

14 *Abstract.* – Many fishery management decisions continue to be guided by science only
15 through “best guess” interpretation of assessment information and deterministic models
16 of fisheries and food webs; until very recently this was true of nearly all fishery
17 management in the Great Lakes. However, fishery management decisions can be
18 improved by formally considering uncertainty when evaluating management options;
19 practical tools for doing this have become increasingly available. Accounting for
20 uncertainty is important because acting as though the best guess is true may be
21 substantially suboptimal if this leads to poor performance for other, less likely, but still
22 plausible “states of the world.” For a variety of critical Great Lakes fishery management
23 issues, including determining appropriate investments in sea lamprey control, setting
24 suitable levels of salmonine stocking, and establishing percid harvest policies, we have
25 considered the importance of explicitly incorporating uncertainty. In each case, we
26 worked closely with fishery managers to conduct a decision analysis of management
27 options they identified, using contemporary statistical methods to formally assess
28 uncertainty about key fishery parameters and stochastic simulation to compare
29 management options. These decision analyses were used by fishery managers to develop
30 policies that more objectively account for uncertainty and to garner support from
31 stakeholders and policy makers. The approach shows considerable promise for future
32 fishery management in the Great Lakes, but will face substantial challenges as managers
33 seek to more effectively involve stakeholders throughout the process, foster the requisite
34 technical expertise within their agencies, and communicate the results of highly technical
35 analyses to both stakeholders and decision makers.

36

37

Introduction

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

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

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

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

81 Where allowable harvests are set (either for commercial fisheries or a combined
82 recreational and commercial fishery), they have generally been based on a “fixed” target

83 fishing mortality rate or fixed total mortality rate (where both sea lamprey and fishing are
84 acknowledged as important temporally varying mortality rates subject to management).
85 Fixed target mortality rates have either been based on staying below levels of mortality
86 that have produced population collapses in other systems (e.g., lake trout and lake
87 whitefish – Healey 1978; TTWG 1984), or on standard reference points such as $F_{0.1}$
88 (Deriso 1987) which is used as a surrogate for F_{MSY} . (e.g., Lake Erie walleye – see case
89 study 3 below).

90 In recent years, Great Lakes fishery managers have become interested in applying
91 techniques for assessing the risk of management strategies and more formally accounting
92 for that risk in their decisions. Two factors have contributed to this growing interest.
93 First, Great Lakes fishery managers have noted the growing number of examples from
94 marine fisheries of both applications of uncertainty-sensitive approaches to policy
95 analysis (Sainsbury et al. 1997; Peterman et al. 1998), and cases where collapses of
96 important fisheries have, in part, been attributed to inadequate attention to uncertainty
97 (Walters and Maguire 1996). Second, recent experience reveals that the success of sea
98 lamprey control (Jones et al. 2003), and salmonine stocking (Hansen and Holey 2002;
99 Szalai 2003) can depend on highly uncertain recruitment. Similarly, Lake Erie fishery
100 managers noted several years of poor walleye (*Sander vitreus*) recruitment during the
101 1990s that elevated concerns about harvest strategies. Increased interest led to the
102 application of decision analysis to each issue, with the goal of providing managers with a
103 more objective means of accounting for uncertainty when decisions are made. Our
104 objectives for this paper are to describe our experiences with each of these applications of
105 decision analysis, reflect on their consequences for management, and draw conclusions

106 about the broader implications of our experience for fisheries management in other
107 systems including AYK salmon fisheries.

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

125

126 **Case study 1 – Sea lamprey control in the St. Marys River**

127 The invasion of the parasitic sea lamprey and its devastating effects on Great
128 Lakes fish stocks has been well documented (e.g., Smith and Tibbles 1980). Sea lamprey

129 control in the Great Lakes has continued since the 1950s when the Great Lakes Fishery
130 Commission (GLFC) was formed by treaty between Canada and the United States
131 (Christie and Goddard 2003). Since the late 1950s sea lampreys have been controlled by
132 killing larval sea lamprey with TFM, the liquid lampricide 4-nitro-3-(trifluoromethyl)
133 phenol, before they become parasites and migrate to the lakes to feed on large-bodied
134 fishes, such as lake trout *Salvelinus namaycush*. This chemical control program reduced
135 sea lamprey populations to 10% of pre-control levels (e.g., Heinrich et al. 2003; Lavis et
136 al. 2003a). Other controls are being used to a lesser extent, including low-head barrier
137 dams to prevent sea lamprey access to spawning habitats (Lavis et al. 2003b), traps to
138 remove migrating adult sea lampreys as they enter rivers to spawn (Mullett et al. 2003),
139 and the release of sterilized male sea lampreys into spawning habitats to compete with
140 unsterilized males (Twohey et al. 2003). The GLFC has stated that they seek to increase
141 the use of these alternative methods in the future, and thereby reduce reliance on
142 chemical control (GLFC 2001).

143 The St. Marys River connects Lake Superior to Lake Huron (Figure 1), and unlike
144 other Great Lakes streams that contain substantial larval sea lamprey populations, has too
145 large a flow to treat with TFM at a reasonable cost. Increasing recruitment of sea
146 lampreys from the St. Marys River led to a large increase in the abundance of sea
147 lampreys in Lake Huron during the 1990s. Consequently, the GLFC sponsored the
148 development of a strategy for integrated pest control of sea lampreys in this large river.
149 In 1997, the strategy was adopted and included three tactics: use of an alternative

150 chemical method (Bayluscide¹) that enabled selective application of lampricide to 981 ha
151 of larval sea lamprey habitat, deployment of traps to capture adult sea lampreys, and
152 releases of chemically sterilized male sea lampreys into spawning areas (Schleen et al.
153 2003). Of these three tactics, the chemical control component was by far the most
154 expensive.

155 The decision to adopt this three-pronged strategy was based on deterministic
156 models presented to the GLFC that forecasted the effects of various management options
157 on Lake Huron sea lamprey and lake trout populations along with a cost-benefit analysis
158 of those management options (Schleen et al. 2003). However, the strategy was not
159 designed as, nor was intended to be, a long-term strategy; its objective was to
160 substantially reduce the St. Marys River sea lamprey population in the short term. This
161 control program was judged necessary in 1997 because of perceived large, but un-
162 quantified, uncertainty about how effective the less costly control actions (trapping and
163 sterile male releases) would be if implemented alone. However, an expensive long-term
164 control strategy that relied heavily on chemical methods would re-direct limited funds
165 from controlling other sea lamprey-producing rivers in the Great Lakes basin.
166 Consequently, the GLFC was challenged with developing a feasible long-term strategy to
167 maintain cost-effective control in the St. Marys River. Recognizing the need for a long-
168 term approach that better reflected uncertainty, the GLFC invited us to apply decision
169 analysis. Our analysis began in 1999 and continued for 3 years. Punctuated by three
170 workshops involving scientists, managers, and decision makers, we developed and

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.

171 evaluated the decision analysis, and then presented and discussed our findings with the
172 GLFC on four occasions during 2001-2002.

