lead to a different conclusion. When we ran simulations with sea lamprey demographic uncertainty removed, i.e., using the maximum posterior density estimates of the demographic parameters

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[2]Measured as the difference between the estimated benefit of reducing sea lamprey abundance (based on an implied value calculation; Lupi et al. 2003) and the annualized cost of the management option, discounted over a 27-year time horizon.

TABLE 2. Management options, management objectives and critical uncertainties selected for consideration by the participants in the St. Marys River sea lamprey control decision analysis.

Management options	Management objectives	Uncertainties
Trap adult sea lampreys—effectiveness levels of 40% and 70%	Minimizing the median forecasted abundance of parasitic sea lampreys in Lake Huron by 2012 (short term) and 2030 (long term)	Sea lamprey demographics: recruitment, larval survival rates, proportion metamorphosing-at-age
Release sterile male adult sea lamprey—sterile to fertile male ratios of 4:1 and 7:1	Maximizing the probability of achieving parasitic sea lamprey abundance below 114,000 in Lake Huron in 2012	Efficacy of Bayluscide applications, based on estimated uncertainty about future spatial distributions of sea lamprey larvae
Apply granular Bayluscide to high density areas—108, 216 and 812 ha	Maximizing the net economic benefit of the management option (see footnote to text)	Efficacy of trapping and sterile male releases, based on past variation in the efficacy of these methods

TABLE 3. Management options considered in the St. Marys River sea lamprey decision analysis, and their performance at achieving management objectives. Rates are expressed as proportions. Trapping rate is the proportion of the spawning run captured by traps; SMRT ratio is the ratio of sterile to fertile males in the spawning population. The target kill rate refers to the expected kill rate if the true larval population distribution was identical to that observed during the 1993–1996 survey, with the area of habitat treated in parentheses.

| Option | Target rates | | | Sea lamprey abundance | | Net benefit |
	Trapping	SMRT	Kill (ha)	2030 Median	% < 114 000 in 2012	Median ($millions)
1	0	0	0 (0)	388,000	18.4	7.9
2	0.4	0	0 (0)	321,000	23.3	13.8
3	0.7	0	0 (0)	189,000	35.0	26.1
4	0.4	4	0 (0)	130,000	41.9	28.5
5	0.7	7	0 (0)	49,000	61.4	41.0
6	0	0	0.15 (108)	348,000	21.6	13.0
7	0.4	4	0.15 (108)	112,000	47.2	31.5
8	0.7	7	0.15 (108)	46,000	65.9	42.1
9	0.4	4	0.25 (260)	96,000	52.0	34.1
10	0.4	4	0.34 (812)	81,000	59.4	29.3

and assuming zero process error in the stock–recruitment relationship, the rank order of management options did not change. Instead, the decision analysis gave decision makers more confidence in the merits of what they had previously judged to be a risky decision, despite the results of a deterministic analysis.

The GLFC also decided to support an ongoing larval assessment program in the St. Marys River using an efficient adaptive sampling strategy. This program will yield new data on sea lamprey recruitment dynamics that can be used to reduce uncertainty about the stock–recruitment relationship and thus potentially contribute to better-informed decisions in the future. With good spatial distribution information, implementation uncertainty can be reduced for future chemical treatments. Most importantly, it facilitates the use of a feedback control policy wherein future chemical treatments are triggered by observations of sea lamprey densities that are sufficient to justify the expense. Our previous analyses assumed a fixed treatment schedule given the absence of such a monitoring program. Further decision analysis modeling will evaluate these feedback policies.

Case Study 2: Salmonine Stocking in Lake Michigan

Stocking of hatchery-reared salmonines is one of the primary fishery management tools available on Lake Michigan. Salmon and trout are annually stocked in large numbers to provide recreational fishing opportunities, restore native lake trout populations, and reduce the abundance of nonnative alewife *Alosa pseudoharengus*. High abundance of alewife is undesirable because this exotic species preys on larvae of native Lake Michigan fishes and at high densities experiences mass mortality (die-offs) which foul beaches that are of high recreational value.

Since the advent of major salmonine stocking programs in the mid-1960s, hundreds of millions of Chinook salmon *Oncorhynchus tschawytscha*, lake trout, rainbow trout *O. mykiss*, brown trout Salmo trutta, and coho salmon *O. kisutch* have been stocked into Lake Michigan (Kocik and Jones 1999; Hansen and Holey 2002). A tradeoff exists, however, between (a) stocking too few predator fish, allowing alewife abundance to rise to undesirable levels and foregoing potential harvest of predators; and (b) stocking too many predators, thereby exceeding the capacity of the alewife population to support the consequent predation pressure (Stewart et al. 1981). Indeed, a dramatic rise in Chinook salmon mortality rates (with commensurate loss of harvest) during the late 1980s in Lake Michigan is widely viewed as having resulted from too many stocked predators (Holey et al. 1998; Hansen and Holey 2002). Therefore, a critical question faced by Lake Michigan fishery managers is "how many salmon and trout should be stocked each year into Lake Michigan?" Again, we were invited by Lake Michigan fishery managers to apply decision analysis to this problem.

