AN ABSTRACT OF THE DISSERTATION OF

Youngah Lim for the degree of Doctor of Philosophy in Applied Economics presented on December 06, 2013.

Title: Cost-Efficient Management of Aquatic Invasive Species: Application to New Zealand Mudsnails in the Pacific Northwest

Abstract approved: ______________________________________________________

Munisamy Gopinath

By affecting the ecological, pecuniary and aesthetic productivity of ecosystems, invasive species (IS) increase production and management costs to business, while straining public agencies' budgets with monitoring, enforcement and management efforts. Understanding invasion pathways or vectors, and identifying costs and benefits of alternative management strategies are critical to public and private decision making in agriculture, natural resource and recreation industries. This study develops an integrated spatial framework to measure IS risk and cost-efficiency of alternative IS management strategies. For a given spatial unit, the framework weighs expected damages, based on measured IS risk, against the cost of alternative management strategies, i.e. spatial cost minimization. The study then applied the spatial cost minimization framework to the case of New Zealand mudsnails, *Potamopyrgus antipodarum*, (NZMS) in the Pacific Northwest (PNW) using data from a variety of sources.

The first stage of the integrated framework is the measurement of NZMS establishment risk, which is estimated as a combination of anthropogenic introduction risk and habitat suitability risk. Since recreational boats are a main vector to disperse NZMS, the normalized boat flows in the PNW states—Idaho, Oregon, and Washington—are used as a proxy for the

anthropogenic introduction risk. An environmental niche model then revealed the relationship between environmental features and NZMS presence, i.e. habitat suitability risk. Results suggest that distance, area size, water body concentration, and accessibility are major determinants of PNW recreational boat flows. Environmental characteristics such as elevation, geologic features, precipitation in January, March, and September, as well as the minimum temperature of June, July, and August, and the maximum temperature of June, August, and October are important determinants of PNW's habitat suitability for NZMS.

Potential damages arising from NZMS include anglers' utility loss, which is caused by aquatic habitat degradation due to NZMS invasion, and biofouling influence on hydroelectricity plants, drinking water treatment plants, and boats. Because NZMS economic damages and related management cost are not yet fully identified in the literature, damages and management cost of zebra mussels serve as proxies for those of NZMS. Expected damages are then derived as the product of NZMS establishment risk from the first stage and potential damages noted above. Statewide management cost information is compiled from a phone survey of PNW invasive species field managers. Statewide and local management strategies are prevention, early detection and rapid response and its follow-up (EDRR plus) and ex-post management without EDRR. Local strategies additionally include boater decontamination and fish hatchery prevention efforts.

Finally, the spatial cost minimization problem evaluates expected damages against the cost of each alternative management strategy (statewide and local). Solutions to this minimization problem, i.e. cost-efficient strategies, are derived for individual spatial units in each of the three PNW states. Reflecting uncertainty in the relationship between NZMS impacts and management, the spatial cost minimization is solved under different scenarios: unconstrained,

NZMS damages are a fraction of those of zebra mussels, variation in the effectiveness of statewide and local management strategies, a budget constraint, and targeted NZMS risk level constraint. Results show that statewide prevention, local boater decontamination and fish hatchery prevention are the cost-efficient strategies for managing NZMS in the Pacific Northwest in most cases.

Cost-Efficient Management of Aquatic Invasive Species:
Application to New Zealand Mudsnails in the Pacific Northwest

by
Youngah Lim

A DISSERTATION

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Doctor of Philosophy

Presented on December 06, 2013
Commencement June 2014

Doctor of Philosophy dissertation of Youngah Lim presented on December 06, 2013

APPROVED:

Major Professor, representing Applied Economics

Head of the Department of Applied Economics

Dean of the Graduate School

I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Youngah Lim, Author

# ACKNOWLEDGEMENTS

I would like to thank the members of my committee for their guidance and warm support to complete my long journey of the Ph.D. (Patiently Hoping for Degree) program. Without their help and patience, I could not have finished this dissertation. In particular, I want to express sincere appreciation to Professor Gopinath for his genuine academic advice and encouragement during the entire school years. I also would like to thank Professor Chan for having inspired me about the current and future research topics and giving me many opportunities to interact with experts and researchers whose fields are not economics. I am grateful to Professor Harte, who has had an interest in my progress after he went abroad and helps to make my writing more readable and scientific. In addition, a thank you to Professor Langpap. If I did not take his class, I must have been lost in equations and numbers.

I am grateful to Tania Siemens and Jennifer Lam in Oregon Sea Grant for helping me to get empirical data and encouraging me all the time. I want to thank my true friend, Nadine, for helping me to revise the manuscript. Moreover, I express deep appreciation to my previous advisor, Professor Kwon, who taught me the attitude of a researcher and why environmental and natural resource economics are exiting to study.

Special thanks to my husband, my mother, my parents- in-law, and my brother-in-law.

This research was funded by Oregon Sea Grant, NA223K-AAR-NOAA SG Gopinath AIS. The survey data used for estimation of anglers' utility loss is provided by Dean Runyan Associates.

# CONTRIBUTION OF AUTHORS

Dr. Munisamy Gopinath, Dr. Samuel Chan, and Dr. Michael Harte contributed to the data collection and the model designs for Chapter 2, Chapter 3, and Dr. Chan helped to get data for Chapter 4. In particular, Dr. Gopinath and Dr. Harte contributed to polishing the entire manuscript.

# TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Continued)

## LIST OF FIGURES

LIST OF FIGURES (Continued)

# LIST OF TABLES

# LIST OF APPENDICIES

LIST OF APPENDICIES (Continued)

LIST OF APPENDICIES (Continued)

# CHAPTER ONE

## Introduction

Invasive species (IS) affect the productivity of ecosystems, ecologically, pecuniary and aesthetically, increase production and management costs to businesses and public agencies for monitoring, enforcement and management (Sala et al., 2000; Perrings et al., 2002; Pimentel et al., 2005). For instance, zebra and quagga mussels, among the most unwanted IS in many U.S. states, have negatively affected native biodiversity and human infrastructure (Caraco et al., 1997; Mann et al., 2010). Despite large current and future damages, the uncertainty of biological invasion has limited characterizing their impacts due to spatial and timing gaps between researches and realized invasion, complexity of multiple invasion, and own spatial and temporal variety in impacts (Park, 2004). To reduce such uncertainty, researchers have expended considerable effort in modeling and predicting species invasions (e.g. Lodge et al., 2006), and these quantitative methods help us to allocate limited resources efficiently among alternative management options such as prevention, early-detection, eradication, containment, and control.

In this study, I develop a cost minimization approach to identify cost-efficient IS management strategies for the New Zealand mudsnails (*Potamopyrgus antipodarum*) invasion in the Pacific Northwest (Idaho, Oregon, and Washington). For this purpose, I estimate IS establishment risk, i.e. the probability of establishment, which combines anthropogenic introduction with habitat suitability; in addition to potential IS damage and management cost to introduce them as factors in the cost minimization.

New Zealand mudsnails (NZMS) are aquatic invertebrates, ranging three to six millimeters, with five to six spiral whorls. Main vectors for NZMS dispersal include fishermen and gamefish (Hoddle, 2013; Benson et al., 2012), as well as hatchery transport (e.g. NZMS were discovered at the Hagerman National Fish Hatchery in 2002). In the USA, NZMS were first found in the Snake River of Idaho in 1987, and then they spread to Montana, Oregon, California, Arizona, and others. They have wide tolerance ranges to environmental conditions such as salinity, temperature, and water depth. Thus, they are known to survive in both fresh water and brackish water such as lakes, rivers, streams, lagoons, and estuaries, and sometimes in deep water. NZMS are also reported to survive around the freezing degree (ISSG, 2011). They may have potential to change the community, prey and predator relationship, and nutrient levels of aquatic ecosystems where they occur by heavily consuming primary producers and outcompeting with native snails (Benson et al., 2012; ISSG, 2011). Furthermore, NZMS are found even indigested after passing though trout leading to fish weight loss (Bruce et al., 2009; Vinson and Baker, 2008).

Although economic damages of NZMS are less described in the literature compared to quagga (*Dreissena rostriformis*) and zebra mussels (*Dreissena polymorpha*), NZMS may cause considerable direct and indirect economic impacts by biofouling, contaminating water pipes, and reducing amenity in recreational fishing industry (Proctor et al., 2007; ISSG, 2011; NNSS, 2013). These impacts are considered similar to those of zebra mussels (Proctor et al., 2007; ISSG, 2011), but Proctor et al. (2007) supposed that biofouling potential of NZMS is lower than that of zebra mussels.

NZMS are selected for the study because they are one of the highly concerned aquatic invasive species in the Pacific Northwest. For example, they are ranked high in invasive scores in the analysis of Boersma et al. (2006) which ranked IS in the Pacific Northwest by using 47 questions about ecological impact, invasive potential, and ecological amplitude and distribution, and determined scores from high to not-listed. Moreover, the availability of NZMS presence data in the Pacific Northwest is another reason to focus on this IS since other IS such as quagga and zebra mussels have not yet appeared in the region.

In Chapters 2 and 3, the two components the relative risk of NZMS invasion are estimated. Chapter 2 analyzes risk of NZMS introduction by boaters. In general, aquatic invasive species have been shown to be transported on boat surfaces and motors, fishing gear, trailers and other water activity gear and equipment (Dolphin and Boatner, 2011). To assess this introduction pathway, I employ a gravity model of recreational boat movements, which quantitatively predicts spatial interactions based on attributes of origins and destinations, and their distance (McAllister and Klett, 1976; Schneider et al., 1998; Bossenbroek et al., 2001; Carlton and Ruiz, 2005). The gravity model has been extensively applied to zebra and quagga mussels, but the focus on NZMS has been limited.

Chapter 3 identifies habitat suitability of the Pacific Northwest for NZMS using a maximum entropy approach, one of the ecological niche models mapping species distribution. Data about environmental conditions including elevation, surficial geology, distance from cities, monthly precipitation, monthly maximum temperature, monthly minimum temperature, and aquatic or terrestrial grid are used to predict NZMS habitat suitability. Also in Chapter 3, results from the gravity model and maximum entropy model are used to derive integrated relative risk in a probability format.

Chapter 4 calculates monetized potential damages and costs of managing NZMS. Damages of NZMS include aquatic habitat quality degradation and the accompanying disutility for anglers, and higher costs for drinking water treatment plants and hydroelectricity plants. In addition, I assume that types of NZMS damages would generally be similar to those of zebra mussels such as loss in water treatment plants and biofouling of boat surface and motors, but at lesser levels. For NZMS management, I consider statewide and local management options in hydroelectricity and drinking water treatment plants, in addition to prevention activities of fish hatcheries, and boaters' decontamination of their fishing gears and boats. The efficacies of alternative management options are taken from previous studies.

A spatial cost minimization problem is developed in Chapter 5, where total cost equals sum of damages weighted by relative risk and management costs. Note that factors to set up the minimization problem come from the previous chapters: the integrated relative risk (Chapter 3), potential NZMS damages (Chapter 4), available management options and their cost (Chapter 4). Finally, the cost-efficient management options are analyzed based on assumptions about relative efficacies of management alternatives and several hypothetical scenarios.

# CHAPTER TWO

## New Zealand Mudsnails Introduction Risk

Non-indigenous species are generally introduced via three mechanisms: natural spread and host range extension, accidental introduction, and intentional introduction by humans (Maynard and Nowell, 2009). Carlton and Ruiz (2005) point out that a key invasive species (IS) vector is the unintentional species transportation by humans among the three modes. In other cases, for example, geographical barriers usually limit the scope of natural dispersal, but human-mediated dispersal, intentional or accidental, can cover any location beyond the bio-geographical barriers. Also, the effect of the intentionally introduced species would be much easier to predict and estimate than those unintentionally introduced because legitimate border processes and public agencies govern such introductions.

Two mechanisms critical to species invasions are propagule pressure and habitat suitability (Leung and Mandrak, 2007). Propagule pressure deals with how species arrive in a new area from either its native range or another invaded area and the associated vectors or pathways of introduction (Lockwood et al., 2005; Veltman et al., 1996). A key pathway is unintentional anthropogenic introduction. Habitat suitability, i.e. environmental conditions of the newly invaded area, determines species survival and abundance after invasion. Sufficient propagule pressure in a suitable habitat can lead to successful colonization of IS potentially resulting in large ecological and economic losses (Peterson, 2003). Predictive models have mostly relied on either propagule pressure or environmental characteristics (Bossenbroek et al., 2007; Ramcharan et al., 1992). Although advanced predictive models incorporating multiple components of the invasion process exist (Muirhead et al., 2011; Leung and Mandrak, 2007; Rouget and Richardson, 2003), applications to specific species are limited.

In this chapter, the number of boat movements between regions is used as a proxy for propagule pressure of New Zealand mudsnails (NZMS) since the species can move by attaching to surface of boats and rotors, fishing gears, or other water activity devices. When more boaters visit a certain area, the likelihood of hitchhiking organisms, including NZMS, increases as well. In general, the propagule pressure is a measure of the number of non-indigenous species introduced into a region, and such pressure is an important determinant of successful bioinvasion (Leung and Mandrak, 2007; Lockwood et al. 2005). Propagule pressure is measured as the absolute number of organisms involved in one release event (propagule size) and the number of release events (propagule number). Thus, the number of recreational boats is a proxy for propagule pressure in terms of the number of boats from infected regions (propagule number) and the level of infection of the origin (propagule size). That is, the probability of IS introduction increases when more boats come from an infected region, or a boat comes from a highly infected region. However, this study only analyzes the propagule number, i.e. the number of boats, due to limited data availability about species population that shows the NZMS status of water bodies.

### 2.1. Spatial Interaction Analysis: Gravity Model

Each boater decides whether or not to visit a given destination based on individual taste and other attributes in her/his origin and targeted destinations. This decision making can be termed as spatial interaction since it is related to an individual agent's choice and the selection of specific location. This is consistent with the definition of spatial interaction, movement or communication between regions through an individual decision making process (Fotheringham and O'Kelly, 1989; Haynes and Fotheringham, 1984).