173 At the initial workshop, we identified levels of each of the three management
174 tactics (trapping, sterile male release, and chemical control) that were to be considered.
175 The performance measures were to be the forecasted future abundance of parasitic sea
176 lampreys in Lake Huron, the frequency of outcomes with parasitic sea lamprey
177 abundance that exceeded a target level, and the net economic benefit of the option²
178 (Table 2). The key uncertainties to be included were demographic processes (particularly
179 recruitment dynamics) in the sea lamprey population, and implementation uncertainty for
180 each control tactic (Table 2).

181 The first workshop was followed by a thorough investigation of these sources of
182 uncertainty, and the development of a stochastic model to forecast future Lake Huron
183 parasitic sea lamprey abundance, conditional on a particular set of management tactics
184 being employed (Haeseker 2001). The demographic analysis was completed using an
185 inverse population modeling approach similar to statistical catch-at-age analysis
186 (Fournier and Archibald 1982) allowing us to quantify the uncertainty associated with sea
187 lamprey population dynamics (Haeseker et al. 2003). Implementation uncertainty for
188 trapping and sterile male releases was quantified by examining empirical data on past
189 inter-annual variation of each tactic's effectiveness. Implementation uncertainty for
190 chemical control was quantified by examining inter-annual variation in the distribution of
191 larval sea lampreys in the area targeted for chemical control (Haeseker 2001), and

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.

192 assuming that future decisions about where to direct future chemical treatment would be
193 based on historical larval distribution patterns derived from a single, exhaustive survey
194 conducted during the mid-1990s – annual distributional surveys for larval sea lampreys in
195 the St. Marys River would be prohibitively expensive.

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

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

210 Before our decision analysis, key GLFC commissioners and staff, as well as the
211 lead author of this paper, were skeptical about the potential of trapping and sterile male
212 releases as control options, believing that these methods would be rendered ineffective by
213 large density-independent recruitment variation (Jones et al. 2003). By explicitly
214 accounting for uncertainty, especially concerning sea lamprey demographics, we

215 demonstrated that enhancing these methods had a high probability of contributing
216 substantially to future suppression of sea lampreys in the St. Marys River. Without our
217 modeling results, the GLFC likely would not have funded enhanced trapping and sterile
218 male releases, principally because of a qualitative impression of the risks (i.e., likelihood
219 of failure) associated with these methods.

220 In this decision analysis, accounting for uncertainty did not lead to a different
221 conclusion. When we ran simulations with sea lamprey demographic uncertainty
222 removed, i.e., using the maximum posterior density estimates of the demographic
223 parameters and assuming zero process error in the stock-recruitment relationship, the
224 rank order of management options did not change. Instead, the decision analysis gave
225 decision makers more confidence in the merits of what they had previously judged to be a
226 risky decision, despite the results of a deterministic analysis.

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

238

239

Case Study 2: Salmonine stocking in Lake Michigan

240

241

242

243

244

245

246

247

248

249

250

251

252

253

254

255

256

257

258

259

260

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 non-native 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 tshawytscha*), 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 tradeoffs exists, however (Stewart et al. 1981), 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. 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.

261 Our decision analysis had four stages. First, we met with experts, managers and
262 non-government stakeholders (recreational and commercial fishers) in March 2000 to
263 discuss and agree upon management objectives, options, and critical uncertainties (Table
264 4). Second, we used historical data from Lake Michigan on salmonine harvests, diet,
265 growth rates, and prey-fish abundance to estimate parameters of a salmonine-prey fish
266 population model and the uncertainty associated with the parameter estimates (Szalai
267 2003). Third, we developed a decision model to forecast the consequences – for alewife
268 abundance, Chinook salmon growth, and Chinook salmon harvests – of alternative
269 stocking strategies. Finally, we met again with experts, managers and stakeholders to
270 demonstrate and discuss the model.

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

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

293 To evaluate stocking policy alternatives, we developed a stochastic model, based
294 on the assessment models described above, that forecasted the alewife abundance and
295 Chinook salmon abundance and size resulting from a specific policy. The model also
296 included all other major stocked salmonine species as predators, and bloater and rainbow
297 smelt as prey. All predators were modeled as dynamic and age-structured. Recruitment
298 of predators in the model was treated as a known input because they derive from hatchery
299 releases and measured production in the wild. For predators other than Chinook salmon,
300 natural mortality was assumed constant and the effective search rate was set at a higher
301 rate than for Chinook salmon. Growth rates of the other predators did not vary in the same
302 manner as for Chinook salmon during the historical period, which suggests that their
303 success at searching for prey was less affected by variations in alewife abundance,
304 indicative of a higher search rate. For computational purposes, size at age for other
305 predators was fixed rather than calculated based on modeled consumption. Prey species
306 other than alewife were not modeled dynamically. Instead they were included as having

307 a constant abundance at age. In this modeling effort we put more effort into
308 incorporating details for the models of Chinook salmon and alewife both because of
309 greater availability of information and because we believed that these two species play a
310 dominant role in the system. We included other predators in a dynamic fashion to retain
311 the ability to evaluate policies where the stocking of those species was changed. One of
312 the two alternative prey species was benthic and the other was pelagic, and their inclusion
313 should be viewed as an approach to incorporating alternative prey for salmonines when
314 alewife became scarce.

315 We compared stocking policies by looking, for each performance indicator, at the
316 distribution of outcomes, the median outcome, and the proportion of outcomes that
317 exceeded or fell below a threshold value deemed to be undesirable. A wide range of
318 outcomes were forecasted for each policy. For continued stocking at current levels, we
319 forecasted average annual Chinook salmon harvests ranging from 6,500 to 360,000 fish
320 per year (Figure 2). For this policy, forecasted average harvests less than 100,000 fish per
321 year were relatively common (29.7%, Table 5), with the most common result lying
322 between 50,000 and 75,000 fish harvested per year (Figure 2, solid bars). Policies with
323 fixed, but lower stocking rates resulted in poorer performance for harvest and alewife
324 indicators, but better performance for Chinook weight (e.g., Table 5, “Reduce Chinook
325 50%”). In contrast, a state-dependent, or feedback policy in which stocking of all
326 salmonines was reduced by 50% when age 3 Chinook weights measured in the fall
327 declined below 7 kg (and restored to current levels when fall weight recovers to 8 kg)
328 resulted in a substantially lower proportion of outcomes with harvests below 100,000 fish
329 per year (15.7%, Table 5, “State dependent”), although the range of possible future

330 harvests was only slightly narrower (18,000-315,000 fish per year), and the alewife
331 biomass performance indicators were worse than for other policies.

332 This policy analysis suggested two important consequences for decision makers
333 seeking an appropriate policy for salmonine stocking. First, our results suggested that
334 feedback policies, where stocking levels are dynamically adjusted in response to evidence
335 of a deteriorating situation, substantially reduced the risk of poor outcomes with respect
336 to Chinook salmon harvest and growth. Second, the uncertainties included in the
337 forecasting model, particularly with respect to alewife recruitment, gave rise to a wide
338 range of possible outcomes from a single policy, regardless of which policy was chosen.
339 We concluded that all feasible strategies still admitted a substantial possibility of
340 undesirable consequences stemming from future Chinook salmon and alewife population
341 trajectories. As a result, flexibility and careful monitoring will be essential to good
342 management of this fishery.