Our decision analysis had four stages. First, we met with experts, managers and nongovernment stakeholders (recreational and commercial fishers) in March 2000 to discuss and agree upon management objectives, options, and critical uncertainties (Table 4). Second, we used historical data from Lake Michigan on salmonine harvests, diet, growth rates, and prey fish abundance to estimate parameters of a salmonine-prey fish population model and the uncertainty associated with the parameter estimates (Szalai 2003). Third, we developed a decision model to forecast the consequences—for alewife abundance, Chinook salmon growth, and Chinook salmon harvests—of alternative stocking strategies. Finally, we met again with experts, managers and stakeholders to demonstrate and discuss the model.

TABLE 4. Management options, management objectives and critical uncertainties selected for consideration by the participants in the Lake Michigan salmonine stocking decision analysis.

Management options	
Category	Details
Adjust annual stocking rates of salmonines	Option 1 – Current stocking levels
	Option 2 – 50% reduction in Chinook stocking
	Option 3 – state-dependent policy[a]

Management objectives	
Category	Performance measures
Maintain acceptable catch rates for salmonines	Median forecasted average annual Chinook harvest
	Proportion of outcomes with Chinook harvest < 100,000/yr
Minimize risks of elevated Chinook salmon mortality	Median forecasted age-3 Chinook salmon weight
	Proportion of outcomes with age-3 weight < 6 kg
Maintain predator-prey balance	Median forecasted alewife biomass
	Proportion of outcomes with alewife biomass < 500 kt

Critical uncertainties	
Category	Rationale
Alewife recruitment dynamics	How much predation pressure can the alewife population support?
Chinook salmon feeding effectiveness	How successful are Chinook salmon at finding prey when the prey are relatively scarce?
Chinook salmon growth-survival linkages	How strongly coupled is Chinook salmon growth to natural mortality rates?

[a]Changes to stocking are triggered by forecasted changes in Chinook salmon weight at age 3 in the fall: stocking of all species is reduced 50% if fall weight falls below 7 kg and restored to current levels if fall weight increases above 8 kg.

The methods for quantifying uncertainties in the parameters of the forecasting model are described in detail in Szalai (2003). Briefly, we developed an estimation model similar to statistical catch-at-age models to reconstruct the historical dynamics of Lake Michigan prey fish (alewife, bloater *Coregonus hoyi*, and rainbow smelt *Osmerus mordax*) populations, but including salmonine predators rather than fishing as additional mortality. By fitting the model to available data, we estimated prey fish abundance and recruitment from 1962 to 1999, as well as the effective search rate of Chinook salmon (i.e., success of Chinook salmon at feeding when prey fish became relatively scarce). This analysis used as inputs estimates of the number of predator fish obtained from separate age-structured assessments, which played a role here similar to that of fishing effort in many traditional assessment models. We used these results to estimate the relationship between average recruitment and spawning stock size, as well as the variability about this relationship, for alewife, the key prey species in the system.

In addition, we used estimates of Chinook salmon mortality rates and size-at-age during 1985–1997 (from just prior to the sharp rise in mortality through the period of Chinook salmon recovery) to estimate a model of the dependence of Chinook salmon mortality on growth. We hypothesized that reduced growth results in an increased probability of elevated mortality, potentially due to disease. We hypothesized further that when elevated mortality occurs, it would persist for a period of time even after growth rates recover (i.e., there is a lag between improved growth rates and reduced mortality rates). This model is consistent with observations, but great uncertainty exists because evidence supporting this relationship comes from a single multi-year episode.