Specifically, spatial interaction models are mathematical frameworks to explain and/or predict the spatial interactions based on attributes of origins and destinations, and spatial separation variables, e.g. distance. A gravity model for spatial interaction is a relatively simple framework consisting of the above three components (Fotheringham and O'Kelly, 1989):

(2-1) $T_{ij} = f\left(\alpha w_i;\ \beta w_j;\ \delta d_{ij}\right)$,

where $T_{ij}$ represents a flow between origin $i$ and destination $j$, $w_i$ and $w_j$ represent levels of attractiveness (or repulsiveness) of $i$ and $j$, and $d_{ij}$ is the distance between $i$ and $j$. The Greek alphabets are parameters to be inferred or estimated. Despite of its simple structure, the gravity model is one of the best known models for explaining spatial interaction with a high level of goodness-of-fit (Ortúzar and Willumsen, 1992; Fotheringham and O'Kelly, 1989).

When it comes to applying the gravity model in IS introduction, the gravity model has consistently explained infrequent and long distance species dispersal by analyzing anthropogenic movement (Muirhead et al. 2009). Most studies of aquatic IS focused on zebra mussels (e.g. Bossenbroek et al. 2007; Leung and Mandrak, 2007; Bossenbroek et al. 2001; Schneider et al. 1998), although several empirical studies have estimated and predicted other aquatic IS distribution by employing the gravity models (e.g. fishhook waterflea in Muirhead et al. 2011). As far as NZMS are concerned, the gravity models have not been used.

This chapter estimates the gravity model with consideration of boat transportation as a key vector of NZMS dispersal. The number of boat from a region $i$ to a region $j$ represents $T_{ij}$ in Equation (2-1), and study areas are decided as 8-digit hydrologic units (HUCs) because they can reflect natural geographic features rather than administrative districts. To reveal what characteristics of the region attract more boaters, I consider hydrologic unit size, the level of water body concentration, accessibility, whether the region is adjacent to ocean, and water quality as attractiveness of the region, i.e. $w_i$ and $w_j$ in Equation (2-1). Distance between hydrologic units is also included in the gravity model as $d_{ij}$ in Equation (2-1).

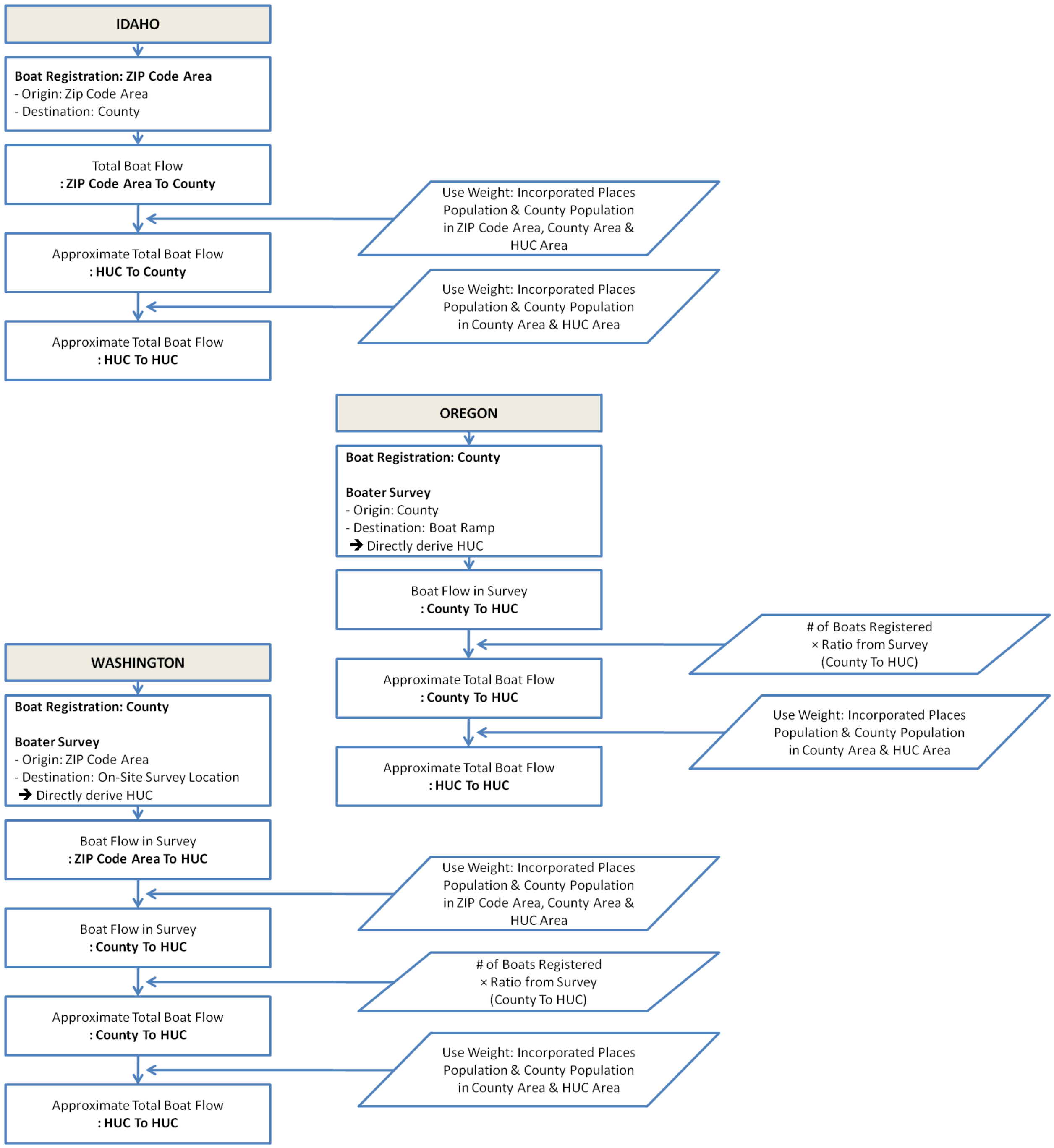
### 2.2. Data and Estimation

In the following, I construct the variables used in estimation and then, explain the estimation results of the gravity model (Table 2.1). The study area is the Pacific Northwest including Idaho, Oregon, and Washington. Boat flows, $T_{ij}$, are derived from each state's boat registration and boater survey data, depending on respective data formats.

Idaho boat flow is directly derived from 2009 boat registration containing the zip code of boat owners and their most preferred county for boating (see Figure 2.1). Although the Idaho Department of Parks and Recreation surveyed boat owners to ask their most journeyed water body in 2009, it cannot represent all Idaho boaters since no one in Camas, Caribou, Clark, Lewis, Minidoka, and Power counties responded. With regard to Oregon boat flow data, its 2010 boat registration and 2008 Oregon triennial boater survey data (3,615 respondents) are utilized. Under the assumption that the survey results represent the entire population of Oregon boat owners, I project the ratio of surveyed boat flows to the number of registered boats in each county. All of geographic units such as zip codes and counties are adjusted to the hydrologic unit (HUC) level by using HUC size, county size, 5-digit zip code tabulation areas, 2009 population of cities, and 2010 county population estimate as weights (see Figure 2.1).

Washington data are derived in a way similar to the Oregon data based on 2010 boat registration and 2008 on-site boater survey (4,073 respondents, see Figure 2.1).

**Figure 2.1 Derivation of $T_{ij}$ from Raw Data**



Note that this study considers boat transportation inside the individual state because information of inter-state boat movement is unobtainable. In other words, the subscripts $i$ and $j$ in variables represent the HUC $i$ and $j$ only inside an individual state: Idaho, Oregon, or Washington. Similarly, the distance between the HUC $i$ and $j$, $d_{ij}$, is measured in meters by the distance between centroids of relevant HUC in each state.

To represent relative attractiveness $w_i$ and $w_j$, i.e. geographic attributes of each area—the size of each HUC, water body dispersion inside the HUC, accessibility (road density), water quality, and adjacency to the Pacific Ocean are considered. Water body dispersion is measured by the Herfindahl index that is commonly used to measure market concentration in economic studies (Cabral, 2000). That is, the water body dispersion is derived as the sum of the squares of water body size proportions (shares) of the relevant HUC. The higher Herfindahl index means the water bodies are more concentrated in a given HUC. The road density is calculated as the total length of primary and secondary road (kilometers) divided by the HUC size (squared kilometers). Adjacency to the Pacific Ocean is included as a dummy variable depending on whether or not the destination HUC adjoins to the Pacific Ocean in Oregon and Washington.

The empirical estimation of the gravity model employs a mixed log/linear model. The variables of the equation are in linear form except the HUC sizes. That is, the coefficients of HUC sizes indicate the absolute change of boat flow with respect to the relative change in HUC sizes when the other coefficients imply the absolute change of boat flow following the absolute change of independent variables. The estimated equation is given by:

$$(2\text{-}2)\quad T_{ij} = \alpha_0 + \alpha_1 \ln(HUC\ size)_i + \alpha_2\ Herfindahl_i + \alpha_3\ Road\ density_i + \beta_1 \ln(HUC\ size)_j + \beta_2\ Herfindahl_j + \beta_3\ Road\ density_j + \gamma_1 Dummy(Ocean)_j + \delta d_{ij} + \varepsilon_{ij}.$$

$T_{ij}$ is a continuous variable, but a significant number of observations are censored at zero (6221 of 8188 observations in Oregon; 3923 of 5078 observations in Washington; and 1367 of 7820 observations in Idaho). To obtain unbiased estimates of coefficients in Equation (2-2) with censored data, I employ the tobit regression method (Maddala, 1983). Following Wooldridge (2002), I predict the unconditional expected value of boat flows, $E\left(T_{ij}\middle|\boldsymbol{X}\right)$ using $\boldsymbol{X}$, the set of attributes on the right hand side of Equation (2-2). Denoting the predicted boat flow from HUC $i$ to $j$ as $\hat{T}_{ij}$, the total boat flows arriving at each hydrologic unit $j$ becomes $\sum_i \hat{T}_{ij}$. Since the relative risk of introduction is proportional to total boat inflows into all HUCs of a state, I normalize such flows as follows:

(2-3) $\tau_j = \frac{\sum_i \hat{T}_{ij}}{\sum_j \sum_i \hat{T}_{ij}}$.

## 2.3. Results and Discussion

The results of estimating the gravity Equation (2-2) for Idaho, Oregon, and Washington are presented in Table 2.1. A positive (negative) sign of estimates in Table 2.1 implies that a higher value of the given attribute is associated with larger (smaller) boat movements across HUCs. The table also reports standardized coefficients, which measure the change in boat flows (latent variable) when a geographic attribute is increased by one standard deviation, holding all else constant. The standardized coefficients allow us to compare impacts of alternative attributes regardless of their measurement units.

Results for Oregon in Table 2.1 show that a negative coefficient of distance implies that water bodies farther from a location are less attractive; large HUCs and large water bodies, i.e.

more concentrated water bodies in destination are more attractive; and high accessibility in the form of high road density both in origin and destination encourages boat movements.

In addition, adjacency to the Pacific Ocean is attractive to boaters while more concentrated water bodies in origin encourage boaters to leave the origin region. In terms of relative importance, standardized coefficients show that the distance between HUCs is more influential in explaining boat flows followed by size of destination area and road density in both origin and destination. A similar pattern of results and relative importance of attributes are observed in Idaho and Washington. The key difference between results of Oregon and those of the other states is boaters' preference about water concentration. Idaho boaters will transport more in the case of more concentrated water bodies in both origin and destination, while Oregon boaters will travel more in the case of less concentrated water bodies in origin and more concentrated water bodies in destination. Boaters' preference in Washing is completely opposite to that of Oregon boaters, i.e. they will travel more in the case of more concentrated water bodies in origin and less concentrated water bodies in destination (see the part of Herfindahl indices in Table 2.1).

In sum, distance, accessibility and dispersion of water bodies are important factors determining boat flows and thus, propagule pressure. In order to quantify the anthropogenic introduction risk, recall that I proposed a normalized predicted boat flow in Equation (2-3). Using Table 2.1's estimates, Figure 2.2 shows the normalized boat flow values ($\tau_j$) across HUCs, where the darker shades mean relatively more boat inflows or a higher value of $\tau_j$. Table 2.2 summarizes the top ten HUCs based on $\tau_j$ along with presence or absence data on NZMS. Note that the introduction risk does not capture inter-state boat movements.

**Table 2.1 Gravity Model Results in Oregon, Washington, and Idaho with Boat Flows, $T_{ij}$, as the Dependent Variable**

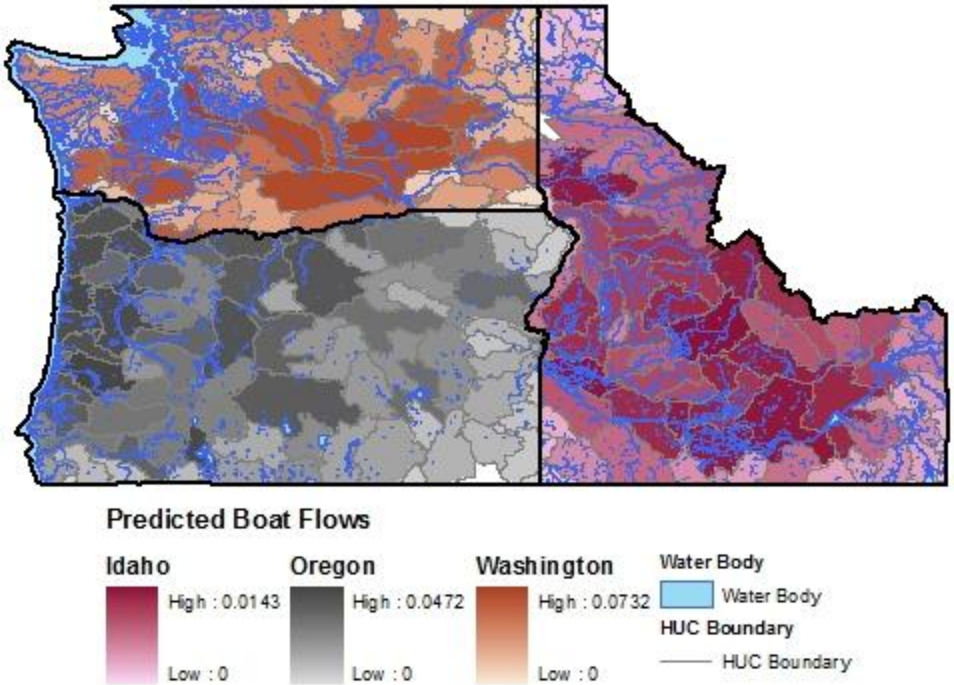
| Independent Variable | Idaho | | Oregon | | Washington | |
|---|---|---|---|---|---|---|
| | Coefficient | Standardized. Coefficient | Coefficient | Standardized Coefficient | Coefficient | Standardized Coefficient |
| Constant | -297.59 *** (38.32) | . | -1384.33 *** (102.87) | . | -3129.51 *** (200.90) | . |
| $Distance_{ij}$ | -4.42 E-4 *** (2.51 E-5) | -80.65 | -1.79 E-3 *** (5.23 E-5) | -270.24 | -2.36 E-3 *** (1.29 E-4) | -299.72 |
| $\ln(\text{HUC size})_i$ | 27.47 *** (2.59) | 64.84 | 35.98 *** (6.04) | 54.53 | 36.36 *** (8.67) | 87.34 |
| $\ln(\text{HUC size})_j$ | 23.03 *** (3.85) | 45.89 | 127.55 *** (10.94) | 175.78 | 303.57 *** (22.55) | 718.52 |
| $Herfindahl_i$ | 0.01 * (0.01) | 11.31 | -0.09 *** (0.02) | -30.34 | 0.07 *** (0.01) | 97.12 |
| $Herfindahl_j$ | 0.02 *** (0.01) | 18.73 | 0.17 *** (0.02) | 58.87 | -0.06 ** (0.03) | -84.90 |
| Road $Density_i$ | 655.59 *** (55.42) | 54.61 | 1497.55 *** (107.13) | 80.22 | 1833.62 *** (209.06) | 115.05 |
| Road $Density_j$ | 282.21 *** (60.98) | 24.11 | 1831.89 *** (117.18) | 98.40 | 3466.46 *** (231.88) | 217.23 |
| Dummy (Ocean) | . | . | 180.76 *** (15.91) | 65.82 | 91.86 * (51.69) | 30.57 |
| Log likelihood | -48178.994 | | -15642.721 | | -10207.657 | |

Note: Standard errors are in parentheses. Standardized coefficient represents the change in the dependent variable resulting from one standard deviation increase of the independent variable: shaded rows indicate the four largest standardized coefficient estimates among independent variables
***, ** and * indicate 1%, 5%, and 10% level of significance, respectively.