343 During 2005, Lake Michigan fishery managers held public meetings with
344 stakeholder groups around the lake to discuss options for future management of the
345 stocking program. At these meetings agency biologists presented data on recent trends in
346 several indicators of the performance of the salmonine fishery (e.g., salmonine catch rates
347 and growth rates, alewife abundance indices, prevalence of bacterial kidney disease in
348 Chinook salmon). These data sets generally indicated moderately elevated stress levels in
349 Chinook salmon, including recent declines in growth rates of Chinook salmon. These
350 observations, together with our decision analysis findings supporting a state-dependent
351 stocking strategy (also presented at these meetings), enabled the Lake Michigan fishery
352 managers to obtain public support for a reduction in Chinook salmon stocking rates.

353 Stocking rates were reduced by 25% in 2006. Although the managers have not formally
354 adopted a state-dependent stocking policy, it is expected that stocking rates will remain at
355 this lower level until evidence is seen of good growth and abundant forage for Chinook
356 salmon.

357

358 **Case Study 3: Walleye harvest management in Lake Erie**

359 Together with yellow perch (*Perca flavescens*), walleye contribute to important
360 commercial and recreational fisheries in Lake Erie. They have the highest landed value
361 (> \$10 million CAD) of any Great Lakes commercial species in Canada, and are targeted
362 by about 5 million angler hours per year of recreational effort, primarily in Ohio and
363 Michigan waters of Lake Erie. Before 2001, Lake Erie fishery managers used a fixed
364 harvest rate ($F_{0.1}$ – Deriso 1987) policy to determine allowable harvests for walleye,
365 based on the results of their stock assessments. However, even when this $F_{0.1}$ policy was
366 in place fishing mortality (F) changed from year to year reflecting changes in stock
367 assessments and methods for determining $F_{0.1}$, and how uncertainty in stock assessment
368 results was translated into the actual allowable harvest (LEWTG 2001). From the late
369 1970s to 2003, the Lake Erie walleye population experienced strong year classes only in
370 1984 and 1988. As a consequence, walleye yields declined steadily from 1995 to 2000
371 and Lake Erie fishery managers became concerned about risks of overfishing. In 2000,
372 the $F_{0.1}$ policy was dropped and a fixed conservative harvest level was chosen that was
373 projected to allow the stock to increase, while the issue of an appropriate long-term
374 harvest policy was reviewed (LEWTG 2004). In 2002, the managers asked us to work

375 with them to develop a decision analysis tool to inform future harvest policy for this
376 fishery.

377 Beginning with a general workshop to explain decision analysis in fall 2002, we
378 convened several meetings with fishery managers and biologists to guide development of
379 a model to evaluate harvest policy options for Lake Erie walleye. Historically, the Lake
380 Erie Committee – the multi-agency committee that collectively guides fishery
381 management on Lake Erie – had used the results of an annual stock assessment to set
382 total allowable harvests for both commercial and recreational fisheries. The stock
383 assessments employed a statistical catch-at-age model to estimate stock size and recent
384 harvest rates, but managers relied only on point estimates to determine harvest rates. Our
385 decision analysis model was structurally similar to the retrospective stock assessment
386 model, but with explicit consideration of uncertainty regarding walleye demographics.
387 We considered a range of policy options including both fixed and variable harvest rates.
388 The principal management objective identified by Lake Erie fishery managers was to
389 maintain adult walleye abundance above a level that would provide for high quality
390 commercial and recreational fisheries: 25 million fish that were age 2 and older. In
391 addition to assessing average performance, managers also wished to evaluate policy
392 performance based on the frequency of outcomes wherein abundance failed to meet the
393 25 million fish target, and the duration of periods when abundance fell below the target
394 level.

395 Early in the analysis, Lake Erie fishery managers and biologists agreed upon a set
396 of critical uncertainties that the decision model should consider. First, they wished to
397 determine how harvest policies were affected by uncertainty in the parameters of the

398 statistical catch-at-age model, including initial population estimates, fishery catchability
399 and age-specific vulnerability to the fishing gears, and natural mortality rates. Second,
400 they wanted to include uncertainty in the stock-recruitment relationship for walleye in the
401 decision model. Third, they were interested in uncertainty surrounding the relationship
402 between walleye abundance and recreational fishing effort. We made structural
403 assumptions about both the stock-recruitment model (Ricker) and the recreational effort –
404 abundance relationship (linear), and evaluated uncertainty via the distribution of
405 parameters for these relationships. We used the existing statistical catch-at-age model to
406 estimate parameters for each of these relationships, and then employed Monte Carlo
407 Markov Chain methods to sample from the joint posterior probability distribution of the
408 complete set of parameters, and thereby quantify the joint uncertainty in all the
409 parameters that we explicitly considered.

410 The decision model forecasted future abundance of walleye conditional on a
411 harvest policy for both commercial and recreational fisheries for a fifty-year time
412 horizon. To account for parameter uncertainty, a single policy simulation was repeated
413 1000 times, each time randomly selecting a set of parameters from the sample of the joint
414 posterior distribution. Model outputs were then summarized as mean and median
415 walleye abundances and harvests, proportions of simulation-years with abundance below
416 25 million age 2 and older fish, and a frequency distribution of durations of periods
417 wherein abundance fell below 25 million fish.

418 In the final workshop managers defined a general state-dependent harvest policy
419 to consider, wherein the commercial fishing mortality rate would be set at a constant low
420 rate when population abundance was below 15 million fish (age-2 and older) and a

421 constant high rate when population abundance exceeded 40 million fish, and increased
422 with abundance in a piece-wise linear fashion for abundances between 15 and 40 million
423 fish, with a change in slope at 20 million fish (Figure 3). We used the decision model to
424 evaluate the performance of this policy, scaled upward and downward proportionally
425 across all stock sizes (Figure 3), and compared its performance to a range of fixed harvest
426 rate policies. Because recreational fishing effort has historically decreased when walleye
427 abundance has been low, and jurisdictions where recreational fisheries dominated have
428 generally not taken their full quota allocation, the policy adjustments to fishing mortality
429 were only applied to the commercial fishery.

430 Comparisons between state-dependent and fixed fishing mortality rate policies are
431 difficult, because the fishing mortality rates for the former, by definition, are not
432 constant. For similar median fishing mortality rates over 1000 simulations the two types
433 of policies produced similar median total harvests (Figure 4), while the risk of adult
434 abundance falling below the 25 million fish target was slightly greater for the fixed
435 fishing mortality rate policy (Figure 5). In view of these findings, and because of a desire
436 to have a policy that lowered fishing rates when abundance was low, the Lake Erie
437 fishery managers adopted a state-dependent harvest policy in 2005. They chose a policy
438 that maintained fishing mortality rates below those that our analysis suggested would
439 result in the highest expected yields, because at high harvest rates the risk of periods of
440 poor fishing due to low population sizes increased substantially.