To evaluate stocking policy alternatives, we developed a stochastic model, based on the assessment models described above, that forecasted the alewife abundance and Chinook salmon abundance and size resulting from a specific policy. The model also included all other major stocked salmonine species as predators, and bloater and rainbow smelt as prey. All predators were modeled as dynamic and age-structured. Recruitment of predators in the model was treated as a known input because they derive from hatchery releases and measured production in the wild. For predators other than Chinook salmon, natural mortality was assumed constant and the effective search rate was set at a higher rate the for Chinook salmon. Growth rates of the other predators did not vary in the same manner as for Chinook salmon during the historical period, which suggests that their success at searching for prey was less affected by variations in alewife abundance, indicative of a higher search rate. For computational purposes, size at age for other predators was fixed rather than calculated based on modeled consumption. Prey species other than alewife were not modeled dynamically. Instead they were included as having a constant abundance at age. In this modeling effort we put more effort into incorporating details for the models of Chinook salmon and alewife both because of greater availability of information and because we believed that these two species play a dominant role in the system. We included other predators in a dynamic fashion to retain the ability to evaluate policies where the stocking of those species was changed. One of the two alternative prey species was benthic and the other was pelagic, and their inclusion should be viewed as an approach to incorporating alternative prey for salmonines when alewife became scarce.

We compared stocking policies by looking, for each performance indicator, at the distribution of outcomes, the median outcome, and the proportion of outcomes that exceeded or fell below a threshold value deemed to be undesirable. A wide range of outcomes were forecasted for each policy. For continued

stocking at current levels, we forecasted average annual Chinook salmon harvests ranging from 6,500–360,000 fish per year (Figure 2). For this policy, forecasted average harvests less than 100,000 fish per year were relatively common (29.7%, Table 5), with the most common result lying between 50,000 and 75,000 fish harvested per year (Figure 2, solid bars). Policies with fixed, but lower stocking rates resulted in poorer performance for harvest and alewife indicators, but better performance for Chinook weight (e.g., Table 5, "Reduce Chinook 50%"). In contrast, a state-dependent, or feedback policy in which stocking of all salmonines was reduced by 50% when age-3 Chinook weights measured in the fall declined below 7 kg (and restored to current levels when weight recovers to 8 kg) resulted in a substantially lower proportion of outcomes with harvests below 100,000 fish per year (15.7%, Table 5, "State

dependent"), although the range of possible future harvests was only slightly narrower (18,000–315,000 fish per year), and the alewife biomass performance indicators were worse than for other policies.

This policy analysis suggested two important consequences for decision makers seeking an appropriate policy for salmonine stocking. First, our results suggested that feedback policies, where stocking levels are dynamically adjusted in response to evidence of a deteriorating situation, substantially reduced the risk of poor outcomes with respect to Chinook salmon harvest and growth. Second, the uncertainties included in the forecasting model, particularly with respect to alewife recruitment, gave rise to a wide range of possible outcomes from a single policy, regardless of which policy was chosen. We concluded that all feasible strategies still admitted a substantial possibility of undesirable
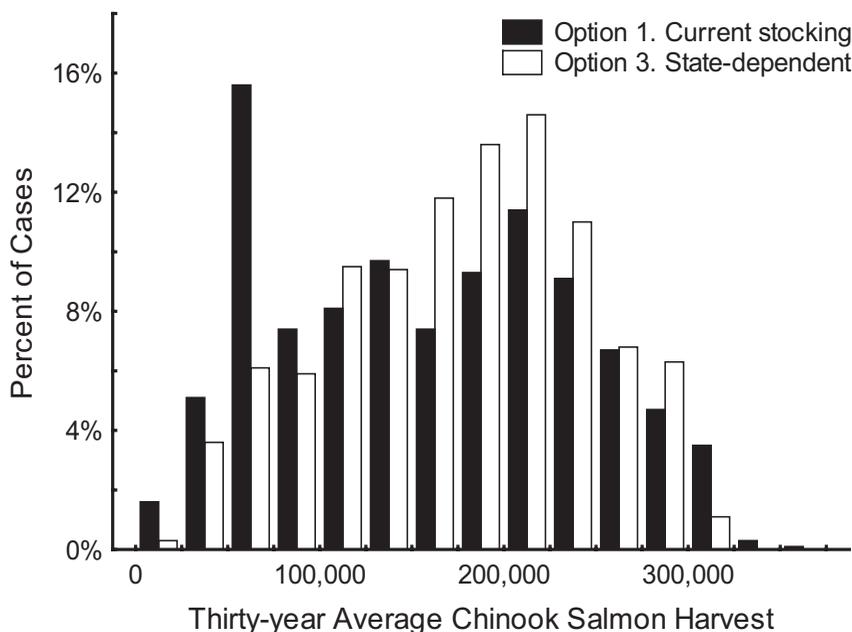

FIGURE 2. A comparison of the distribution of forecasted Chinook salmon *Oncorhynchus tshawytscha* harvests for two contrasting stocking policies. Shaded bars are for a policy representing continued stocking at current (2005) levels; Open bars represent a state-dependent policy with 50% reductions in stocking of all species when forecasted Chinook salmon age-3 weight falls below 7 kg, and increases in stocking to current levels if age-3 weight subsequently rises above 8 kg.