**Table 2.2 Hydrologic Units with High Risk of NZMS Introduction**

| Hydrologic Unit Name | Normalized Boat Inflow $\tau_j$ (%) | | Observed NZMS |
|---|---|---|---|
| Idaho | | | |
| Upper Salmon | 0.0143 | ( 1.43% ) | Present |
| Lower Boise | 0.0142 | ( 1.42% ) | Present |
| Lake Walcott | 0.0139 | ( 1.39% ) | Present |
| Upper Snake-Rock | 0.0139 | ( 1.39% ) | Present |
| Clearwater | 0.0138 | ( 1.38% ) | Present |
| Big Lost | 0.0137 | ( 1.37% ) | Absent |
| Middle Salmon-Panther | 0.0137 | ( 1.37% ) | Present |
| Big Wood | 0.0136 | ( 1.36% ) | Present |
| Upper Middle Fork Salmon | 0.0134 | ( 1.34% ) | Absent |
| American Falls | 0.0134 | ( 1.34% ) | Present |
| Oregon | | | |
| Lower Willamette | 0.0472 | ( 4.72% ) | Absent |
| Lower Columbia | 0.0400 | ( 4.00% ) | Present |
| Umpqua | 0.0261 | ( 2.61% ) | Present |
| Siletz-Yaquina | 0.0258 | ( 2.58% ) | Present |
| Upper Klamath Lake | 0.0234 | ( 2.34% ) | Absent |
| Middle Willamette | 0.0221 | ( 2.21% ) | Absent |
| Upper Willamette | 0.0218 | ( 2.18% ) | Absent |
| Wilson-Trusk-Nestuccu | 0.0200 | ( 2.00% ) | Present |
| Alsea | 0.0194 | ( 1.94% ) | Present |
| Siuslaw | 0.0187 | ( 1.87% ) | Absent |
| Washington | | | |
| Lake Washington | 0.0732 | ( 7.32% ) | Absent |
| Puget Sound | 0.0485 | ( 4.85% ) | Present |
| Duwamish | 0.0365 | ( 3.65% ) | Absent |
| Lower Crab | 0.0345 | ( 3.45% ) | Absent |
| Lower Yakima, Washington | 0.0301 | ( 3.01% ) | Absent |
| Upper Yakima | 0.0275 | ( 2.75% ) | Absent |
| Upper Columbia-Priest Rapids | 0.0269 | ( 2.69% ) | Absent |
| Snohomish | 0.0262 | ( 2.62% ) | Absent |
| Lower Cowlitz | 0.0224 | ( 2.24% ) | Absent |
| Puyallup | 0.0218 | ( 2.18% ) | Absent |

**Figure 2.2 Predicted Normalized Boat Flow as NZMS Introduction Risk**



# CHAPTER THREE

## New Zealand Mudsnails Habitat Suitability and Integrated Risk

Whether or not introduced species will survive in a new habitat is an important part of the analysis of invasive species (IS) risk. Species distribution models, often referred to as ecological niche models, bioclimatic envelopes, or habitat suitability models, can estimate habitat suitability for observed species and predict the probability of species occurrence when environmental information and predictors are available (Elith and Graham, 2009; Segurado and Araújo, 2004; ).

The niche concept, which determines habitat suitability, is based on joint environmental and ecological conditions that allow the species to meet the minimum requirement that the birth rate of a local population to be equal to or greater than the death rate, and per capita effects of the species on these environmental conditions (Chase and Leibold, 2003). The niche concept has been applied to predict the distribution of IS, e.g. Broennimann and Guisan, 2008; Peterson, 2003; Beerling et al. 1995. However, , but only a few studies have analyzed New Zealand mudsnails (NZMS). For example, Vinson et al. (2007) utilized ecological niche factor analysis to predict NZMS distribution in Idaho, Montana, Utah, and Wyoming while Loo et al. (2007) used the generic algorithm for rule production to predict NZMS distribution in Australia and North America. Simple logistic regression was used by Schreiber et al. (2003) to study NZMS dispersal in southern Victorian streams, Australia.

### 3.1. Species Distribution Model: Maximum Entropy Model

If presence and absence data are available, the outcome of niche models is usually more accurate than that of models based on presence-only data (Franklin, 2009). However, absence data is only obtainable under strict and consistent sampling, so the presence-only data requires caution in interpreting an unobservable occurrence as species absence or other possibilities. For example, species absence may be due to lack of survey of specific locations, or the previous absence data have not been updated to check recent infestations. Niche models using presence-only data include: ecological niche factor analysis, generic algorithms for rule production, and maximum entropy (Franklin, 2009). All three are non-parametric methods that identify rules of species distribution between species occurrence and environmental conditions without assuming a pre-determined distribution or parameters.

This study employs maximum entropy (Maxent) method because of presence-only data availability. Moreover, Maxent provides a probabilistic output, which can be combined with the output of the gravity model. Advantages of Maxent are the following: it requires presence-only data; it can employ both categorical and continuous data; it converges well to the optimum (maximum) entropy; the Maxent probability distribution has a mathematical definition; over-fitting can be prevented; it has potential to handle sampling bias, and its output is continuous, so fine distinction is possible among different regions. The disadvantages of Maxent are that it is sensitive to the number of regulations that can be placed and that conventional statistics software cannot estimate the model. Despite of its disadvantages, Maxent appears to have outperformed other presence-only data methods such as a genetic algorithm for rule production and envelope method in several studies (e.g. Elith and Graham, 2009; Elith et al. 2006; Phillips et al. 2006).

The following describes Maxent species distribution modeling based on Phillips et al. (2006) Let $\pi$ be an unknown distribution over a finite set $X$, which can be considered as grids of ecological domains. The distribution $\pi$ assigns a probability $\pi(x)$ to each element of $X$. Let $\hat{\pi}$ denote an approximation of the unknown distribution. The entropy of $\hat{\pi}$,

(3-1) $H(\hat{\pi}) = -\sum_{x \in X} \hat{\pi}(x)\, ln\hat{\pi}(x)$.

Equation (3-1) is an application of Shannon's (1948) measure of entropy representing uncertainty in a set of events. Based on given incomplete information (here, species observation and environmental conditions), the aim is to maximize this entropy value to find the unknown distribution. Assume that $f_1, \dots, f_n$ are known functions of features, e.g. environmental conditions, on $X$, and $f_j(x)$ is a realized value of the function. Accordingly, the expectation of features under $\pi$ is defined as $\sum_{x \in X} \pi(x) f_j(x)$ and denoted by $\pi[f_j]$. This expectation can be approximated by using empirical average of features based on independently drawn $m$ samples, $\tilde{\pi}[f_j] = \frac{1}{m}\sum_{i=1}^{m} f_j(x_i)$.

The objective is to find the probability distribution $\hat{\pi}$ that solves the problem:

(3-2) $\max H(\hat{\pi}) = -\sum_{x \in X} \hat{\pi}(x)\, ln\hat{\pi}(x)$

$\text{s.t. } \hat{\pi}[f_j] = \tilde{\pi}[f_j]$,

that makes the approximate expected features of unknown distribution equal to the approximate expected features of empirical samples. In fact, the derived means cannot be equal to the true means, so the constraint is relaxed as $\left|\hat{\pi}[f_j] - \tilde{\pi}[f_j]\right| \le \beta_j$. As a result, the raw output of Maxent is the exponential function that assigns a probability to each site. The results are not necessarily proportional to probabilities of the species presence since their sum must be equal to one and researchers usually handle a limited size of geographic area. That is, the raw result of Maxent is not an absolute probability of species occurrence, but it represents a ranking of species survival risk among regions.

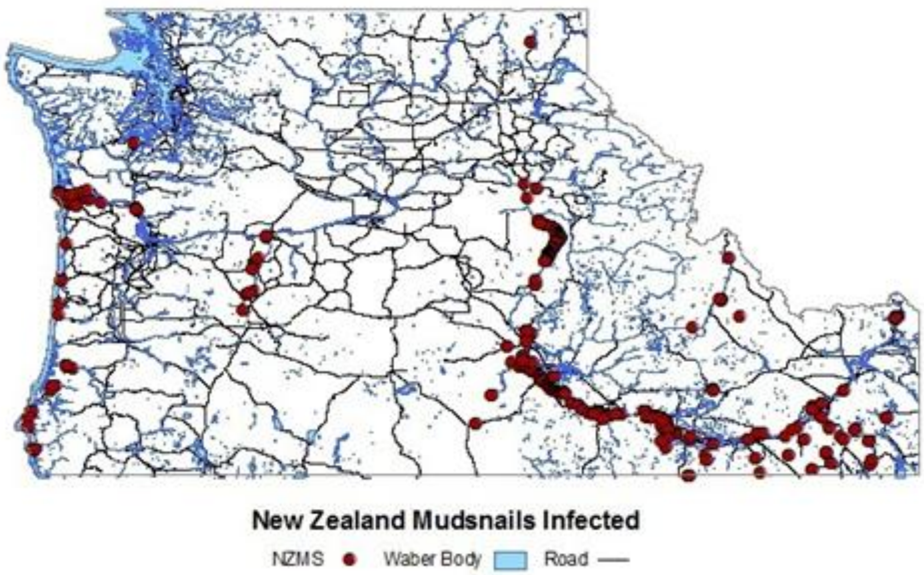
**3.2. Data and Estimation**

Standard statistical software cannot be used for Maxent analysis (Phillips et al., 2006), so I use the Maxent program developed by Steven Phillips (available at Schapire's webpage, see Bibliography). The above program utilizes raster geographic information systems (GIS) data and provides users a predicted map, simple statistic value, and response curves to each environmental factor. The GIS data generally involve two spatial features: vector and raster data. The vector data involves points, lines, and polygons while the raster data is composed of grids and each grid has a corresponding value for a location. Therefore, the raster data is known to be more useful to model continuous spatial variation such as precipitation, elevation, and soil erosion (Chang, 2010). Thus, the following described datasets are the raster data or they are converted to the raster data formats if the original data formats are not raster.

NZMS occurrence data comes from the U.S. Geological Survey Nonindigenous Aquatic Species by personal request, and Montana State University database. Note that both datasets are presence-only data. The occurrence data in these databases have been reported by different researchers at different time, so the sampling methods are less likely to be consistent across observations. Absence data is almost impossible to obtain. Figure 3.1 illustrates the distribution of NZMS in 2011.

Based on controlled experiments, the University of California-Santa Barbara's Riparian Invasion Research Laboratory (UCSB RIVRLab) considered the following habitat characteristics for NZMS survival and abundance: seasonality impacting reproduction, substrate, light, water temperature, velocity, salinity, and conductivity. In addition to these variables, stream order, pH of water, precipitation, and elevation are additional environmental factors determining the suitability of a habitat to NZMS.

**Figure 3.1 NZMS Distribution in 2011**




In reality, however, data availability and comparability in a broader region such as the Pacific Northwest, and correlation among environmental features in the invasion process constrain the entire reflection of characteristics noted above. For example, the Idaho Department of Environmental Quality does not provide water characteristics such as pH or conductivity and reports stream macroinvertebrate, habitat, and fish indexes only. Moreover, water characteristics data from the United States Geological Survey (USGS) provide incomplete coverage of the Pacific Northwest. Searching for daily, monthly, or annual dissolved oxygen statistics in Pacific Northwest Hydrologic Region from the USGS Water-Quality Data for the Nation, we found data reported for only 39 out of 2938 sites. Other studies have faced similar problems, e.g. missing water quality data accounted for 24 percent of Muirhead et al. (2011) study area.

This study considers the following basic environmental characteristics for the Maxent analysis: elevation, surficial geology, distance from cities, monthly precipitation, monthly maximum temperature, monthly minimum temperature, and whether the grid is aquatic or terrestrial. I anticipate that elevation can proxy stream order or velocity of water while surficial geology can identify suitable substrates. Use of monthly precipitation and temperature is likely to capture the suitability of specific seasons, water temperature, light and hydrology for NZMS survival and abundance. Distance to cities and water or land grid are the same GIS data used in the gravity model, but converted to the raster format. I employ terrestrial and aquatic grids because clipping aquatic habitats only could eliminate marsh or wet habitats around water streams. Also, there might be loss of information on boundary of water bodies due to conformity between vector (polygon) and raster data if only aquatic habitats are clipped. Data sources for the Maxent analysis are described in Appendix 3.1.