441 The harvest policy implemented by Lake Erie fishery managers in 2005 resulted
442 in commercial quotas in 2005 and 2006 that did not differ much from what would likely
443 have been imposed based on their past procedures for setting harvest quotas. The 2003

444 year class of walleye in Lake Erie was the largest on record since stock assessments
445 began in 1978; this year class recruited to the fishery in 2005, allowing substantially
446 larger quotas than had been permitted for several prior years. Likely, managers would
447 have increased quotas based on the observed strength of this year class even in the
448 absence of an explicit state-dependent harvest policy.

449 The decision analysis facilitated two important changes to the process for
450 managing walleye exploitation in Lake Erie. First, the explicit consideration of risk in the
451 decision model allowed managers to more objectively justify a policy perceived by the
452 stakeholders as conservative. The analysis suggested that higher commercial fishing
453 mortality rates would actually lead to higher sustained yields, on average, but it also
454 showed that large, unpredictable variation in walleye recruitment, well known to
455 biologists and fishers alike, can frequently lead to declines in population size below
456 levels associated with good fishing conditions, at these same higher fishing mortality
457 rates. Second, the analysis motivated the development of a general rule for setting
458 commercial fishing mortality rates, eliminating the need to rationalize a new quota each
459 year. Prior to 2001, this fishery was nominally managed by a constant fishing mortality
460 rate policy; however, the reality was that managers responded in an ad hoc fashion to
461 changes in walleye abundance in an attempt to avoid low populations. The policy
462 adopted in 2005 was developed based on this same objective and can be applied to any
463 future fishery state, at least until a decision is made to update the walleye population
464 model used to evaluate this policy.

465 **Discussion**

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

476 Decision analysis is often advocated because explicitly accounting for uncertainty
477 may suggest a different optimal decision than would result from a deterministic
478 assessment of the choices available to managers. This did not occur for any of the three
479 case studies described herein. The same two options ranked highest for the St. Marys
480 River decision analysis when we used a deterministic model. We did not explicitly
481 evaluate stocking strategies for Lake Michigan using a deterministic model, but other
482 lines of evidence from fishery assessments also had led managers to advocate a reduction
483 in Chinook stocking rates until salmon growth rates stabilized or began to increase
484 (James Dexter, Michigan Department of Natural Resources and Chair, Lake Michigan
485 Committee, personal communication). In Lake Erie, fishery managers likely would have
486 allowed higher fishing mortality due to the strength of the 2003 year-class, whether or not
487 we had conducted the decision analysis. In the case of sea lamprey management our
488 analysis may have facilitated a decision that differed from that which would have

489 occurred without the analysis, but only because of an overly pessimistic view of the
490 uncertain potential of the non-chemical alternatives. In the other two cases, the decision
491 analysis did not appear to significantly change the subsequent decisions.

492 What, then, has been the benefit to fishery managers of these decision analyses,
493 and why is there continued interest in the use of this approach? We suggest three reasons
494 explain why Great Lakes fishery managers consider decision analysis a useful tool. First,
495 in each case the decision analysis provided a formal and transparent methodology for
496 rationalizing and documenting the decisions that were ultimately made. Managers are
497 frequently criticized for making decisions in an opaque fashion; stakeholders challenge
498 the rationale for the decisions, and are left dissatisfied by the answers they get (e.g., “we
499 feel we need to reduce stocking rates because the risks of an alewife population collapse
500 are too great”). The decision analysis process can involve stakeholders directly, as in the
501 Lake Michigan stocking decision analysis. Further, decision analysis requires clear,
502 explicit statements of management objectives and options, and the process for evaluating
503 management options involves a formal model wherein the performance of the different
504 options can be deduced objectively from the set of assumptions and hypotheses that
505 comprise the model. The model itself may be so complicated that understanding its
506 behavior poses a large challenge, particularly to non-technical stakeholder groups (and
507 this remains a serious obstacle for the application of decision analysis to public policy),
508 but it is nevertheless possible to document the basis for conclusions reached. A more
509 transparent decision-making process builds trust between stakeholders and decision
510 makers; our impression is that a lack of trust is a primary reason why so many fishery
511 management decisions are controversial, both in the Great Lakes region and elsewhere.

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

524 Explicitly defined state-dependent policies are likely to be superior to more ad
525 hoc reactive strategies for reasons beyond their performance in meeting the types of
526 management objectives discussed above. The ability of management agencies to quickly
527 implement ad hoc changes to management as a reaction to system changes, whether or
528 not these occur as a consequence of prior management decisions, has decreased
529 significantly in recent years, as stakeholder groups have become more influential.
530 Managers now devote large amounts of time and effort to participatory processes
531 intended to inform stakeholders and facilitate changes to management. Both managers
532 and stakeholders with whom we have spoken during the past decade have frequently
533 found these processes frustrating, stressful, and ineffective. A state-dependent policy that
534 prescribes the management actions that should be taken across the range of plausible

535 system states would avoid the need to “reinvent the wheel” every time the system
536 changes. Admittedly, such a policy still requires a process to facilitate stakeholder buy-in,
537 but the process could occur less often, and more importantly not at a time of crisis (e.g.,
538 very low stock abundances for an exploited fishery) when rapid decision-making is
539 needed. Lake Erie fishery managers presented their state-dependent harvest policy to
540 walleye fishermen in 2005 and remain optimistic that they have obtained buy-in for this
541 approach. The real test, however, will come when walleye abundance falls to levels that
542 call for a reduction in fishing mortality from recent levels.

543 Third, by incorporating process uncertainty into the models used to compare
544 management options, particularly uncertainty about recruitment dynamics, each of our
545 decision analyses exposed the limited extent to which decision makers can control the
546 future states of these systems. This limitation was especially evident for Lake Michigan
547 salmonine stocking. Both managers and stakeholders need to appreciate this extremely
548 important reality. While we can identify management strategies that, on average,
549 perform better than others through decision analysis, the long-term outcome of any
550 strategy could be far worse (or better) than suggested by the expected, or average,
551 outcome. For example the declining walleye yields in Lake Erie during the 1990s
552 resulted primarily from a long period of years without high walleye recruitment, rather
553 than from an overly liberal harvest strategy. This underscores the wisdom of the correct,
554 if somewhat idealistic, view that decisions should be judged, not by their consequences,
555 but by the quality of the thinking that went into making the decision in the first place.
556 The highly uncertain future of each of the systems discussed here is undoubtedly typical
557 of other fishery systems, and points to both the merits of policies that are state-dependent,

558 and to the continuing need to learn about these systems and adapt management
559 appropriately.

560 Finally, while each of the decision analyses we discussed here involved highly
561 technical analyses, we emphasize that the process of doing the decision analyses, more
562 than the analysis itself, made these case studies effective. In each case the decision
563 analysis involved active interactions with decision makers, fishery experts, and in the
564 salmonine stocking case, non-government stakeholders. These interactions ensured that
565 those using the results of the analysis retained a strong sense of ownership of the work
566 throughout, even though their involvement in the actual uncertainty assessment or
567 modeling may have been minimal. The skills necessary to conduct the technical work are
568 not widespread in management agencies, so future applications of decision analysis will
569 likely continue to require partnerships between decision makers and decision analysts.
570 Such partnerships may actually be beneficial, because involvement of decision analysis
571 experts that are not “within” the management agency may enhance the perception of
572 neutrality of the analysis. Nevertheless, the more inclusive the process can be of experts,
573 decision makers, and those stakeholders likely to be affected by the resulting decisions,
574 the more likely the analysis will lead to meaningful, beneficial changes to how fisheries
575 are managed.