TABLE 5. Decision model outputs that summarize key performance measures for three Lake Michigan stocking policies.

Policy	Median Chinook harvest (numbers)	Proportion of harvests < 100,000	Median Chinook weight (kg)	Proportion of weights < 6 kg	Median alewife biomass ($\times 10^3$ kg)	Proportion of biomasses > 500,000 MT
Current stocking	160,000	29.7	7.0	47.6	417,000	47.8
Reduce Chinook	126,000	35.4	9.9	41.2	667,000	53.6
State-dependent	182,000	15.7	11.6	33.9	870,000	59.5

consequences stemming from future Chinook salmon and alewife population trajectories. As a result, flexibility and careful monitoring will be essential to good management of this fishery.

During 2005, Lake Michigan fishery managers held public meetings with stakeholder groups around the lake to discuss options for future management of the stocking program. At these meetings agency biologists presented data on recent trends in several indicators of the performance of the salmonine fishery (e.g., salmonine catch rates and growth rates, alewife abundance indices, prevalence of bacterial kidney disease in Chinook salmon). These data sets generally indicated moderately elevated stress levels in Chinook salmon, including recent declines in growth rates of Chinook salmon. These observations, together with our decision analysis findings supporting a state-dependent stocking strategy (also presented at these meetings), enabled the Lake Michigan fishery managers to obtain public support for a reduction in Chinook salmon stocking rates. Stocking rates were reduced by 25% in 2006. Although the managers have not formally adopted a state-dependent stocking policy, it is expected that stocking rates will remain at this lower level until evidence is seen of good growth and abundant forage for Chinook salmon.

Case Study 3: Walleye Harvest Management in Lake Erie

Together with yellow perch *Perca flavescens*, walleye contribute to important commercial and recreational fisheries in Lake Erie. Walleye have the highest landed value (>$10 million CAD) of any Great Lakes commercial species in Canada, and are targeted by about 5 million angler-hours per year of recreational effort, primarily in Ohio and Michigan waters of Lake Erie. Before 2001, Lake Erie fishery managers used a fixed har-

vest rate ($F_{0.1}$ – Deriso 1987) policy to determine allowable harvests for walleye, based on the results of their stock assessments. However, even when this $F_{0.1}$ policy was in place fishing mortality (F) changed from year to year reflecting changes in stock assessments and methods for determining $F_{0.1}$, and how uncertainty in stock assessment results was translated into the actual allowable harvest (LEWTG 2001). From the late 1970s to 2003, the Lake Erie walleye population experienced strong year classes only in 1984 and 1988. As a consequence, walleye yields declined steadily from 1995 to 2000 and Lake Erie fishery managers became concerned about risks of overfishing. In 2000, the $F_{0.1}$ policy was dropped and a fixed conservative harvest level was chosen that was projected to allow the stock to increase, while the issue of an appropriate long-term harvest policy was reviewed (LEWTG 2004). In 2002, the managers asked us to work with them to develop a decision analysis tool to inform future harvest policy for this fishery.

Beginning with a general workshop to explain decision analysis in fall 2002, we convened several meetings with fishery managers and biologists to guide development of a model to evaluate harvest policy options for Lake Erie walleye. Historically, the Lake Erie Committee—the multi-agency committee that collectively guides fishery management on Lake Erie—had used the results of an annual stock assessment to set total allowable harvests for both commercial and recreational fisheries. The stock assessments employed a statistical catch-at-age model to estimate stock size and recent harvest rates, but managers relied only on point estimates to determine harvest rates. Our decision analysis model was structurally similar to the retrospective stock assessment model, but with explicit consideration of uncertainty regarding walleye demographics. We considered a range of policy options including both fixed and variable harvest rates. The

principal management objective identified by Lake Erie fishery managers was to maintain adult walleye abundance above a level that would provide for high quality commercial and recreational fisheries: 25 million fish that were age 2 and older. In addition to assessing average performance, managers also wished to evaluate policy performance based on the frequency of outcomes wherein abundance failed to meet the 25 million fish target, and the duration of periods when abundance fell below the target level.

Early in the analysis, Lake Erie fishery managers and biologists agreed upon a set of critical uncertainties that the decision model should consider. First, they wished to determine how harvest policies were affected by uncertainty in the parameters of the statistical catch-at-age model, including initial population estimates, fishery catchability and age-specific vulnerability to the fishing gears, and natural mortality rates. Second, they wanted to include uncertainty in the stock–recruitment relationship for walleye in the decision model. Third, they were interested in uncertainty surrounding the relationship between walleye abundance and recreational fishing effort. We made structural assumptions about both the stock–recruitment model (Ricker) and the recreational effort—abundance relationship (linear), and evaluated uncertainty via the distribution of parameters for these relationships. We used the existing statistical catch-at-age model to estimate parameters for each of these relationships, and then employed Monte Carlo Markov Chain methods to sample from the joint posterior probability distribution of the complete set of parameters, and thereby quantify the joint uncertainty in all the parameters that we explicitly considered.