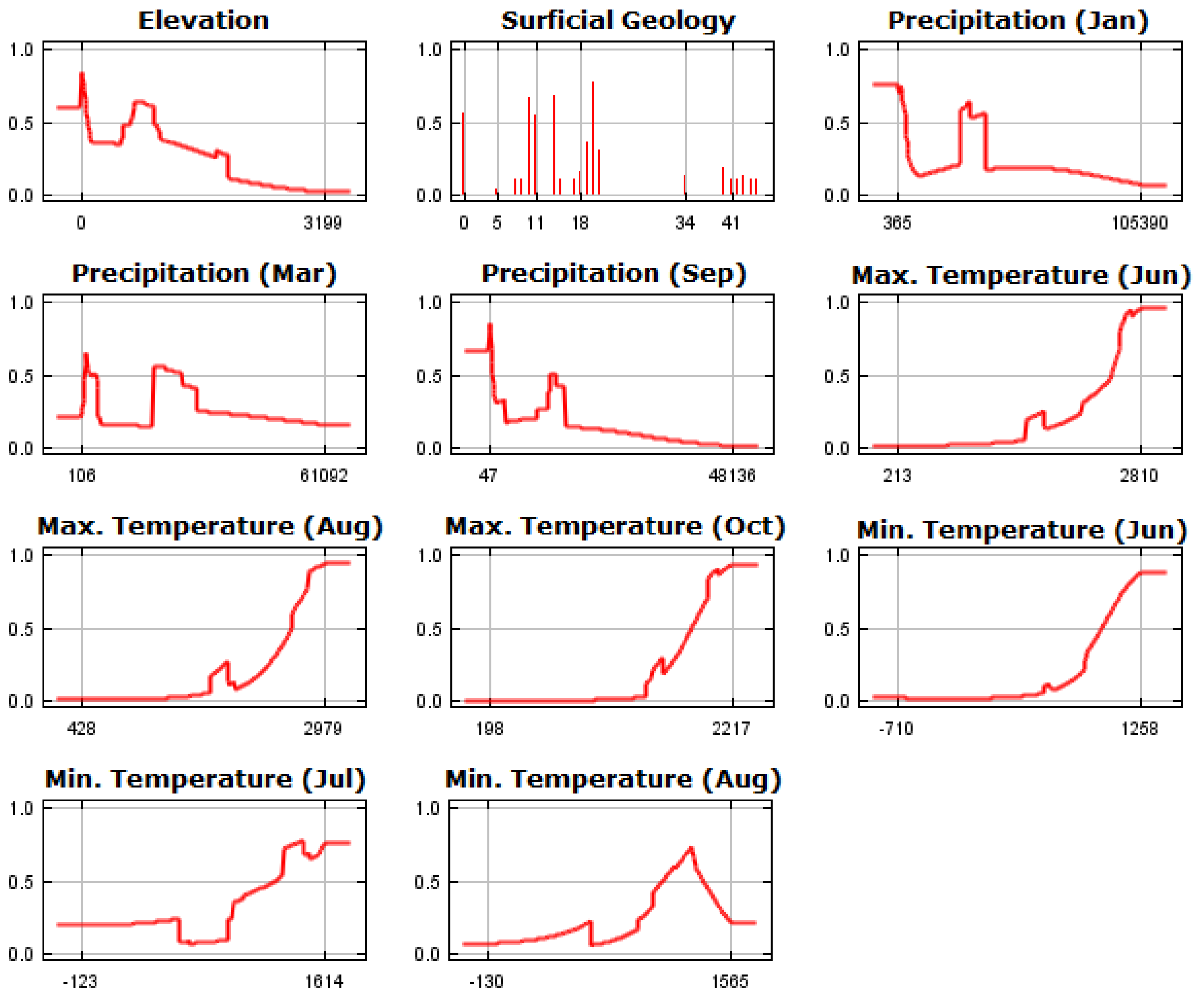
### 3.3. Results and Discussion

Maxent model's fit is assessed using the receiver-operation characteristic. For this purpose, the area under the curve (AUC) plotting the false-positive rate (prediction of species presence when absence is observed) against true positive rate (prediction of species presence when presence is observed) is computed. The higher the AUC, the greater is the predictive performance of Maxent (Franklin, 2009). Application of the Maxent model has predicted NZMS occurrence with high accuracy since the AUC of 75% training data (25% test data) is 0.978 (0.931). Additional validation of Maxent application comes from the jackknife test, which measures the contribution of environmental characteristics by removing each of them in order (Phillips, 2011). If there are N observations, the jackknife sampling employs N subsamples with a size of N-1 observations by dropping each observation in order and evaluates the estimators N times with subsamples (Cameron and Trivedi, 2005). Variables used in the jackknife sampling are described in Appendix 3.1.

Figure 3.2 shows response curves describing the change in logistic probability by altering each relevant variable (only) of the model. The environmental variables in Figure 3.2 are selected based on the jakknife test result. Figure 3.2 suggests that the probability of high elevations being suitable for NZMS is low. If a water body is located in high elevation, it is more likely to have a high velocity or lower temperature. High velocity or lower temperature may hinder NZMS from grazing surfaces of objects including aquatic plants, and this is consistent with result of Vinson et al. (2007). The second graph shows that surficial geologic characteristics such as bedrock (category 20), floodplain and alluvium gravel terraces (category 10), and lake deposits (category 14) are more suitable habitats for NZMS. A particular range of precipitation in January, March, and September (around 270-405 mm, 175-290 mm, and 130-155 mm, respectively, which are above average for those three months) appear to suit NZMS habitat.

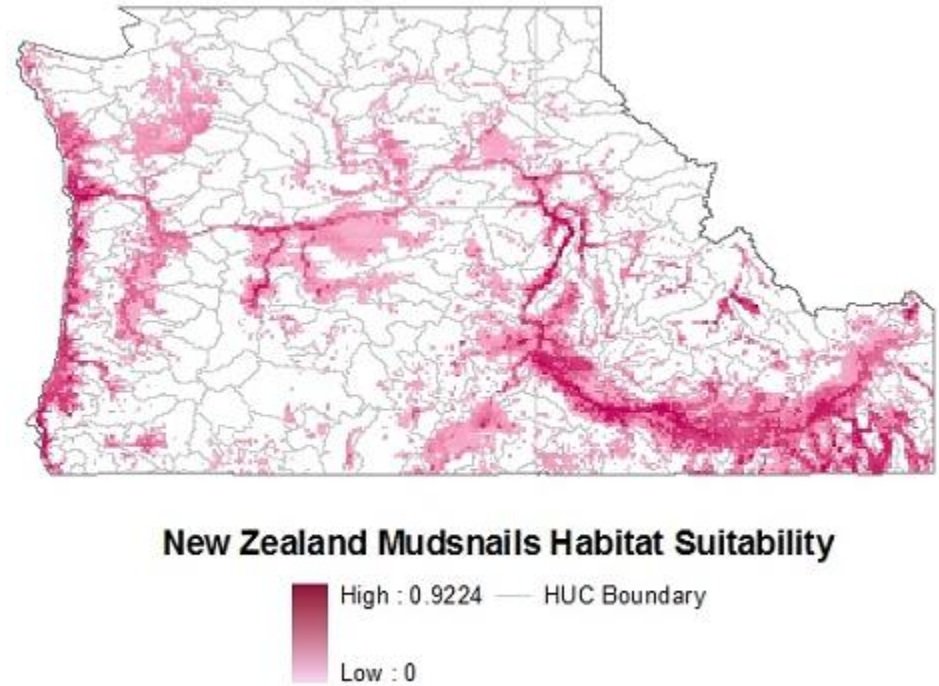
With regard to temperature, experiments at UCSB RIVRLab (2011) show that the 10-week average growth rate of NZMS was highest when water temperature is 20 ℃, compared with 13 ℃ and 27 ℃. Similarly, Dybdahl and Kane (2005) estimated NZMS population growth rate was optimal at 18 ℃ rather than 12 ℃ and 24 ℃ in water. The temperature response curves in Figure 3.2 show spikes around 17 ℃, 18 ℃, and 15 ℃, respectively, during June, September, and October (maximum temperatures) suggesting suitability of such environments to NZMS. Note, however, that I do not find data on water temperature to refine this association. In the case of minimum temperatures, response curves of June and July are positively sloped until their highest temperatures: 13 ℃ and 16 ℃. Although the response curve for August temperature spikes around 13 ℃, it appears to be positively sloped, a result consistent with that of Hall et al. (2003).

**Figure 3.2 Response Curves of Maxent Results**




The default Maxent output in logistic form, which ranges between 0 and 1, can be interpreted as the probability of habitat suitability (Phillips and Dud k, 2008). The Maxent probabilities are presented in Figure 3.3, where the darker shade represents a higher probability of an environment suitable for the specific species.

**Figure 3.3 Maxent Results as NZMS Habitat Suitability**




The probability of habitat suitability ranges from almost 0 to 0.9224. In order to precisely interpret this spatial risk, I average the probabilities of habitat suitability in water bodies of a given hydrologic unit code area (HUC), and reclassified the average probability percentiles. As a result, the class with the highest 10% average probability of habitat suitability in HUCs ranges from 0.2894 to 0.5896, the highest 20% average probability ranges from 0.1644, the highest 30% average probability ranges from 0.0866 (Table 3.1).

**Table 3.1 Hydrologic Units with High Risk of NZMS Habitat Suitability**

| Invasion Status | Hydrologic Unit Name with High Risk Percentile |
|---|---|
| NZMS Observed | 10%<br>Middle Bear, Lower Bear-Malad, Curlew Valley, American Falls, Portneuf, Lake Walcott, Raft, Upper Snake-Rock, C. J. Idaho, Middle Snake-Succor, Lower Boise, Middle Snake-Payette, Lower Malheur, Brownlee Reservoir, Hells Canyon, Lower Snake-Asotin, Lower Columbia, Necanicum, Wilson-Trusk-Nestuccu, and Siletz-Yaquina |
| | 20%<br>Little Wood, Crooked-Rattlesnake, Lower Owyhee, Bully, Pahsimeroi, Lower Deschutes, Lower Columbia-Clatskanie, Umpqua, Coos, and Sixes |
| | 30%<br>Upper Henrys, Salmon Falls, Big Wood, Bruneau, and Alsea |
| NZMS Not-Observed | 10%<br>Willapa Bay and Siltcoos |
| | 20%<br>Thousand-Virgin, Idaho Falls, Goose, Willow (HUC code 17050119 and 17070104), Lower Salmon, Middle Columbia-Hood, Lower John Day, Grays Harbor, Nehalem, Siuslaw, and Coquille |
| | 30%<br>Central Bear, Bear Lake, Payette, Weiser, Powder, Imnaha, Lower Grande Ronde, Lower Snake-Tucannon, Middle Columbia-Lake Wallula, Klickitat, Trout, Upper Willamette, Middle Willamette, Lower Willamette, Middle Rogue, Chetco, and Alvord Lake |

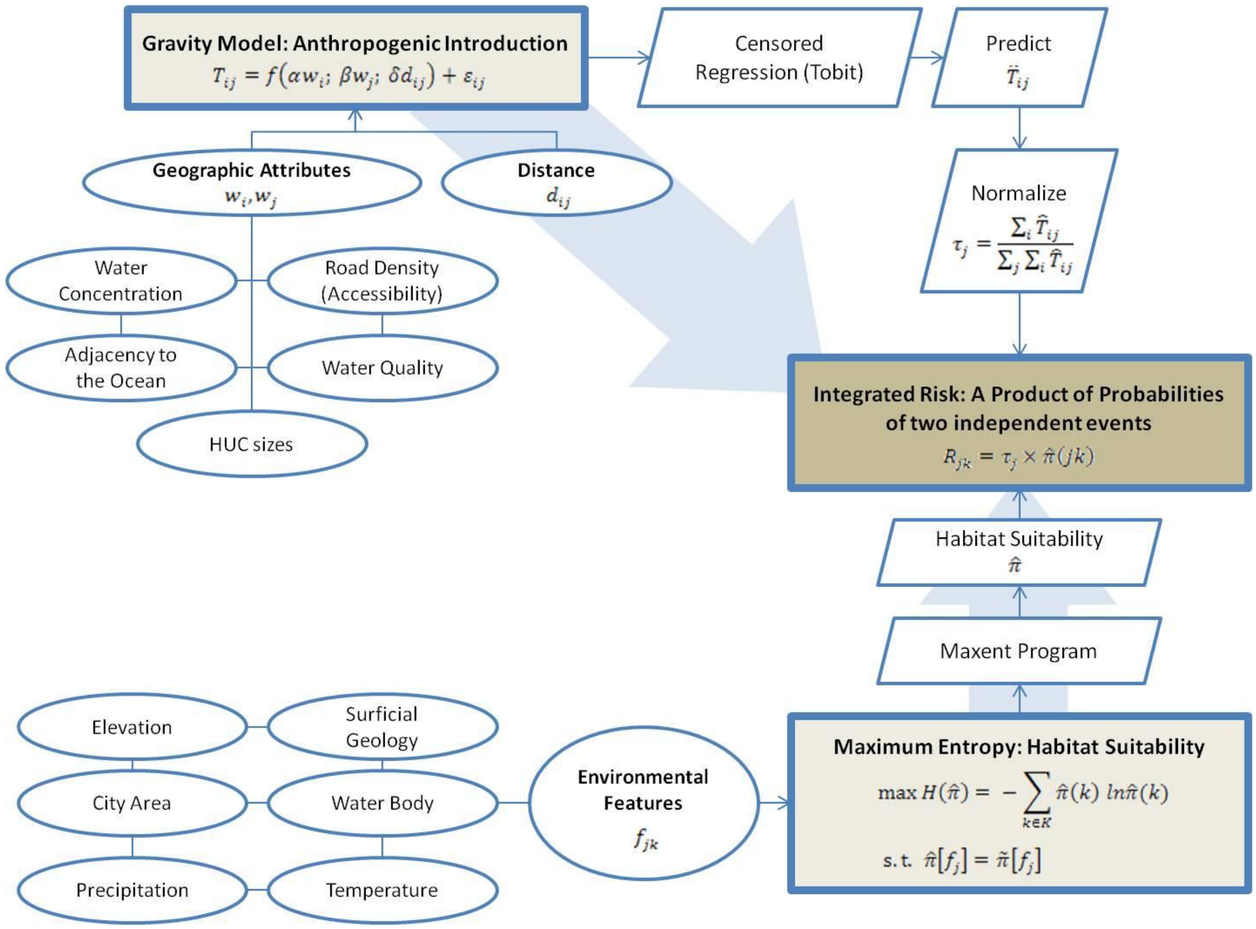
### 3.4. Integrated probability of NZMS invasion

From the results of gravity and Maxent models, I integrate two probabilistic events, anthropogenic introduction and habitat suitability, in a cross-sectional or spatial context (Leung and Mandrak, 2007):

(3-3) $R_j = \tau_j \times \pi(j)$,

where $R_j$ is region $j$'s relative establishment risk or probability, which is a product of the probability of anthropogenic introduction, $\tau_j$, and of habitat suitability, $\pi(j)$ (see Figure 3.4).