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

581 management of salmon harvest; and (3) setting annual escapement goals for individual
582 stocks.

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

598 From our experience in the Great Lakes, however, we would propose that the
599 greatest benefit for AYK managers from adopting a decision analysis approach would
600 result from the process, not the subject of the actual analysis. The transparency,
601 objectivity, and inclusiveness of the decision analysis approaches we have described
602 above can greatly aid decision makers to gain support for more defensible, flexible, and
603 uncertainty-sensitive policies for the assessment and management of salmon fisheries.

604

Acknowledgements

605 The decision analysis projects discussed in the paper were supported by the Great Lakes
606 Fishery Commission, Michigan Sea Grant College Program, and Michigan DNR
607 Fisheries Division (Studies 230724, 230713, and 236102, with partial support from the
608 USFWS Sport Fish Restoration Program). We wish to thank the members of the Sea
609 Lamprey Integration Committee, the Lake Michigan Committee, and the Lake Erie
610 Committee for their guidance and support. Gavin Christie, James Dexter, and Roger
611 Knight were especially helpful in facilitating our interactions with managers and
612 stakeholders throughout the projects. This is contribution number 2008-xx of the
613 Quantitative Fisheries Center at Michigan State University.

614

References

615 Butterworth, D. S., K.L.Cochrane, and J.A.A. de Oliveira. 1997. Management
616 procedures: A better way to manage fisheries? The South African experience.
617 Pages 83-90 in E.L. Pikitch, D.D. Huppert, and M.P. Sissenwine, editors. Global
618 Trends: fisheries management. American Fisheries Society, Symposium 20,
619 Bethesda, Maryland.

620 Christie, G.C. and C.I. Goddard. 2003. Sea Lamprey International Symposium (SLIS II):
621 Advances in the integrated management of sea lamprey in the Great Lakes.
622 Journal of Great Lakes Research 29 (Supplement 1):1-14.

623 Christie, G.C., J.V. Adams, T.B. Steeves, J.W. Slade, D.W. Cuddy, M.F.Fodale, R.J.
624 Young, M. Kuc, and M.L. Jones. 2003. Selecting Great Lakes streams for
625 lampricide treatment based on larval sea lamprey surveys. Journal of Great Lakes
626 Research 29 (Supplement 1):152-160.

627 Clemen, R.T., and T. Reilly. 2001. Making hard decisions with DecisionTools.
628 Duxbury. Pacific Grove, CA.

629 de Bruin, S., and G. J. Hunter. 2003. Making the trade-off between decision quality and
630 information cost. *Photogrammetric Engineering & Remote Sensing* 69:91-98.

631 Deriso, R.B. 1987. Optimal $F_{0.1}$ criteria and their relationship to maximum sustainable
632 yield. *Canadian Journal of Fisheries and Aquatic Sciences* 44 (Supplement 2):
633 339-348.

634 Deroba, J.J. and J.R. Bence. In press. A review of harvest policies: understanding
635 relative performance of control rules. *Fisheries Research*.

636 Fenichel, E.P., J.I. Tsao, M.L. Jones, and G.J. Hickling. 2008. Real options for
637 precautionary fisheries management. *Fish and Fisheries* 9:1-17.

638 Fournier, D., and C.P. Archibald. 1982. A general theory for analyzing catch at age data.
639 *Canadian Journal of Fisheries and Aquatic Sciences* 39:1195-1207.

640 GLFC (Great Lakes Fishery Commission). 2001. Strategic vision of the Great Lakes
641 Fishery Commission for the first decade of the new millennium. Great Lakes
642 Fishery Commission. Ann Arbor, MI.

643 Haeseker, S.L., M.L. Jones, and J.R. Bence. 2003. Estimating uncertainty in the stock-
644 recruit relationship for St. Marys River sea lampreys. *Journal of Great Lakes*
645 *Research* 29 (Supplement 1):728-741.

646 Haeseker, S.L. 2001. Incorporating uncertainty into St. Marys River sea lamprey
647 management through decision analysis. Doctoral dissertation. Michigan State
648 University, East Lansing, MI.

649 Hansen, M.J. and M.E. Holey. 2002. Ecological factors affecting sustainability of
650 Chinook and coho salmon populations in the Great Lakes. Pages 155-179 in K.D.
651 Lynch, M.L. Jones and W.W. Taylor, editors. Sustaining North American salmon:
652 perspectives across regions and disciplines. American Fisheries Society,
653 Bethesda, MD.

654 Healey, M.C. 1978. Dynamics of exploited lake trout populations and implications for
655 management. *Journal of Wildlife Management* 42: 307-328

656 Heinrich, J.W., K.M. Mullett, M.J. Hansen, J.V. Adams, G.T. Klar, D.A. Johnson, G.C.
657 Christie, and R.J. Young. 2003. Sea lamprey abundance and management in Lake
658 Superior, 1957-1999. *Journal of Great Lakes Research* 29 (Supplement 1): 566-
659 583.

660 Holey, M.E., R.F. Elliot, S.V. Marcquenski, J.G. Hnath, and K.D. Smith. 1998. Chinook
661 salmon epizootics in Lake Michigan: possible contributing factors and
662 management implications. *Journal of Aquatic Animal Health* 10: 201-210.

663 Irwin, B.J., M.J. Wilberg, J.R. Bence, and M.L. Jones. In press. Evaluating alternative
664 harvest policies for yellow perch in southern Lake Michigan. *Fisheries Research*.

665 Jones, M.L., J.F. Koonce, and R. O'Gorman. 1993. Sustainability of hatchery dependent
666 salmonine fisheries in Lake Ontario: the conflict between predator demand and
667 prey supply. *Transactions of the American Fisheries Society*. 122:1002-1018.

668 Jones, M.L., R.A. Bergstedt, M.B. Twohey, M.F. Fodale, D.W. Cuddy, and J.W. Slade.
669 2003. Compensatory mechanisms in Great Lakes sea lamprey populations:
670 implications for alternative control strategies. *Journal of Great Lakes Research*.
671 29 (Supplement 1):113-129.

672 Kocik, J.F., and M.L. Jones. 1999. Pacific salmonines in the Great Lakes basin. Pages
673 455-488 in W.W. Taylor, and C.P. Ferrari, editors. Great Lakes Fisheries Policy
674 and Management: A Binational Perspective. Michigan State University Press, E.
675 Lansing, MI

676 LEWTG (Lake Erie Walleye Task Group) 2001. Report for 2000 by the Lake Erie
677 Walleye Task Group. Prepared for Lake Erie Committee, Great Lakes Fishery
678 Commission. Ann Arbor, MI

679 LEWTG (Lake Erie Walleye Task Group) 2004. Report for 2003 by the Lake Erie
680 Walleye Task Group. Prepared for Lake Erie Committee, Great Lakes Fishery
681 Commission. Ann Arbor, MI

682 Lane, D.E., and R.L. Stephenson. 1998. A framework for risk analysis in fisheries
683 decision-making. ICES Journal of Marine Science 55:1-13.