The decision model forecasted future abundance of walleye conditional on a harvest policy for both commercial and recreational fisheries for a fifty-year time horizon. To account for parameter uncertainty, a single policy simulation was repeated 1,000 times, each time randomly selecting a set of parameters from the sample of the joint posterior distribution. Model outputs were then summarized as mean and median walleye abundances and harvests, proportions of simulation-years with abundance below 25 million age 2 and older fish, and a frequency distribution of durations of periods wherein abundance fell below 25 million fish.

In the final workshop managers defined a general state-dependent harvest policy to consider, wherein the commercial fishing mortality rate would be set at a constant low rate when population abundance was below 15 million fish (age-2 and older) and a constant high rate when population abundance exceeded 40 million fish, and increased with abundance in a piece-wise linear fashion for abundances between 15 and 40 million fish, with a change in slope at 20 million fish (Figure 3). We used the decision model to evaluate the performance of this policy, scaled upward and downward proportionally across all stock sizes (Figure 3), and compared its performance to a range of fixed harvest rate policies. Because recreational fishing effort has historically decreased when walleye abundance has been low, and jurisdictions where recreational fisheries dominated have generally not taken their full quota allocation, the policy adjustments to fishing mortality were only applied to the commercial fishery.

Comparisons between state-dependent and fixed fishing mortality rate policies are difficult, because the fishing mortality rates for the former, by definition, are not constant. For similar median fishing mortality rates over 1,000 simulations the two types of policies produced similar median total harvests (Figure 4), while the risk of adult abundance falling below the 25 million fish target was slightly greater for the fixed fishing mortality rate policy. In view of these findings, and because of a desire to have a policy that lowered fishing rates when abundance was low,
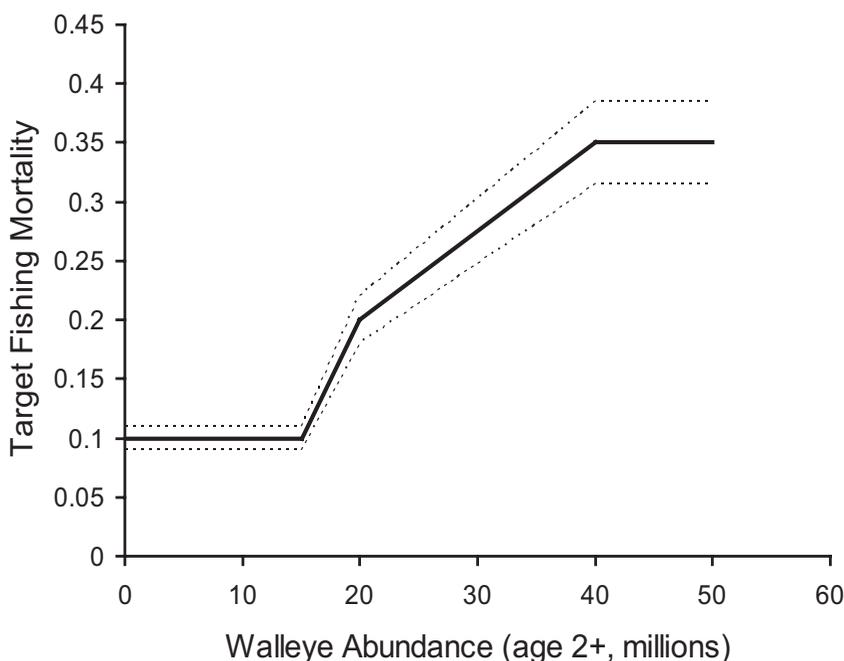
Jones and Bence

FIGURE 3. State-dependent harvest policies for the Lake Erie walleye *Sander vitreus* fishery. The solid line represents the policy adopted by Lake Erie fishery managers in 2005. Alternative state-dependent harvest policies increased or decreased fishing mortality rates by the same percentage at all population levels, and the dashed lines correspond to examples of 10% increases and decreases in the target fishing mortality rates from the adopted policy.

the Lake Erie fishery managers adopted a state-dependent harvest policy in 2005. They chose a policy that maintained fishing mortality rates below those that our analysis suggested would result in the highest expected yields, because at high harvest rates the risk of periods of poor fishing due to low population sizes increased substantially.