**Figure 3.4 Flow Diagram of Integrated Risk Estimation Model**




Both $\tau_j$ and $\pi(j)$ take values between 0 and 1, so the relative establishment probability of the region $j$ in Equation (3-3) is also in the range between 0 and 1. The relative risk will be 0 if either $\tau_j$ or $\pi(j)$ is 0: if there is no propagule pressure, or a given habitat is not suitable for the species, then the risk of establishment in the recipient region is zero.

Figure 3.5 shows the integrated establishment probability, i.e. Equation (3-3) adjusted for the possibility that the gravity model and Maxent analysis use different spatial units, $R_{jk} = \tau_j \times \hat{\pi}(jk)$ where $\hat{\pi}$ indicates an approximated distribution of unknown distribution $\pi$. Similar to Figure 3.3, a darker shade area means higher probability of NZMS invasion.

**Figure 3.5 Integrated Risk of NZMS Invasion (Relative Probability/Year)**

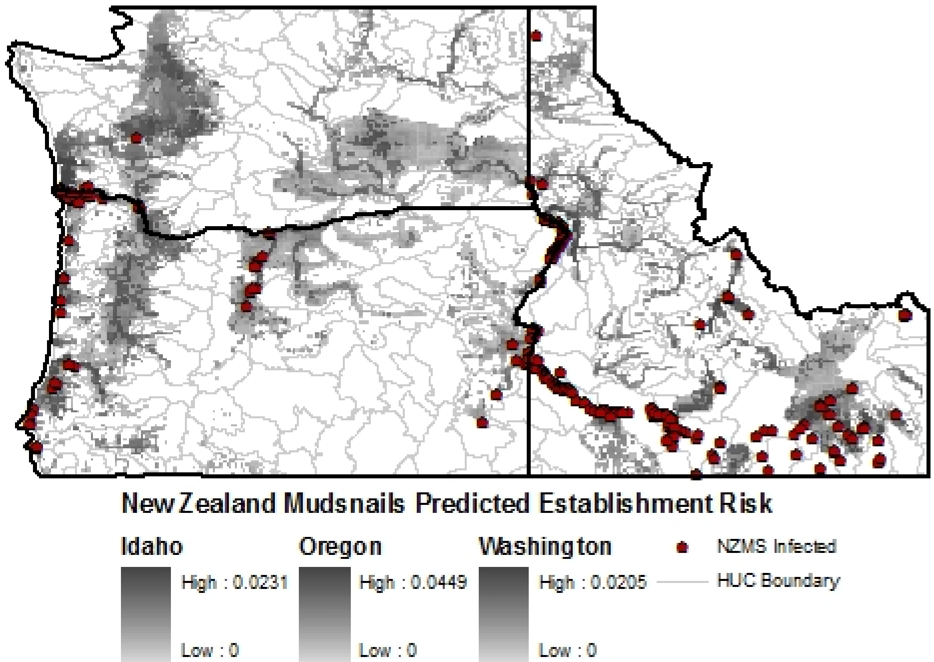



**Table 3.2 Hydrologic Units with High Integrated Risk of NZMS Invasion**

| Invasion Status | Hydrologic Unit Name with High Risk Percentile (10%) |
|---|---|
| NZMS Observed | Idaho<br>Middle Snake-Payette, Middle Snake-Succor, American Falls, Middle Bear, Upper<br>Oregon<br>Lower Columbia, Siletz-Yaquina, Necanicum, Umpqua, Wilson-Trusk-Nestuccu, Middle Snake-Payette, and Coos<br>Washington<br>Lower Columbia and Lower Columbia-Clatskanie |
| NZMS Not-Observed | Idaho<br>(Lower Salmon and Goose if the percentile is 20%)<br>Oregon<br>Siltcoos and Lower Willamette<br>Washington<br>Willapa bay, Lake Washington, Middle Columbia-Hood, Grays Harbor, and Upper Columbia-Priest Rapids |

Table 3.2 categorizes Pacific Northwest HUCs according to establishment probability and species presence. Unlike the ranking of habitat suitability, the categorization of establishment probability considers states' boundaries because the predicted normalized boat flows, $\tau_j$, apply to individual states. Finally, the relative establishment risks of water bodies are averaged in each HUC and classified into percentiles.

HUCs with the highest risk (top 10%) have already been invaded by NZMS in Idaho and Oregon. Table 3.2 shows the high risk HUCs whose probability of establishment ranges between 0.0045-0.0065 in Idaho, 0.0048-0.0259 in Oregon, and 0.0018-0.0063 in Washington. Siltcoos and Lower Willamette in Oregon, Willapa Bay, Lake Washington, Middle Columbia-Hood, Grays Harbor, and Upper Columbia-Preist Rapids in Washington are predicted to have high invasion probability of NZMS among HUC where presence has not been reported. In Idaho, NZMS have invaded all HUCs with the highest 10% percentile of integrated probability. A comparison of Table 3.2 with Tables 2.2 in the previous chapter and Table 3.1 shows that habitat suitability plays a bigger role relative to introduction in determining NZMS invasion.

# CHAPTER FOUR

# Potential Damages and Management Cost of New Zealand Mudsnails

## 4.1. Damages of New Zealand Mudsnails: Biodiversity Loss and Utility Loss

To derive the impact of New Zealand mudsnails (NZMS) on aquatic habitats, NZMS presence is considered as a threat source that would reduce suitability to other aquatic species. I employ Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) developed by the Natural Capital Project, which is a tool to estimate the value of ecosystem (Tallis et al., 2011). Applications of InVEST considering invasive species (IS) as a main threat are readily found from the Ecosystem Services Project Database by the Natural Capital Project. These applications also take other threats such as climate change, habitat conversion, or overharvest into account while this study considers IS as the only threat to ecosystem.

Specifically, "Biodiversity: habitat quality and rarity" module in InVEST is used in this study. This module calculates habitat degradation and habitat quality by using current land cover and source of threats using raster datasets with assumptions about maximum distance and relative impact of each threats as well as relative barriers (accessibility) to threat sources and sensitivity of habitats to each threat. The following describes the biodiversity module (Tallis et al., 2011).

(4-1) $$D_{xj} = \sum_r \sum_y \left(\frac{w_r}{\sum_r w_r}\right) r_y i_{rxy} \beta_x S_{jr}$$

where $D_{xj}$ represents the total threat level in grid cell $x$ with habitat type $j$, $w_r$ is a weight of each threat $r$, and $y$ indexes a grid cell in threat sources. $i_{rxy}$ is the impact of threat $r$ in grid cell

$y$ to grid cell $x$, and $\beta_x$ represents accessibility to threat sources, so a small $\beta_x$ implies less impact of relevant threats in grid cell $x$. Finally, $S_{jr}$ indicates sensitivity of habitat type $j$ to threat $r$. Therefore, the total threat in grid $x$ with habitat type $j$ is a sum of weighted impact of threat $r$ from threat sources to grid $x$, combined with relative barriers to threat sources and sensitivity of given habitat type. A habitat quality value is then derived as

(4-2) $$Q_{xj} = H_j\left(1 - \left(\frac{D_{xj}^2}{D_{xj}^2 + k^2}\right)\right).$$

A habitat quality value in grid $x$ with habitat $j$, $Q_{xj}$, increases in habitat suitability $H_j$ while decreasing in the total threat level $D_{xj}$ from equation (4-1). $H_j$ indicates habitat suitability of land use/land cover type $j$ which can be binary, i.e. 0 means non-habitat and 1 means habitat. $k$ is a scaling constant. $Q_{xj}$ then ranges from 0 to 1, and higher value indicates better habitat quality.

In order to use the InVEST model, the Pacific Northwest area with water bodies (U.S. Census Bureau, 2011) and NZMS observation data (from Montana State University and U.S. Geological Survey, personal request) are converted to raster datasets with 1km resolution and fed into the InVEST biodiversity model. It is assumed that maximum distance of NZMS impact is 10km, and the impact decays exponentially. Since NZMS presence is the only threat in the model, the weight of NZMS threat is set to be 1. Habitat types are categorized aquatic and non-aquatic, and sensitivity of aquatic habitat to NZMS is also set to be 1. The estimated aquatic habitat quality values from the InVEST are averaged in water bodies in a given county.

The next question here is how to assign a value to the above measure of habitat quality. Since habitat quality is a non-market good, non-market valuation methods such as travel cost method, hedonic pricing, benefit transfer, contingent valuation, and others are needed in deriving a value. In this study, a discrete choice model is adopted to evaluate willingness to pay (WTP) of anglers according to habitat quality change led by NZMS presence. Specifically, a random utility model (RUM) with a linear utility function is employed to analyze angler's choice behavior (Haab and McConnell, 2002). The RUM can estimate anglers' loss of utility from locations with NZMS invasion, which can be translated into a value for habitat quality. The random utility function can be expressed as

(4-3) $U_{nj} = \beta' x_{nj} + \varepsilon_{nj}$

where $x_{nj}$ represents the observable attributes of alternative $j$ that an individual $n$ chooses, including aquatic habitat quality, and $\varepsilon_{nj}$ is a random variable. Let us assume that each $\varepsilon_{nj}$ is independent and identically distributed Type-I extreme value, then the probability that the individual $n$ chooses the county $j$ is

(4-4) $P_{nj} = \frac{exp(\beta' x_{nj})}{\sum_i \exp(\beta' x_{ni})}$

which is the logit choice probability. The parameter vector $\beta$ is obtainable by estimating a conditional logit model.

The linear utility model is specified

(4-5) $U_{nj} = (1 - No_j) \times (\beta_y Price_j + \beta_s \ln Water\ area_j + \beta_r Road\ density_j$

$+\beta_o Ocean\ dummy_j + \beta_w Water\ Herfindahl_j + \beta_p Park\ Herfindahl_j$

$+\beta_q Habitat\ quality_j) + \beta_{no} No_j + \varepsilon_{nj}.$

$No_j$ is a dummy variable indicating whether the angler $n$ chooses not to visit any counties in Oregon, so choice of not to visit Oregon is one of the alternative $j$'s in addition to 36 counties. $Price_j$, $\ln Water\ area_j$, $Road\ density_j$, $Ocean\ dummy_j$, $Water\ Herfindahl_j$, $Park\ Herfindahl_j$, and $Habitat\ quality_j$ reflect attributes of each alternative county $j$. They represent travel cost and opportunity cost of traveling, the natural log of water size, road density, adjacency to the Pacific Ocean, water body concentration, national and state park area concentration, and habitat quality value from the InVEST model, respectively. Price is a sum of transportation cost calculated as $0.35 per mile and opportunity cost of travel time derived as "annual income/2040" by following an example from Haab and McConnell (2002). The travel distance and time are derived by using the Google Map service. The natural log of water size plays a role of a size variable to relieve aggregation of alternatives. Spatial units in real alternatives (e.g. launch site, campground, etc.) and available data (e.g. counties) occurs in many cases. Adding size variables is the way to deal with the aggregation problem when we do not know the size of an aggregate alternative. However, when we have a single size variable like this study, we can simply introduce it into the model as if we know the size of each alternative (Ben-Akiva and Lerman, 1985). In addition, equation (4-5) states that utility of the angler who did not choose to travel would be $U_{nj} = \beta_{no} + \varepsilon_{nj}$.

The Oregon travel survey data (Dean Runyan Associates, 2009) are used to estimate the conditional logit model. Oregon angler license holders were asked whether they had fished in Oregon from April 2008 to September 2008. However, the information for anglers visiting Idaho and Washing is not available. I assumed that most anglers visiting each state are residents of the state and its neighbor states which share the borders, and then the logit model is estimated with sub-samples of the Oregon travel survey data. This assumption is supported by the Oregon travel survey data since 97% of anglers visiting Oregon came from Oregon and its neighbor states. The data is divided according to anglers' residence state: one group from Oregon and its neighbor states—Washington, California, Nevada, and Idaho; another group from Idaho and its neighbor states—Washington, Oregon, Nevada, Utah, Wyoming, and Montana; and the last group from Washington and its neighbor states—Oregon and Idaho. In conclusion, the decision making of three groups would represent anglers' behavior visiting Oregon, Idaho, and Washington, respectively. The logit models are estimated separately with each group to derive individual angler's WTP with respect to habitat quality change on average. Total WTP of anglers visiting each state are calculated by multiplying the individual average WTP and the number of visitors. The estimation results are in Table 4.1.

**Table 4.1 Anglers' Choice to Visit: Results of the Conditional Logit Model**

| Independent Variable | Oregon and Neighbor States | | Idaho and Neighbor States | | Washington and Neighbor States | |
|---|---|---|---|---|---|---|
| | **Coefficient** | **Standard Error** | **Coefficient** | **Standard Error** | **Coefficient** | **Standard Error** |
| $Price_j$ | -0.001 *** | 9.67E-05 | -0.001 *** | 9.85E-05 | -0.001 *** | 9.95E-05 |
| $\ln(\text{Water area})_j$ | 0.268 *** | 0.018 | 0.263 *** | 0.018 | 0.259 *** | 0.018 |
| Road $density_j$ | 1.689 *** | 0.136 | 1.803 *** | 0.138 | 1.797 *** | 0.139 |
| Ocean $dummy_j$ | 0.726 *** | 0.039 | 0.713 *** | 0.040 | 0.709 *** | 0.040 |
| Water $Herfindahl_j$ | -0.014 *** | 0.001 | -0.015 *** | 0.001 | -0.015 *** | 0.001 |
| Park Herfindahlj | -0.019 *** | 0.006 | -0.023 *** | 0.006 | -0.023 *** | 0.006 |
| Habitat $quality_j$ | 0.516 ** | 0.236 | 0.489 ** | 0.236 | 0.492 ** | 0.235 |
| $No_j$ | 5.309 *** | 0.226 | 5.287 *** | 0.225 | 5.273 *** | 0.225 |
| Log likelihood | -17415.206 | | -16656.347 | | -16477.396 | |
| $-\frac{\Delta Habitat\ quality \cdot \beta_q}{\beta_y}$ | $\Delta Habitat\ quality \times \$363.71$ | | $\Delta Habitat\ quality \times \$350.20$ | | $\Delta Habitat\ quality \times \$353.02$ | |

NOTE: *** and ** indicate 1% and 5% level of significance, respectively.