684 Lavis, D.S., M.P. Henson, D.A. Johnson, E.M. Koon, and D.J. Ollila. 2003a. A case
685 history of sea lamprey control in Lake Michigan: 1979 to 1999. Journal of Great
686 Lakes Research 29 (Supplement 1): 584-598.

687 Lavis, D.S., A. Hallett, E.M. Koon, and T.C. McAuley. 2003b. History of and advances
688 in barriers as an alternative method to suppress sea lampreys in the Great Lakes.
689 Journal of Great Lakes Research 29 (Supplement 1): 362-372.

690 Mullett, K.M., J.W. Heinrich, J.V. Adams, R.J. Young, M.P. Henson, R.B. McDonald,
691 and M.F. Fodale. 2003. Estimating lake-wide abundance of spawning-phase sea
692 lampreys (*Petromyzon marinus*) in the Great Lakes: Extrapolating from sampled
693 streams using regression models. Journal of Great Lakes Research 29
694 (Supplement 1): 240-252.

695 Peterman, R.M. , and J.L. Anderson. 1999. Decision analysis: a method for taking
696 uncertainties into account in risk-based decision making. *Human and Ecological*
697 *Risk Assessment* 5: 231-244.

698 Peterman, R.M., C.N. Peters, C.A. Robb, and S.W. Frederick. 1998. Bayesian decision
699 analysis and uncertainty in fisheries management. Pages 387-398 in T.J. Pitcher,
700 P.J.B. Hart, and D. Pauly, editors. *Reinventing Fisheries Management*. Kluwer
701 Academic Publishers, The Netherlands.

702 Peters, C.N. and D.R. Marmorek. 2001. Application of decision analysis to evaluate
703 recovery a for threatened Snake River spring and summer Chinook salmon
704 (*Oncorhynchus tshawytscha*). *Canadian Journal of Fisheries and Aquatic Sciences*
705 58: 2431-2446.

706 Punt, A.E., A.D.M. Smith, and G. Cui. 2002. Evaluation of management tools for
707 Australia's south east fishery. 3. Towards selecting appropriate harvest strategies.
708 *Marine and Freshwater Research* 53: 645-660.

709 Quinn, T.J. and R.B. Deriso. 1999. *Quantitative fish dynamics*. Oxford University Press,
710 NY.

711 Sainsbury, K.J., R.A.Campbell, R.Lindholm, and A.W. Whitelaw. 1997. Experimental
712 management of an Australian multispecies fishery: examining the possibility of
713 trawl induced habitat modification. Pages 107-122 in E.K. Pikitch, D.D. Huppert,
714 and M.P. Sissenwine, editors. *Global Trends: Fisheries Management*. American
715 Fisheries Society, Symposium 20. Bethesda, MD.

716 Schleen, L.P., G.C. Christie, J.W. Heinrich, R.A. Bergstedt, R.J. Young, T.J. Morse, D.S.
717 Lavis, T.D. Bills, J.E. Johnson, and M.P. Ebener. 2003. Development and

718 implementation of an integrated program for control of sea lampreys in the St.
719 Marys River. *Journal of Great Lakes Research*. 29 (Supplement 1):677-693.

720 Smith, B.R., and J.J. Tibbles. 1980. Sea lamprey (*Petromyzon marinus*) in Lakes Huron,
721 Michigan, and Superior: history of invasion and control, 1936-1978. *Canadian*
722 *Journal of Fisheries and Aquatic Sciences* 27:1780-1801.

723 Stern, P.C. and H.V. Fineburg, editors. 1996. *Understanding risk: Informing decisions in*
724 *a democratic society*. National Academy Press, Washington, D.C.

725 Stewart, D.J. and M. Ibarra. 1991. Predation and production by salmonine fishes in Lake
726 Michigan, 1978-88. *Canadian Journal of Fisheries and Aquatic Sciences* 48:909-
727 922.

728 Stewart, D. J., J.F. Kitchell, and L.B. Crowder. 1981. Forage fish and their salmonid
729 predators in Lake Michigan. *Transactions of the American Fisheries Society* 110:
730 751-763.

731 Szalai, E.B. 2003. Uncertainty in the population dynamics of alewife (*Alosa*
732 *pseudoharengus*) and bloater (*Coregonus hoyi*) and its effects on salmonine
733 stocking strategies in Lake Michigan. Doctoral dissertation. Michigan State
734 University, East Lansing, MI.

735 Twohey, M.B., J.W. Heinrich, J.G. Seelye, K.T. Fredricks, R.A. Bergstedt, C.A. Kaye,
736 R.J. Scholefield, R.B. McDonald, and G.C. Christie, 2003. The sterile-male-
737 release technique in Great Lakes sea lamprey management. *Journal of Great*
738 *Lakes Research*. 29 (Supplement 1):410-423.

739 TTWG (Tripartite Technical Working Group). 1984. Status of the fishery resource –
740 1984. A report by the Tripartite Technical Working Group on the assessment of

741 major fish stocks in the treaty-ceded waters of the upper Great Lakes: State of
742 Michigan. Mimeo. Rep. 49 pp.

743 Walters, C.J. 1986. Adaptive management of renewable resources. Macmillan, New
744 York, New York.

745 Walters, C.J. and J.J. Maguire. 1996. Lessons for stock assessment from the northern cod
746 collapse. *Reviews in Fish Biology and Fisheries* 6:125-137.

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

748

749 1. Define management options

750 2. Define management objectives

751 3. Identify critical uncertainties (alternative states of nature)

752 4. Assign probabilities to alternative states of nature

753 5. Develop a model to forecast outcomes of management options, in terms of

754 performance meeting management objectives

755 6. Rank management options in terms of their performance

756 7. Conduct a sensitivity analysis

757 Table 2. Management options, management objectives and critical uncertainties selected for consideration by the participants in the St
 758 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

759

760 Table 3. Management options considered in the St. Marys River sea lamprey decision
 761 analysis, and their performance at achieving management objectives. Rates are
 762 expressed as proportions. Trapping rate is the proportion of the spawning run
 763 captured by traps; SMRT ratio is the ratio of sterile to fertile males in the spawning
 764 population. The target kill rate refers to the expected kill rate if the true larval
 765 population distribution was identical to that observed during the 1993-1996 survey,
 766 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

767

768 Table 4. Management options, management objectives and critical uncertainties selected
 769 for consideration by the participants in the Lake Michigan salmonine stocking
 770 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?