The harvest policy implemented by Lake Erie fishery managers in 2005 resulted in commercial quotas in 2005 and 2006 that did not differ much from what would likely have been imposed based on their past procedures for setting harvest quotas. The 2003 year-class of walleye in Lake Erie was the largest on record since stock assessments began in 1978; this year-class recruited to the fishery in 2005, allowing substantially larger quotas than had been permitted for several prior years. Likely, managers would have increased

quotas based on the observed strength of this year-class even in the absence of an explicit state-dependent harvest policy.

The decision analysis facilitated two important changes to the process for managing walleye exploitation in Lake Erie. First, the explicit consideration of risk in the decision model allowed managers to more objectively justify a policy perceived by the stakeholders as conservative. The analysis suggested that higher commercial fishing mortality rates would actually lead to higher sustained yields, on average, but it also showed that large, unpredictable variation in walleye recruitment, well known to biologists and fishers alike, can frequently lead to declines in population size below levels associated with good fishing conditions, at these same higher fishing mortality rates. Second, the analysis motivated the development of a general
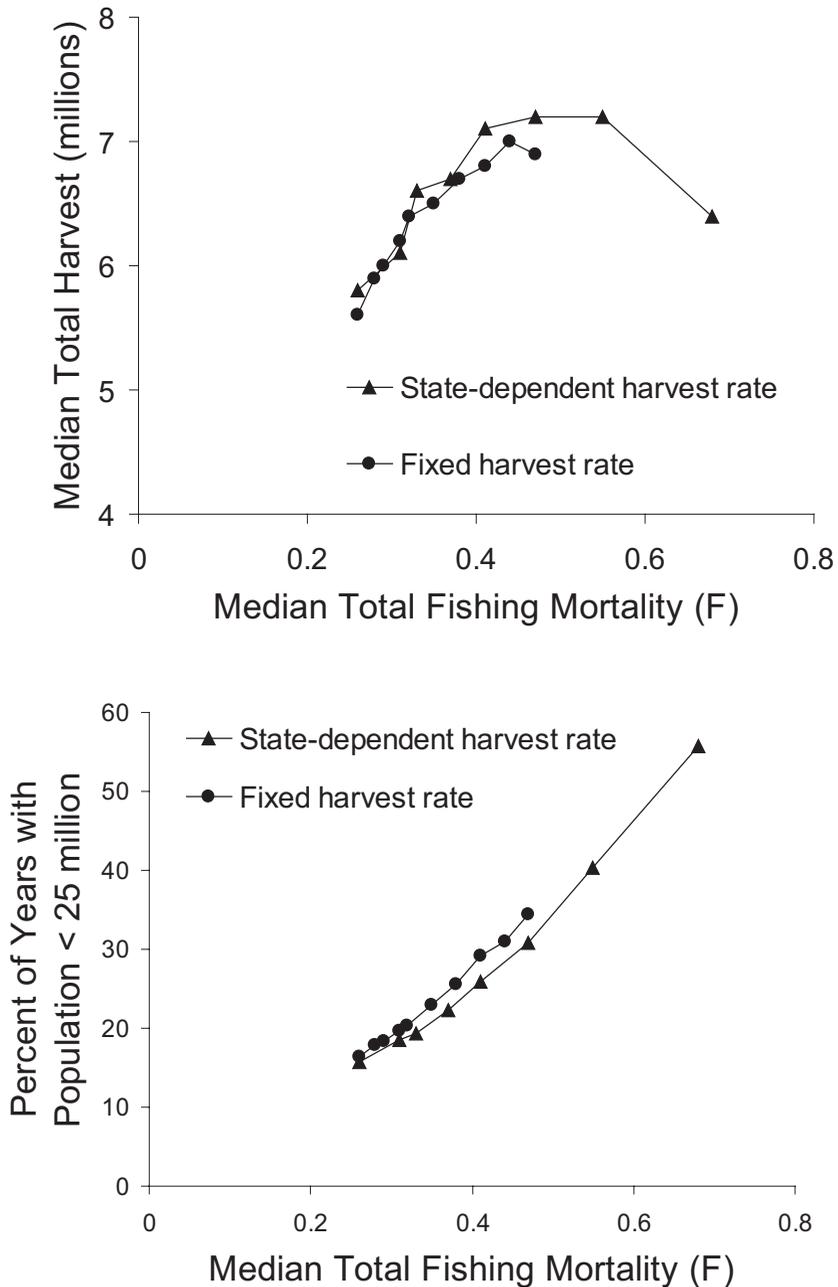
FIGURE 4. Top panel: Forecasted median walleye *Sander vitreus* harvests in the commercial and recreational fisheries, averaged over a 50-year simulation time horizon, for harvest policies with a range of fixed and state-dependent fishing mortality rates. Bottom panel: Forecasted percentages of simulation years wherein the adult walleye population fell below 25 million fish. The fishing mortality rate for each policy was calculated as the median value of *F* for commercial and recreational fisheries combined over 1,000 simulations of the policy.