In all groups, all variables are statistically significant at 1% level except that habitat quality is significant at 5% level. However, the signs of marginal effects can be different from those of the coefficients because the marginal effects of a conditional logit model are not equal to the coefficients. Alternatively, odds ratio are calculated to compare explanatory variables' effects on probability in choosing to visit a county (Table 4.2).

Increase in travel cost and opportunity cost, water body concentration, and national and state park area concentration would decrease the probability of choosing that destination, while increase in water body size, road density, adjacency to the Pacific Ocean, and habitat quality would increase the probability. For example, the probability to choose the site would decrease by 0.1% if travel and opportunity costs increase by one dollar, but the probability would increase by 30% if water body size (in natural log) increases by 1 unit.

**Table 4.2 Anglers' Choice: Odds Ratio of the Conditional Logit Model**

| **Independent Variable** | **Oregon and Neighbor States** | **Idaho and Neighbor States** | **Washington and Neighbor States** |
|---|---|---|---|
| $Price_j$ | 0.999 | 0.999 | 0.999 |
| $\ln(Water\ area)_j$ | 1.300 | 1.307 | 1.296 |
| Road $density_j$ | 6.067 | 5.415 | 6.031 |
| Ocean $dummy_j$ | 2.040 | 2.066 | 2.032 |
| Water $Herfindahl_j$ | 0.985 | 0.986 | 0.985 |
| Park Herfindahlj | 0.978 | 0.981 | 0.977 |
| Habitat $quality_j$ | 1.630 | 1.676 | 1.635 |

Figure 4.1 also supports the odds ratio, depicting the relationship between predicted probabilities and the explanatory variables in choosing a site among 36 counties in Oregon. The shapes of graphs are similar among three groups: Oregon and neighbor states, Idaho and neighbor states, and Washington and neighbor states. As the odds ratio implies, travel and opportunity costs has a negative relationship with the predicted probabilities, and water size, road density, adjacency to the ocean, and habitat quality has a positive relationship with the predicted probabilities. The predicted probabilities of water body concentration and park area

concentration have inversed U-shape and U-shape graphs, so it is ambiguous as to whether they have negative or positive relationships.

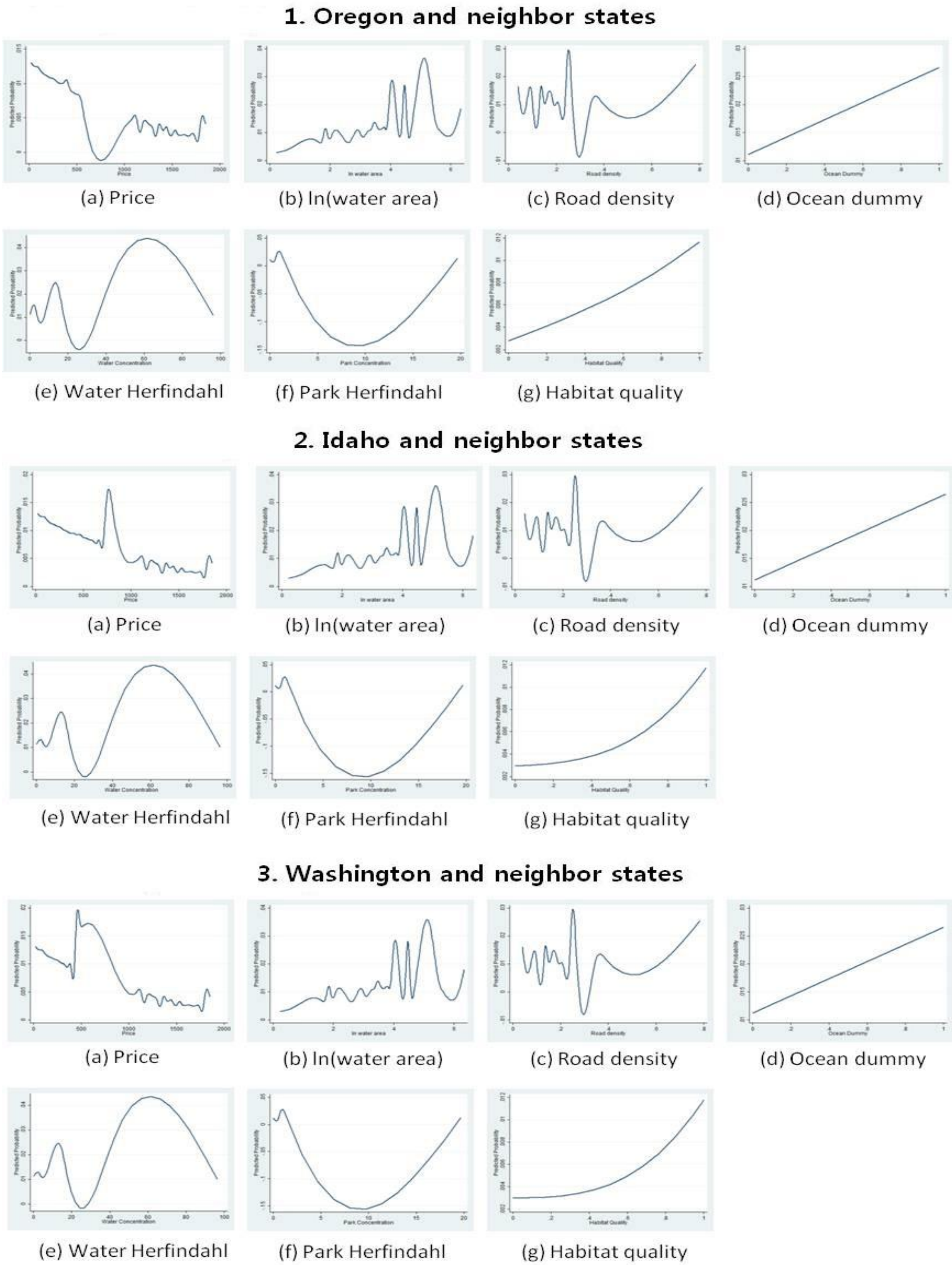
From the logit model, an angler's WTP for improving aquatic habitat quality is derived as the following (Haab and McConnell, 2002):

(6) $$WTP = -\frac{\Delta Habitat\ quality \cdot \beta_q}{\beta_y}.$$

$\beta_Q$ and $\beta_y$ indicate marginal utility of aquatic habitat quality and income, respectively; and $\Delta Habitat\ quality$ represents aquatic habitat quality improvement. Accordingly, the average WTP of individual angler for one unit improvement in aquatic habitat quality is \$363.71, \$350.20, and \$353.02 in Oregon, Idaho, and Washington, respectively (shaded row in Table 2.1). Note that the aquatic habitat quality is a relative value.

The habitat quality of sites where NZMS have been found is used as proxy for future habitat quality change, and it is assumed that all water bodies are candidates for invasion by NZMS. Specifically, the average value of habitat qualities at pin-pointed NZMS-present area is derived and assumed as future habitat quality. The average habitat quality of NZMS-present areas is 0.159; thus, habitat quality change ($\Delta Habitat\ quality$) is equal to the difference between 0.159 and the estimated current habitat quality. For example, if there is a region with the current habitat quality equals 1 where NZMS have not observed up to now, the habitat quality change caused by future NZMS invasion would be 0.841 (i.e. 0.841=1-0.159). Then, an individual angler's WTP of this example comes to be \$305.88, \$294.52, and \$296.89, for Oregon, Idaho, and Washington, respectively.

**Figure 4.1 In-Sample Predicted Probabilities of the Conditional Logit Model**



**4.2. Damages of New Zealand Mudsnails: Water Facilities and Boat Contamination**

NZMS damages in water treatment and hydroelectricity plants are calculated based on Connelly et al. (2007) who summarized survey of damages and management costs of zebra mussels. Although realized damages of NZMS are not fully analyzed, partial imputation from relatively abundant analyses on zebra mussels such as Connelly et al. (2007) can be helpful as noted by Proctor et al. (2007). Proctor et al. (2007) explain that biofouling is a typical direct economic impact of invasive mollusks and introduced an example of NZMS blocking water pipes. Risk assessment report of Non-native Species Secretariat in U.K. (NNSS) and Invasive Species Specialist Group (ISSG) database also consider, biofouling and blocking intake water pipes as potential NZMS damages.

Thus, I employ average damages per hydroelectricity plant or water treatment plant from Connelly et al. (2007) and assumed that NZMS damages would be proportional to zebra mussel damages as 50% level since Proctor et al. (2007) suggest that damage potential of NZMS may be lower than that of zebra mussels. Note that this is a provisional assumption in this chapter, and the proportion to zebra mussel damages will change to derive more management implication in the next chapter. In their article, Connelly et al. originally summarized that the mean "lost production and revenues" of power generation plants and drinking water treatment facilities is $124,110 annually.

The number of hydroelectricity plant in each county of Idaho, Oregon, and Washington is taken from the U.S. Energy Information Administration (2011) and normalized by county area. The number of drinking water treatment plants is approximated by using the number of public water systems whose source is surface from the Safe Drinking Water Information System data (U.S. Environmental Protection Agency, 2011). However, this public water system data only provides information about the primary counties and population size served by the systems, not about water sources in which the water treatment plants are located. Therefore, I derive the number of public water system in each county by matching source water map data with each public water system identity number (PWSID), and then derived the number of public water systems in each county. The source water maps are available from Idaho Department of Environmental Quality, Oregon Department of Environmental Quality, and Washington Department of Health. Unlike the case of hydroelectricity plants, Connelly et al. (2007) provided the average annual "lost production and revenues" of water treatment plants by capacity categories: $0 for facilities with capacity less than or equal to 1 million gallons per day (MGD), or greater than or equal to 11 MGD; $1,453 for facilities with capacity 2-10 MGD. However, it might be unreasonable that there is no damage in a water treatment facility regardless of its capacity. Thus, I adopted $726.5, half of $1,453, for facilities of capacity less than 2 MGD and $1,453 for those of capacity greater than or equal to 2 MGD. Based on information about the amount of surface water withdrawals in each county from U.S. Geological Survey's 2005, the average capacity of water treat plants in each county is calculated.

I also consider cost of frequency increase in painting a boat and replacing a boat motor as NZMS boat damages. This is because NZMS can attach to material's surface like zebra mussels, and boat contamination is one of the major pathways of zebra mussels (Griffiths et al., 1991). The number of boats is derived from boat registration data (also used in Chapter 2) and Recreational Boating Statistics 2011 (U.S. Department of Homeland Security and U.S. Coast Guard Office of Auxiliary and Boating Safety, 2012). The number of boats less than 26 feet in study area is derived since 95% of boats registered in the U.S. were less than 26 feet in 2011 according to Recreational Boating Statistics and most large vessels are usually used in the sea, not freshwater water bodies. The replacement of a motor and painting a boat are assumed to happen every 10 years and 3 years, respectively, and then expenditure on replacement and painting are converted to annual expenditure.

**Table 4.2 Summary of Estimated NZMS damages (USD/Year)**

| 6-digit Hydrologic Unit | | Hydroelectricity Plants | Drinking Water Treatment Plants | Boat Maintenance | Utility Loss of Anglers |
|---|---|---|---|---|---|
| ID | 160101 | 122 | 0 | 114,596 | 3,402,254 |
| | 160102 | 353,930 | 0 | 1,471,850 | 10,369,226 |
| | 160203 | 11,290 | 0 | 218,642 | 2,303,628 |
| | 170101 | 357,993 | 3,269 | 833,162 | 6,050,931 |
| | 170102 | 523,944 | 5,086 | 6,176,472 | 6,885,400 |
| | 170103 | 361,106 | 6,902 | 12,556,554 | 10,772,723 |
| | 170401 | 362,689 | 0 | 1,851,226 | 7,739,445 |
| | 170402 | 6,555,652 | 363 | 14,727,695 | 13,188,720 |
| | 170501 | 1,609,691 | 10,171 | 19,538,093 | 12,988,406 |
| | 170502 | 82,742 | 363 | 529,998 | 6,128,305 |
| | 170601 | 2,231 | 1,090 | 1,173,517 | 5,350,738 |
| | 170602 | 106,699 | 2,180 | 3,681,004 | 8,568,447 |
| | 170603 | 406,651 | 8,355 | 4,635,098 | 9,389,787 |
| OR | 170501 | 171,949 | 727 | 438,392 | 9,378,520 |
| | 170502 | 246,908 | 1,090 | 1,218,862 | 8,849,838 |
| | 170601 | 257,583 | 727 | 443,690 | 5,515,966 |
| | 170701 | 1,638,017 | 2,906 | 2,043,145 | 11,628,987 |
| | 170702 | 847,689 | 0 | 255,147 | 5,776,610 |
| | 170703 | 2,305,712 | 727 | 7,930,460 | 11,197,335 |
| | 170800 | 1,158,596 | 5,812 | 4,499,587 | 5,338,226 |
| | 170900 | 3,654,750 | 29,060 | 18,449,732 | 13,870,272 |
| | 171002 | 159,891 | 14,530 | 7,834,304 | 22,787,462 |
| | 171003 | 1,250,428 | 21,069 | 9,765,328 | 23,331,186 |
| | 171200 | 24,982 | 0 | 235,755 | 14,530,351 |
| | 180102 | 250,072 | 0 | 2,672,215 | 10,931,116 |
| | 180200 | 225 | 0 | 675,299 | 5,703,338 |
| WA | 170102 | 544,200 | 2,180 | 0 | 13,487,522 |
| | 170103 | 687,727 | 0 | 2,180,712 | 15,670,054 |
| | 170200 | 8,323,726 | 6,902 | 21,781,635 | 29,655,425 |
| | 170300 | 532,865 | 3,633 | 2,872,977 | 16,861,124 |
| | 170601 | 966,686 | 0 | 288,287 | 18,925,155 |
| | 170701 | 1,164,868 | 2,543 | 2,074,107 | 20,480,838 |
| | 170800 | 969,544 | 5,086 | 9,453,676 | 42,141,064 |
| | 171001 | 673,333 | 6,175 | 2,190,546 | 2,076,353 |
| | 171100 | 3,884,369 | 42,864 | 27,207,423 | 515,365 |

The motor prices are collected from the website (boats.net) based on assumption boats less than 16 feet and between 16 and 26 feet would use motors less than 8 horsepower and between 8 and 9.9 horsepower, respectively. And price of paint is set to be $320 for boats less than 16 feet and $551.25 for boats between 16 and 26 feet. Since this is another case of biofouling that can be also caused by zebra mussels, the boat maintenance costs will also be changed like the damages of water facilities in the next chapter. In other words, I regard 10-year boat motor change and 3-year repainting as 50% level of biofouling caused by zebra mussels.