771

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

775 Table 5. Decision model outputs that summarize key performance measures for three
 776 Lake Michigan stocking policies.
 777

Policy	Median Chinook harvest	Proportion of harvests < 100,000	Median Chinook weight (kg)	Proportion of weights < 6 kg	Median alewife biomass (x10 ³ kg)	Proportion of biomasses > 500,000 MT
1. Current stocking	160,000	29.7	7.0	47.6	417,000	47.8
2. Reduce Chinook 50%	126,000	35.4	9.9	41.2	667,000	53.6
3. State- dependent	182,000	15.7	11.6	33.9	870,000	59.5

778

Figure Captions

779

780

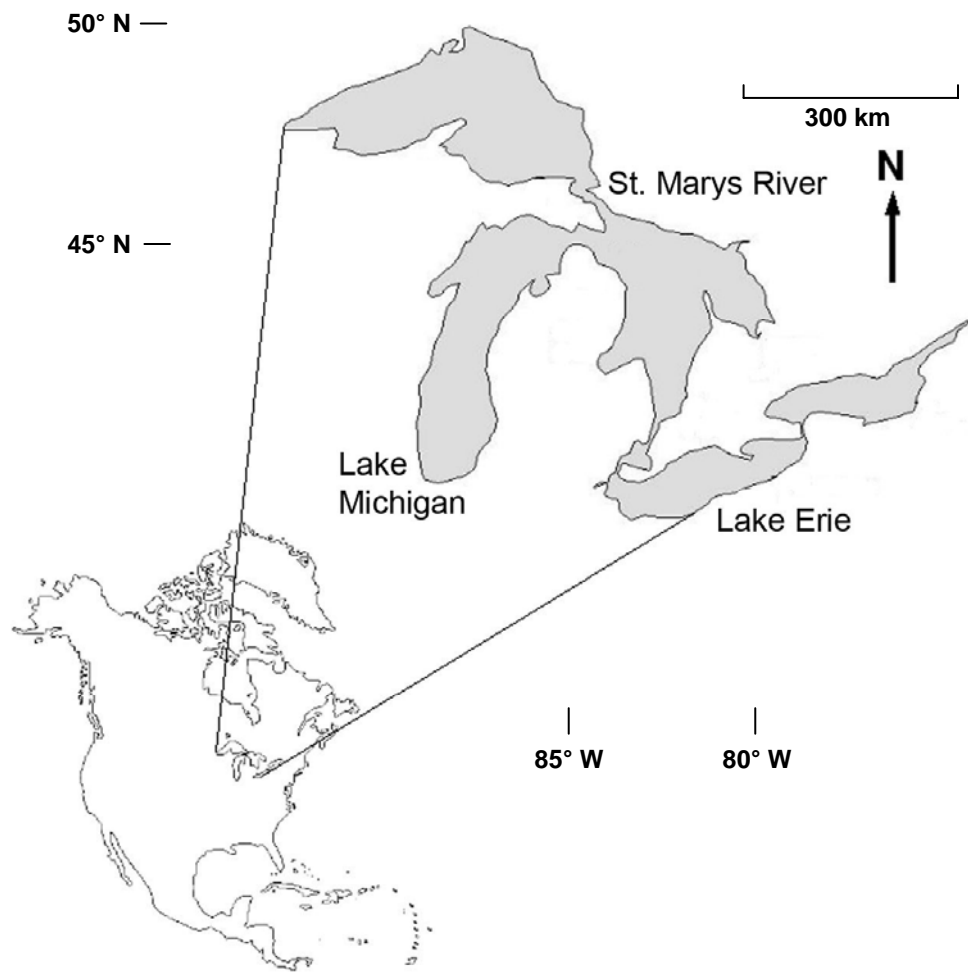
781 Figure 1. Map of the North American Great Lakes, showing the locations of the three
782 case studies discussed in the paper: St Marys River (sea lamprey control); Lake
783 Michigan (salmonine stocking); and Lake Erie (walleye exploitation).

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

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

796 Figure 4. Top panel: Forecasted median walleye harvests in the commercial and
797 recreational fisheries, averaged over a 50-year simulation time horizon, for harvest
798 policies with a range of fixed and state-dependent fishing mortality rates. Bottom panel:
799 Forecasted proportions of simulation years wherein the adult walleye population fell
800 below 25 million fish. The fishing mortality rate for each policy was calculated as the
801 median value of F for commercial and recreational fisheries combined over 1000

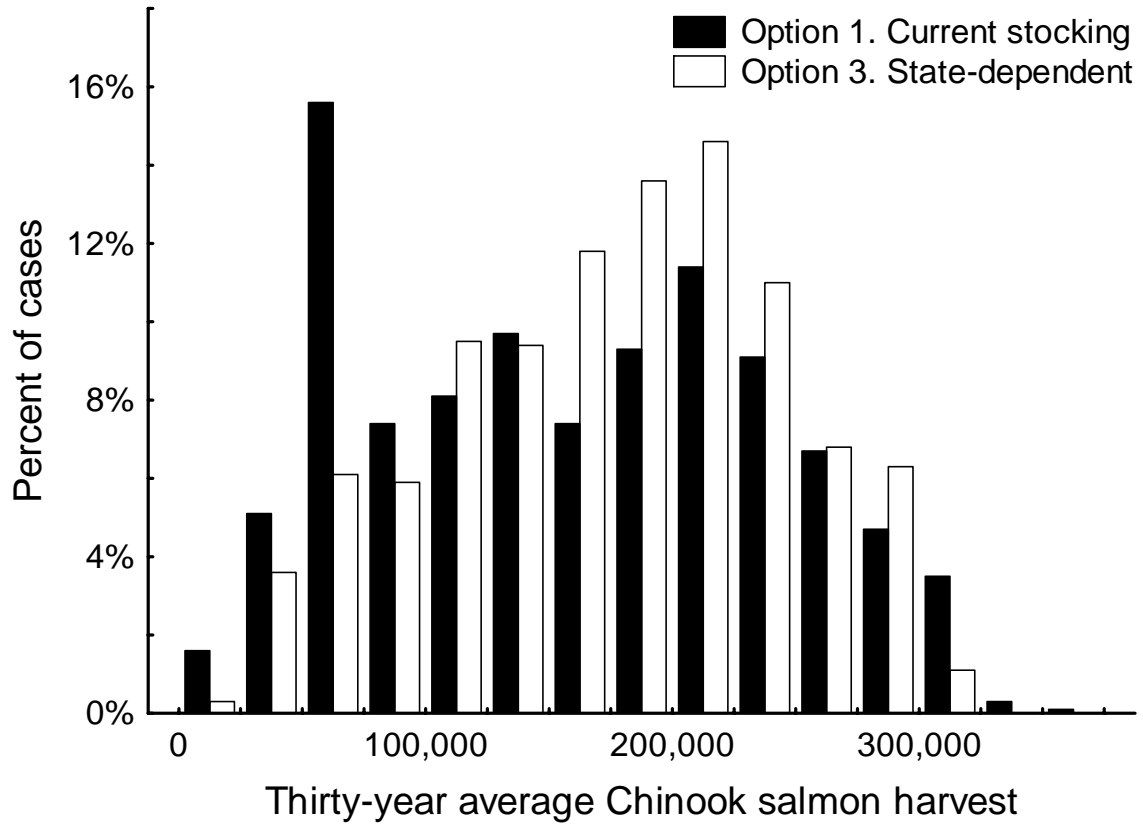
802 simulations of the policy.