rule for setting commercial fishing mortality rates, eliminating the need to rationalize a new quota each year. Prior to 2001, this fishery was nominally managed by a constant fishing mortality rate policy; however, the reality was that managers responded in an ad hoc fashion to changes in walleye abundance in an attempt to avoid low populations. The policy adopted in 2005 was developed based on this same objective and can be applied to any future fishery state, at least until a decision is made to update the walleye population model used to evaluate this policy.

Discussion

Great Lakes fishery managers have begun to embrace formal consideration of uncertainty as an important part of their decision-making process. In each case study described above, managers were quite receptive to the use of decision analysis, and in the Lake Erie case, managers actually initiated the process. Decision analysis and other uncertainty-sensitive decision-making approaches are being used or actively discussed for several other Great Lakes fishery issues. These include development of harvest policies for yellow perch in Lake Michigan (Irwin et al. in press), evaluation of alternative methods of larval sea lamprey assessment for determination of target streams for chemical control, and the use of real options analysis (Fenichel et al. 2008) to assist decisions about deliberately translocating fish species among the five Great Lakes.

Decision analysis is often advocated because explicitly accounting for uncertainty may suggest a different optimal decision than would result from a deterministic assessment of the choices available to managers. This outcome did not occur for any of the three case studies described herein. The same two options ranked highest for the St. Marys River decision analysis when we used

a deterministic model. We did not explicitly evaluate stocking strategies for Lake Michigan using a deterministic model, but other lines of evidence from fishery assessments also had led managers to advocate a reduction in Chinook stocking rates until salmon growth rates stabilized or began to increase (James Dexter, Michigan Department of Natural Resources and Chair, Lake Michigan Committee, personal communication). In Lake Erie, fishery managers likely would have allowed higher fishing mortality due to the strength of the 2003 year-class, whether or not we had conducted the decision analysis. In the case of sea lamprey management our analysis may have facilitated a decision that differed from that which would have occurred without the analysis, but only because of an overly pessimistic view of the uncertain potential of the nonchemical alternatives. In the other two cases, the decision analysis did not appear to significantly change the subsequent decisions.

What, then, has been the benefit to fishery managers of these decision analyses, and why is there continued interest in the use of this approach? We suggest three reasons explain why Great Lakes fishery managers consider decision analysis a useful tool. First, in each case the decision analysis provided a formal and transparent methodology for rationalizing and documenting the decisions that were ultimately made. Managers are frequently criticized for making decisions in an opaque fashion; stakeholders challenge the rationale for the decisions, and are left dissatisfied by the answers they get (e.g., "we feel we need to reduce stocking rates because the risks of an alewife population collapse are too great"). The decision analysis process can involve stakeholders directly, as in the Lake Michigan stocking decision analysis. Further, decision analysis requires clear, explicit statements of management objectives and options, and the process for evaluating management options involves a formal mod-

el wherein the performance of the different options can be deduced objectively from the set of assumptions and hypotheses that comprise the model. The model itself may be so complicated that understanding its behavior poses a large challenge, particularly to nontechnical stakeholder groups (and this remains a serious obstacle for the application of decision analysis to public policy), but it is nevertheless possible to document the basis for conclusions reached. A more transparent decision-making process builds trust between stakeholders and decision makers; our impression is that a lack of trust is a primary reason why so many fishery management decisions are controversial, both in the Great Lakes region and elsewhere.

Second, in all three cases the decision analysis suggested that state-dependent policies, wherein changes to management are triggered by observations of changes in the state of the system, are likely to perform as well, if not better than, nonfeedback policies. Numerous comparisons have been made of fixed-rate and feedback policies for exploited fisheries, and in many cases feedback policies have compared favorably to other alternatives, especially when the state of the system is observed with relatively low error (Deroba and Bence, in press). In the Great Lakes, however, feedback polices have generally not been used explicitly for harvest, stocking, or sea lamprey control (but see Krueger and Dehring 1986). Many, if not most, fisheries have experienced changes to management strategies as the system changes, but such changes tend to be reactions to system dynamics, not implementation of prescribed strategies according to a plan developed *a priori*. An example of this approach would be the Lake Erie walleye fishery prior to 2005.