### 4.3. Management Costs of New Zealand Mudsnails

Statewide and local management are categorized into three categories: prevention, EDRR and follow-up activities such as eradication and containment (referred to as EDRR plus), and ex-post management without EDRR. This is because the distinction between ex-post management such as eradication and containment may vary, depending on the definition of their effectiveness. Moreover, the most practical NZMS management activities are prevention and EDRR because it is almost impossible to remove NZMS chemically and physically if they have established (Proctor et al., 2007).

Specifically, the management options include

- statewide prevention, EDRR plus, and ex-post management without EDRR;
- local prevention, EDRR plus, and ex-post management in water facilities; and prevention activities of recreational boaters and hatcheries which would reduce introduction risk of NZMS.

In addition, prevention by boaters and hatcheries to keep NZMS from being introduced can also be containment in terms of blocking NZMS dispersal from invaded areas to uninvaded areas.

The statewide NZMS management costs are derived from a phone survey that asked IS field managers in Idaho, Oregon, and Washington about their real expenditure on IS management from 2008 to 2011 (Lam, 2012). The responses related to NZMS and aquatic invasive species are considered. Moreover, if there had been expenditure on local government such in a certain county or water body, the expenditure is converted to hypothetical statewide one weighted of related area and water body sizes.

**Table 4.3 Summary of NZMS Management Costs: Statewide (USD/Year)**

| State | Prevention | EDRR plus | Ex-post management |
|---|---|---|---|
| Idaho | 605,414 | 10,938,462 | 10,544,451 |
| Oregon | 396,103 | 13,492,907 | 13,070,545 |
| Washington | 416,500 | 47,999,754 | 47,634,095 |

The local management costs in water facilities are adapted from Connelly et al. (2007) Specifically, "monitoring and inspection" is considered as EDRR, and "chemical treatment," "planning, design, and engineering," "retrofit and/or reconstruction," "filtration or other mechanical exclusion," and "nonchemical treatment" are considered as the ex-post management options. As a result, prevention, EDRR plus, and the ex-post management without EDRR would cost annually $186,557, $236,964, and $215,566 per hydroelectricity plant, respectively. Moreover, annual management cost of a drinking water treatment plant would be $17,078, $88,711, and $71,096 for facilities with capacity less than or equal to 1 MGD, and $59,144, $84,264, and $72,877 for facilities with capacity greater than or equal to 2 MGD. The number of hydroelectricity plants and drinking water treatment plants, and capacity of drinking water treatment plants are adopted from the previous result about estimation of NZMS damages.

In addition to statewide and water facilities' management, management of boaters and hatcheries are taken into account. Recreational boating and hatcheries have received attention since decontamination of boats and fishing gears are strongly recommended by IS experts and government agencies not only because recreational boaters are main vector to transport aquatic invasive species including NZMS, but also because there is no feasible method to completely eradicate NZMS so far. Boaters are recommended to wash their boats with high-pressure water spray and to treat their gears physically or chemically after use through drying, freezing, soaking them in hot water, or using disinfectants. Chemical treatment of gears is generally more effective than physical treatment for decontamination although it may reduce life period of fishing gears and damage nearby water bodies if boaters let chemicals flow in. Cost of washing a boat is assumed to be $3 by following the example in Potapov and Lewis (2008), and chemical decontamination cost is assumed $16 per boat use by approximating retail price for 1 gallon of antibacterial Formula 409. Antibacterial Formula 409 is chosen because it is relatively easier to obtain the chemical and it is reported that 10-minute exposure to 50% or 100% of Formula 409 are highly effective to disinfect NZMS (Schisler et al., 2008). For management cost of fish hatcheries, a fish hatchery is assumed to install 6 units of hydrocyclone to prevent NZMS invasion to fish hatcheries. Hydrocyclone is one of the filtration methods using gravity force, and it is chosen because of its relatively low cost (Nielson et al., 2012). The installation expense of a fish hatchery is set to be $12,000 for 6-unit hydrocyclone, based on oral presentation of Nielson et al. (2008) The number of hatcheries is then obtained from StreamNet database. Table 4.4 summarizes the total local management cost in each hydrologic unit when all possible management actions are fully taken.

**Table 4.4 Summary of NZMS Management Costs: Local (USD/Year)**

| 6-digit Hydrologic Unit | | Hydroelectricity Plants | | | Drinking Water Treatment Plants | | | Boater Deconta-mination | Fish Hatchery Prevention |
|---|---|---|---|---|---|---|---|---|---|
| | | Prevention | EDRR plus | EX-post | Prevention | EDRR plus | EX-post | | |
| ID | 160101 | 365 | 464 | 422 | 0 | 0 | 0 | 6,861 | 0 |
| | 160102 | 1,064,026 | 1,351,522 | 1,229,478 | 0 | 0 | 0 | 88,119 | 12,000 |
| | 160203 | 33,940 | 43,111 | 39,218 | 0 | 0 | 0 | 13,090 | 0 |
| | 170101 | 1,076,241 | 1,367,038 | 1,243,593 | 153,702 | 798,399 | 639,864 | 49,881 | 0 |
| | 170102 | 1,575,142 | 2,000,739 | 1,820,071 | 239,092 | 1,241,954 | 995,344 | 369,784 | 24,000 |
| | 170103 | 1,085,599 | 1,378,924 | 1,254,406 | 324,482 | 1,685,509 | 1,350,824 | 751,759 | 12,000 |
| | 170401 | 1,090,359 | 1,384,969 | 1,259,906 | 0 | 0 | 0 | 110,833 | 0 |
| | 170402 | 19,708,369 | 25,033,496 | 22,772,956 | 17,078 | 88,711 | 71,096 | 881,745 | 120,000 |
| | 170501 | 4,839,242 | 6,146,787 | 5,591,729 | 478,184 | 2,483,908 | 1,990,688 | 1,169,743 | 48,000 |
| | 170502 | 248,748 | 315,959 | 287,428 | 17,078 | 88,711 | 71,096 | 31,731 | 0 |
| | 170601 | 6,706 | 8,518 | 7,749 | 51,234 | 266,133 | 213,288 | 70,258 | 36,000 |
| | 170602 | 320,772 | 407,443 | 370,650 | 102,468 | 532,266 | 426,576 | 220,381 | 264,000 |
| | 170603 | 1,222,522 | 1,552,843 | 1,412,620 | 392,794 | 2,040,353 | 1,635,208 | 277,503 | 312,000 |
| OR | 170501 | 516,933 | 656,606 | 597,314 | 59,144 | 84,264 | 72,877 | 26,246 | 0 |
| | 170502 | 742,282 | 942,844 | 857,705 | 51,234 | 266,133 | 213,288 | 72,973 | 24,000 |
| | 170601 | 774,375 | 983,608 | 894,788 | 34,156 | 177,422 | 142,192 | 26,564 | 60,000 |
| | 170701 | 4,924,399 | 6,254,953 | 5,690,127 | 236,576 | 337,056 | 291,508 | 122,323 | 192,000 |
| | 170702 | 2,548,423 | 3,236,997 | 2,944,694 | 0 | 0 | 0 | 15,276 | 0 |
| | 170703 | 6,931,701 | 8,804,620 | 8,009,557 | 59,144 | 84,264 | 72,877 | 474,795 | 72,000 |
| | 170800 | 3,483,105 | 4,424,227 | 4,024,717 | 323,224 | 1,233,060 | 998,906 | 269,390 | 120,000 |
| | 170900 | 10,987,338 | 13,956,076 | 12,695,833 | 2,165,856 | 4,115,824 | 3,469,600 | 1,104,583 | 144,000 |
| | 171002 | 480,683 | 610,562 | 555,428 | 783,072 | 3,175,808 | 2,566,580 | 469,039 | 156,000 |
| | 171003 | 3,759,184 | 4,774,901 | 4,343,725 | 1,240,404 | 4,213,658 | 3,430,418 | 584,649 | 72,000 |
| | 171200 | 75,103 | 95,396 | 86,782 | 0 | 0 | 0 | 14,115 | 0 |
| | 180102 | 751,797 | 954,930 | 868,699 | 0 | 0 | 0 | 159,985 | 12,000 |
| | 180200 | 677 | 860 | 782 | 0 | 0 | 0 | 40,430 | 0 |
| WA | 170102 | 1,636,037 | 2,078,088 | 1,890,435 | 102,468 | 532,266 | 426,576 | 0 | 0 |
| | 170103 | 2,067,527 | 2,626,165 | 2,389,020 | 0 | 0 | 0 | 130,559 | 0 |
| | 170200 | 25,023,760 | 31,785,086 | 28,914,873 | 424,434 | 1,312,877 | 1,073,564 | 1,304,063 | 180,000 |
| | 170300 | 1,601,960 | 2,034,804 | 1,851,060 | 270,732 | 514,478 | 433,700 | 172,005 | 12,000 |
| | 170601 | 2,906,164 | 3,691,398 | 3,358,062 | 0 | 0 | 0 | 17,260 | 24,000 |
| | 170701 | 3,501,961 | 4,448,178 | 4,046,505 | 169,522 | 434,661 | 359,042 | 124,176 | 108,000 |
| | 170800 | 2,914,758 | 3,702,314 | 3,367,993 | 314,056 | 962,480 | 787,399 | 565,990 | 204,000 |
| | 171001 | 2,024,252 | 2,571,197 | 2,339,016 | 365,290 | 1,228,613 | 1,000,687 | 131,148 | 180,000 |
| | 171100 | 11,677,643 | 14,832,898 | 13,493,478 | 3,114,676 | 6,368,946 | 5,339,468 | 1,628,904 | 468,000 |

Available literature reveals that real ecological and economic damages of NZMS are not fully examined yet (Benson et al., 2012; Proctor et al., 2007), albeit many researchers suggested that their potential negative impact would be severe due to their high reproduction rate and wide tolerance ranges. Therefore, the damages of NZMS considered here are potential, but chosen based on available information from prior literature and opinions of IS experts (NNSS, 2013; ISSG, 2011; Proctor et al., 2007). Unlike the damages, NZMS management costs are probably similar with those of zebra mussels because management activities are not necessarily different to deal with invasive mollusks. That is why NZMS management costs will not vary while NZMS potential damages will change in scenarios of the next chapter. The management decision may differ if the multi-invasive species are consider, e.g. zebra mussels and NZMS together, since they share the effects of IS management. However, multi-invasive species is beyond this study now, so the multi-species can be the next step of this study.

# CHAPTER FIVE

# Evaluation of Alternative Invasive Species Management Strategies

## 5.1. Conceptual Framework

Total cost of invasive species (IS) includes not only their economic, ecological, and human health damages, but also related costs of management activities such as prevention, early detection and rapid response, eradication, containment, and control. When dealing with IS problems, people have to consider damages and management costs differently because of a trade-off between them—more investment on management activities would raise total cost, but also it may decrease IS damages and/or IS distribution risk. In the study, I set up a representative resource manager's optimization problem, where different management strategies are chosen to minimize total IS.

The model follows Potapov and Lewis (2008), who examined two types of cost minimization problems: (1) to minimize only total management costs; and (2) to minimize the sum of management costs and damages. In Potapov and Lewis's (2008), management options, washing a boat before use in uninfected areas and after use in infected areas, were considered with costs given by $s$ and $x$, respectively. The total management cost minimization, not including damages, is described as

(5-1-1) $E_C = \min_{s,x} \sum_j \left( s_j \frac{\sum_i T_{ij}}{\sum_i \sum_j T_{ij}} + \ x_j \frac{\sum_i T_{ji}}{\sum_i \sum_j T_{ij}} \right)$

where $T_{ij}$ represents the number of boats per unit time traveling from lake $i$ to lake $j$. The second objective function including both IS damages and management costs is

(5-1-2) $E_{min} = \min_{s,x}(E_C + \sum_i u_i g_i)$

where $u_i$ indicates whether the lake $i$ is invaded or not, and $g_i$ represents losses per unit time in the invaded lake $i$. These two minimization problems are subject to a constraint about colonization threshold incorporating the Allee effect, which indicates that a positive relationship between population size or density, and the overall individual fitness or one of its components is a critical factor in successful bioinvasion (Taylor and Hastings, 2005). The resource manager would choose washing boats in order to prevent IS from dispersing by having the species migration flow be less than the colonization threshold.

$$\left(1 - u_j\right) \sum_i \exp\left(-s_j\right) \tau_{ij} \exp(x_i)\, u_i \leq \tau_0, \text{ for all } j.$$

where $\tau_{ij}$ represents normalized boat flow from the lake $i$ to the lake $j$, and $\tau_0$ indicates the normalized threshold boat flow.

Aspects of the Potapov and Lewis (2008) model do not apply to New Zealand mudsnails (NZMS). For example, they assumed that people know whether a lake is invaded by IS and overall boat traffic from invaded lakes to uninvaded ones is known. However, boaters have limited knowledge about a water body's invasion. Moreover, insufficient resources for total inspection have forced most researchers to use presence-only data when modeling species distribution. Because of insufficient total inspection, density data are also often unavailable. Therefore, I assume that a water body's invasion status is unknown, but the species introduction risk is directly proportional to the total incoming boat flows regardless of their origins. Furthermore, there is not sufficient information about exact boat flows between each water body, although Potapov and Lewis (2008) assume that the mean boat flows per unit time is known. Accordingly, boat flows in this study are approximated from boat registration and boater survey data like the previous studies (e.g. Bossenbroek et al, 2001; Rothlisberger and Lodge, 2011).

Potapov and Lewis (2008) did not consider habitat suitability of recipient regions as a factor for successful bioinvasion. Species survival after introduction depends on ecological characteristics, so adding habitat suitability into the IS distribution model is critical in empirical application. Recall from Chapter 3 that I derived the integrated IS distribution risk based on anthropogenic introduction risk and habitat suitability. Additionally, Potapov and Lewis (2008) supposed that washing boats is the only management option to prevent IS from dispersing, but in reality other management policies include prevention, early detection and rapid response (EDRR), eradication, containment, and control (Clout and Williams, 2009). Three types of management activities are considered as choice variables: (1) prevention, (2) EDRR plus (EDRR and its follow-up management activities including eradication, containment, and control), and (3) ex-post management options without EDRR.