803

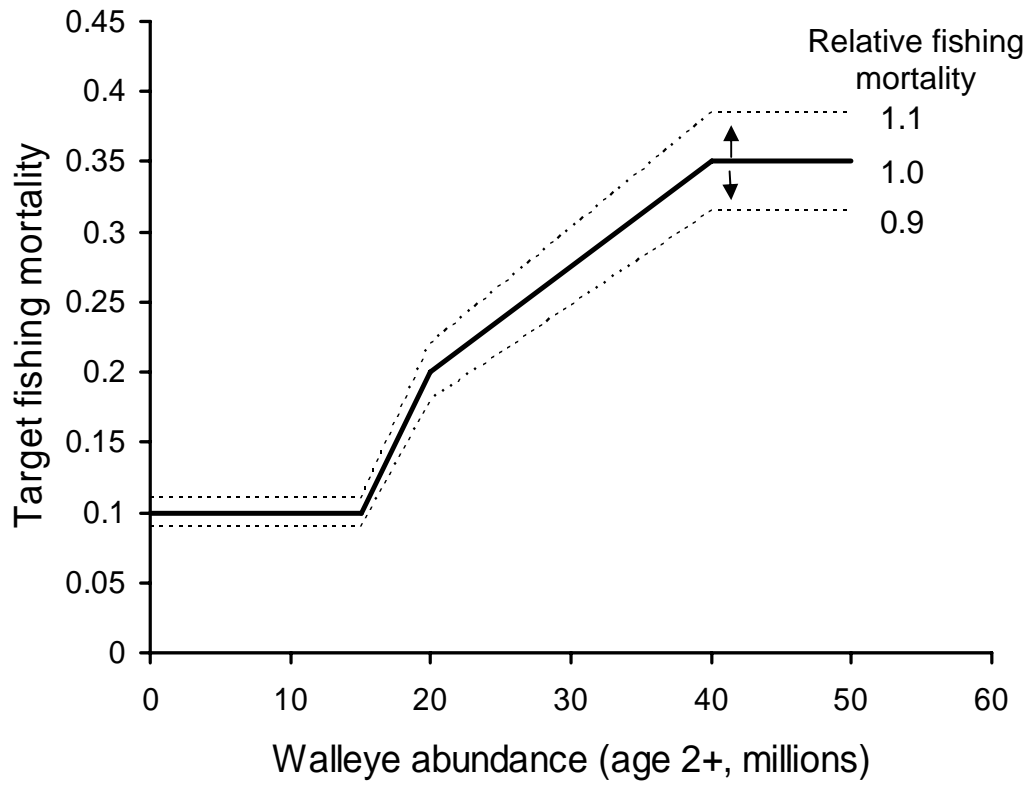
804 Figure 1.

805



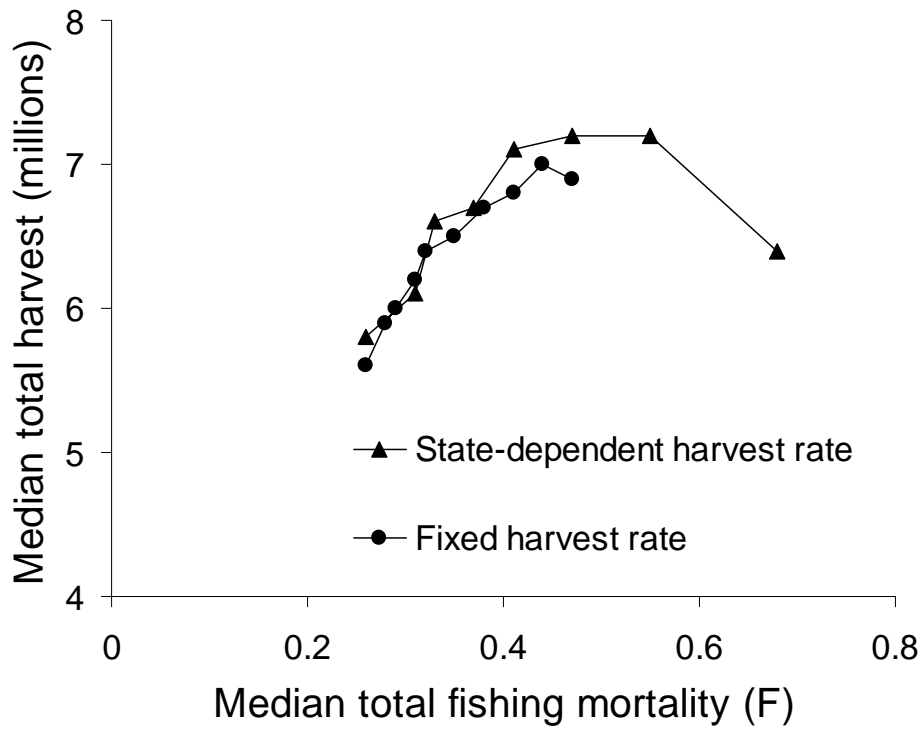
806
807

808 Figure 2.

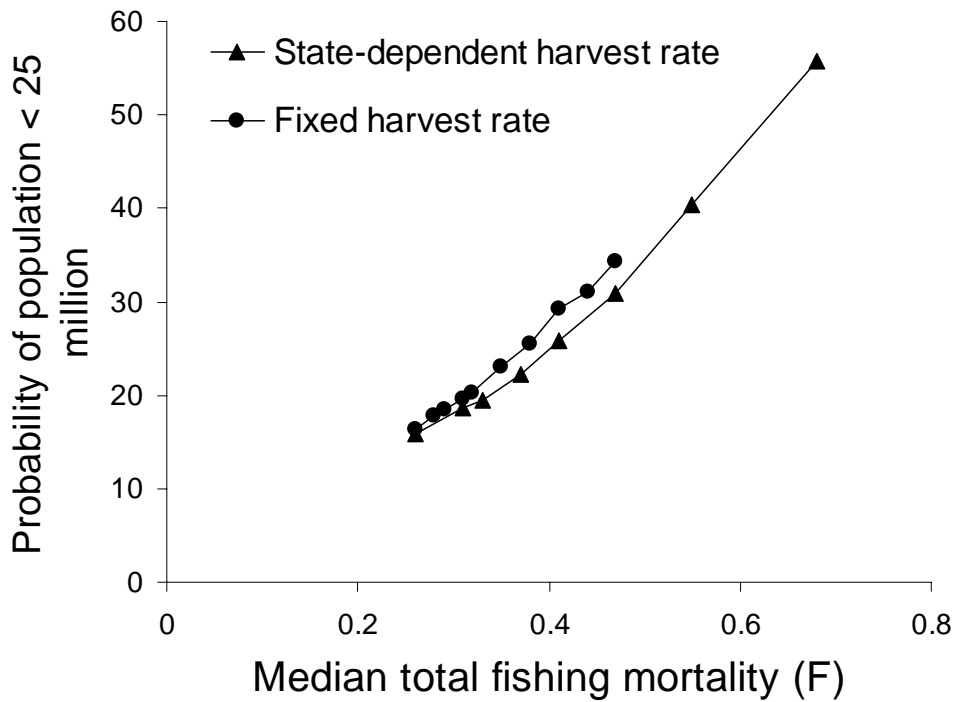


809

810 Figure 3.



811



812

813 Figure 4.

814