Explicitly defined state-dependent policies are likely to be superior to more ad hoc reactive strategies for reasons beyond their performance in meeting the types of management objectives discussed above. The ability of management agencies to quickly implement ad hoc changes to management as a reaction to system changes, whether or not these occur as a consequence of prior management decisions, has decreased significantly in recent years, as stakeholder groups have become more influential. Managers now devote large amounts of time and effort to participatory processes intended to inform stakeholders and facilitate changes to management. Both managers and stakeholders with whom we have spoken during the past decade have frequently found these processes frustrating, stressful, and ineffective. A state-dependent policy that prescribes the management actions that should be taken across the range of plausible system states would avoid the need to "reinvent the wheel" every time the system changes. Admittedly, such a policy still requires a process to facilitate stakeholder buy-in, but the process could occur less often, and more importantly not at a time of crisis (e.g., very low stock abundances for an exploited fishery) when rapid decision-making is needed. Lake Erie fishery managers presented their state-dependent harvest policy to walleye fishermen in 2005 and remain optimistic that they have obtained buy-in for this approach. The real test, however, will come when walleye abundance falls to levels that call for a reduction in fishing mortality from recent levels.

Third, by incorporating process uncertainty into the models used to compare management options, particularly uncertainty about recruitment dynamics, each of our decision analyses exposed the limited extent to which decision makers can control the future states of these systems. This limitation was especially evident for Lake Michigan salmonine stocking. Both managers and stakeholders need to appreciate this extremely important reality. While we can identify management strategies that, on average, perform better than others through decision analysis, the long-term outcome of any strategy could

be far worse (or better) than suggested by the expected, or average, outcome. For example the declining walleye yields in Lake Erie during the 1990s resulted primarily from a long period of years without high walleye recruitment, rather than from an overly liberal harvest strategy. This underscores the wisdom of the correct, if somewhat idealistic, view that decisions should be judged, not by their consequences, but by the quality of the thinking that went into making the decision in the first place. The highly uncertain future of each of the systems discussed here is undoubtedly typical of other fishery systems, and points to both the merits of policies that are state-dependent, and to the continuing need to learn about these systems and adapt management appropriately.

Finally, while each of the decision analyses we discussed here involved highly technical analyses, we emphasize that the process of doing the decision analyses, more than the analysis itself, made these case studies effective. In each case the decision analysis involved active interactions with decision makers, fishery experts, and in the salmonine stocking case, nongovernment stakeholders. These interactions ensured that those using the results of the analysis retained a strong sense of ownership of the work throughout, even though their involvement in the actual uncertainty assessment or modeling may have been minimal. The skills necessary to conduct the technical work are not widespread in management agencies, so future applications of decision analysis will likely continue to require partnerships between decision makers and decision analysts. Such partnerships may actually be beneficial, because involvement of decision analysis experts that are not "within" the management agency may enhance the perception of neutrality of the analysis. Nevertheless, the more inclusive the process can be of experts, decision makers, and those stakeholders likely to be affected by the resulting decisions, the more likely the

analysis will lead to meaningful, beneficial changes to how fisheries are managed.

Our experience with decision analysis in the Great Lakes has obvious relevance to Pacific salmon management in the AYK region. Three important aspects of salmon management for which a decision analysis approach would be particularly valuable are (1) the evaluation of different options for assessment sampling of returning adult salmon, used to determine whether escapement targets are being met; (2) strategies for in-season management of salmon harvest; and (3) setting annual escapement goals for individual stocks.

These three options for an AYK salmon management decision analysis are hierarchically related. A powerful use of decision analysis is to assess the "value of information" for making decisions (Clemen and Reilly 2001, Chapter 12; de Bruin and Hunter 2003), wherein the management options are alternative assessment strategies rather than controls on fishing. AYK salmon fisheries use a variety of tools (weir counts, aerial spawning ground counts, tower observations) to assess adult salmon returns that yield escapement information of variable accuracy and precision. A formal assessment of these alternatives using decision analysis could help managers to allocate scarce monitoring resources. A decision analysis for in-season management could compare options for opening and closing fisheries based on these in-season assessment data and uncertainties about the population dynamics of salmon stocks. Finally managers could be aided by an even broader decision analysis that compared different escapement goals for salmon stocks while accounting for uncertainties about stock–recruitment relationships, long-term changes in stock productivity, and the quality of in-season and long-term data available to inform management.

From our experience in the Great Lakes, however, we would propose that the greatest benefit for AYK managers from adopting a

decision analysis approach would result from the process, not the subject of the actual analysis. The transparency, objectivity, and inclusiveness of the decision analysis approaches we have described above can greatly aid decision makers to gain support for more defensible, flexible, and uncertainty-sensitive policies for the assessment and management of salmon fisheries.

Acknowledgments

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