Potapov and Lewis (2008) also assumed that washing boats would reduce introduction risk, i.e. the number of non-indigenous species introduced into a region related to boat flows. However, I assume that alternative management options would have different impacts on the integrated IS risk and potential damages. In short, management actions will reduce expected damages which reflect uncertainties in bioinvasion and potential damages, not just introduction risk only.

As mentioned before, the total cost of IS consists of two components—expected damages and related management costs. The effect of management is expressed as an exponential form with an efficacy parameter following Potapov et el. (2007). The total cost minimization problem is described as

(5-2) $$\min_{x\in\{x_j^{k,h}\}_+} \sum_j \left[\sum_h \left\{ED_j^h exp\left(-\sum_k \theta^{k,h} x_j^{k,h}\right) + \sum_k x_j^{k,h}\right\}\right].$$

In a given region $j$, $ED_j^h$ denotes the expected IS damage $h$ which is derived as a multiplication of the integrated risk in $j$ and a specific damage $h$. $x_j^{k,h}$ represents the $k$ type of management alternatives in region $j$. Since the same management options may have a differential impact on alternative sources of damages, the alternative $x_j^{k,h}$ can vary across damage $h$'s. $\theta^{k,h}$ , ranging between 0 and 1, represents the efficacy of the management alternative $x_j^{k,h}$, and it is assumed that a management option has the same efficacy across regions. Note that this study deals with a cross-sectional problem although Potapov and Lewis (2008) solved a dynamic optimization problem. This is attributable to lack of data about transitional IS introduction risk and habitat suitability, and IS population change over time. However, if there is a steady-state solution for the dynamic problem as Potapov and Lewis (2008) proved, it is possible that the solution for the cross-sectional problem becomes the optimal control solution.

Possible constraints imposed on the optimization problem are:

(5-3-1) $\sum_h \sum_k x_j^{k,h} \leq \overline{BC}_j , \forall j;$

(5-3-2) $\sum_j \sum_h \sum_k x_j^{k,h} \leq \overline{BC}_{total};$

(5-4-1) $\sum_h \{ED_j^h exp(-\sum_k \theta^{k,h} x_j^{k,h})\} \leq \overline{ED}_j , \forall j;$ and/or

(5-4-2) $\sum_j \sum_h \{ED_j^h exp(-\sum_k \theta^{k,h} x_j^{k,h})\} \leq \overline{ED}_{total}.$

The constraints (5-3-1) and (5-4-1) are local budget and targeted damage level constraints which mean that the resource manager considers whether total management costs and total expected damages in the given area $j$ to be equal to or less than available budget in $j$ ($\overline{BC}_j$) and the targeted damage level in $j$ ($\overline{ED}_j$), respectively. In contrast, the constraints (5-3-2) and (5-4-2) describes that the representative resource manager considers cross-regional budget and targeted expected damage level. Note that the expected damage in this model is derived from multiplication of relative risk and possible damage values, so targeted expected damage can also be expressed by targeted risk level.

The problems can be divided into local and global problems. According to the resource manager's purpose, the total cost minimization subject to constraints (5-3-1) or (5-4-1) will be the local problem while the total cost minimization subject to constraints (5-3-2) or (5-4-2) will be the global problem. Lagrangian functions given a region $j$ are

(5-5-1) $L_j = \sum_h \{ED_j^h exp(-\sum_k \theta^{k,h} x_j^{k,h}) + \sum_k x_j^{k,h}\} + \lambda_j [\sum_h \sum_k x_j^{k,h} - \overline{BC}_j]$; and

(5-5-2) $L_j = \sum_h \{ED_j^h exp(-\sum_k \theta^{k,h} x_j^{k,h}) + \sum_k x_j^{k,h}\} + \mu_j [\sum_h \{ED_j^h exp(-\sum_k \theta^{k,h} x_j^{k,h})\} - \overline{ED}_j]$

where $\lambda_j$ and $\mu_j$ are Lagrange multipliers. Note that it is unnecessary to impose both budget and targeted risk level constraints here. If Equation (5-5-2) is solved, a sum of management costs is also derivable. The budget constraint becomes redundant if the sum of management costs is less than available budget ($\overline{BC}_j$). On the other hand, if the sum of management costs is greater than available budget, it implies that the minimization problem subject to both constraints, (5-3-1) and (5-4-1), is unsolvable.

Similarly, the Lagrangian functions with respect to the global constraints (5-3-2) or (5-4-2) are denoted as

(5-6-1) $L = \sum_j [\sum_h \{ED_j^h exp(-\sum_k \theta^{k,h} x_j^{k,h}) + \sum_k x_j^{k,h}\}] + \lambda [\sum_j \sum_h \sum_k x_j^{k,h} - \overline{BC}_{total}]$; and

(5-6-2) $L = \sum_j [\sum_h \{ED_j^h exp(-\sum_k \theta^{k,h} x_j^{k,h}) + \sum_k x_j^{k,h}\}]$

$$+\mu [\sum_j \sum_h \{ED_j^h exp(-\sum_k \theta^{k,h} x_j^{k,h})\} - \overline{ED}_{total}].$$

However, the minimization problem subject to the global budget constraint, i.e. Equation (5-6-1), can be also constrained by the local targeted risk level condition (5-4-1). This is the case where the resource manager wants to reduce IS risk in some target areas. The Lagrangian function is

$$(5\text{-}7)\quad L = \sum_j \left[\sum_h \left\{ED_j^h exp\left(-\sum_k \theta^{k,h} x_j^{k,h}\right) + \sum_k x_j^{k,h}\right\}\right]$$

$$+\lambda\left[\sum_j \sum_h \sum_k x_j^{k,h} - \overline{BC}_{total}\right] + \sum_{j'} \mu_{j'}\left[\sum_h \left\{ED_{j'}^h exp\left(-\sum_k \theta^{k,h} x_{j'}^{k,h}\right)\right\} - \overline{ED}_{j'}\right]$$

where $j'$ indicates certain target areas for reduced relative risk.

In the following sections, I will explore management choices to minimize total IS cost based on scenarios about whether or not the resource manager is only concerned with his/her own region or is concerned about entire area and for different budget and targeted damage constraints.

### 5.2. Cost-efficient Management Strategies for the New Zealand Mudsnails Case

Recall that the integrated relative risk is taken from Chapters 2 and 3, and expected damages are estimated by the product of the relative risk and possible NZMS damages derived in Chapter 4. Although NZMS management cost is derived in the Chapter 4, not many studies have examined NZMS management strategies' effects on possible damages. Thus, I assume relative efficacies of various management alternatives based on experts' opinions.

As discussed in Chapter 4, statewide and local management in water facilities are categorized into prevention, EDRR plus, and ex-post management without EDRR. Prevention is distinct from EDRR plus and ex-post management since it is conducted before species introduction while the others are conducted after some introduction. Note that EDRR plus and ex-post management are exclusive; that is, if EDRR was undertaken in a certain area, ex-post management cannot be chosen there, and vice versa. Distinctions inside ex-post management such as eradication, containment, and control are not considered due to data limitations on management costs and their effectiveness.  In addition, prevention and EDRR plus are the most feasible NZMS management due to difficulty in removing NZMS after they have been established (Proctor et al., 2007).

The basic assumptions about NZMS management are the following:

- Statewide management includes prevention, EDRR plus, and ex-post management without EDRR.
- Local management includes prevention, EDRR plus, and ex-post management of water facilities (hydroelectricity plants and drinking water treatment plants), in addition to boater decontamination and fish hatchery prevention.
- In general, the effectiveness is higher in the following order: prevention, EDRR plus, ex-post management without EDRR.
- Local management of water facilities is more effective than statewide management.
- If the region is invaded, prevention or prevention and EDRR become less effective, depending on bioinvasion phases.
- All management affects all damages except that water facilities' management affects its own facilities (Figure 5.1).

**Figure 5.1  Management Effects on NZMS Damages**

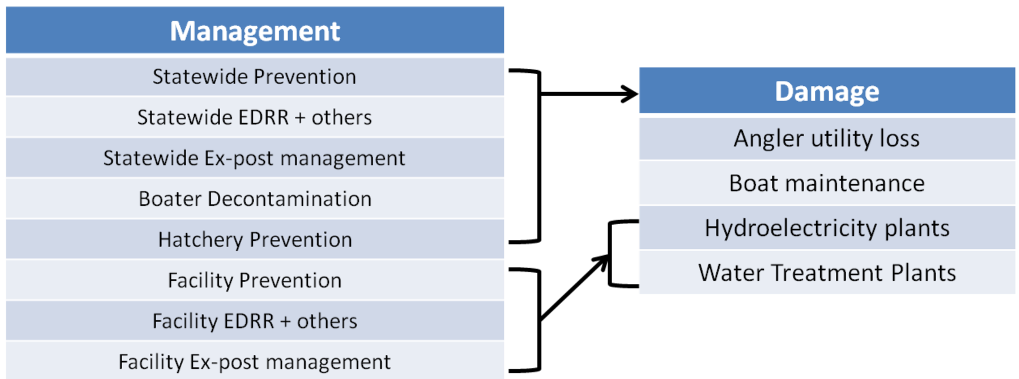
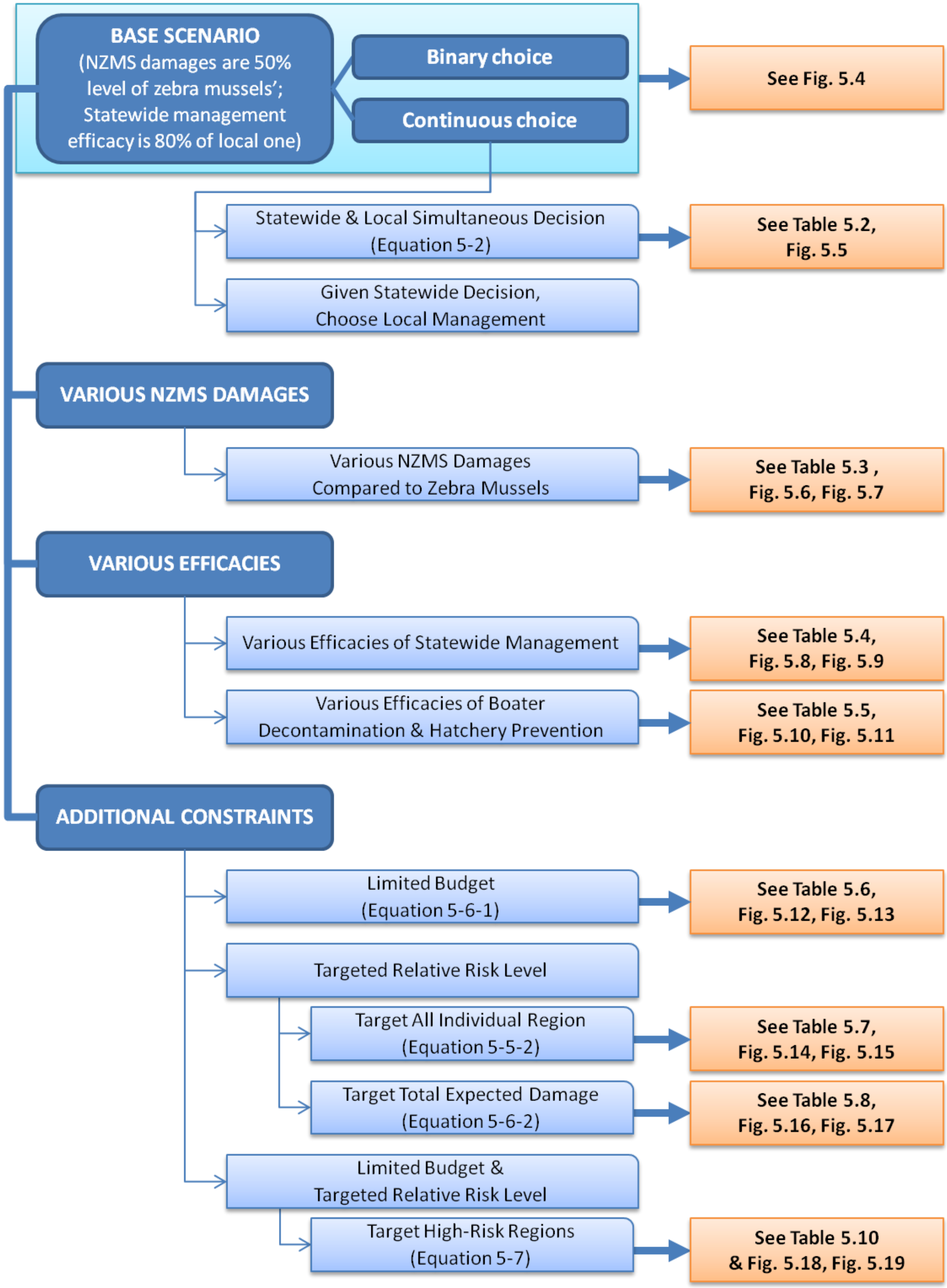


**Figure 5.2 Developed Scenarios with Different Assumptions and Constraints**



Several scenarios were developed (see Figure 5.2). The differential efficacies were reflected by alternative θ values (Equation 5-1). In the base scenario, the most effective management is local prevention activity by hydroelectricity plants and water treatment plants, and statewide management is set to be as 80% effective as local management. Recall that boater decontamination and fish hatchery prevention are considered to be local prevention strategies. However, boater decontamination and fish hatchery prevention may be indirectly effective compared to other prevention actions because they are related to IS vectors, i.e. boaters and fish hatcheries. In other words, boater decontamination and fish hatchery prevention would prevent the surrounding regions from being invaded, while other prevention actions would have more direct impact in the targeted region where the management is conducted. That is why boater decontamination and fish hatchery prevention are set to be less effective than the other prevention actions (Table 5.1).

Furthermore, prevention and EDRR plus are assumed to be less effective when the region is already invaded. Whether or not the region is invaded was based on NZMS observation data, and the data is used as a proxy for bioinvasion phases. When comparing the number of observations in the study region, three Pacific Northwest states, the number ranges from 0 to 869. Based on the number of NZMS observations, I divide the study area into three groups: 0 observation, 1-31 observations, and 191-869 observations (see Figure 5.3). I assume that prevention becomes less effective in the second group (1-31 observations), and both prevention and EDRR plus are least effective in the third group (191-869 observasions). That is why the parameters in the shaded area in Table 5.1 is 70% of the level of other parameters.

**Figure 5.3 Number of NZMS Observations in Study Area**

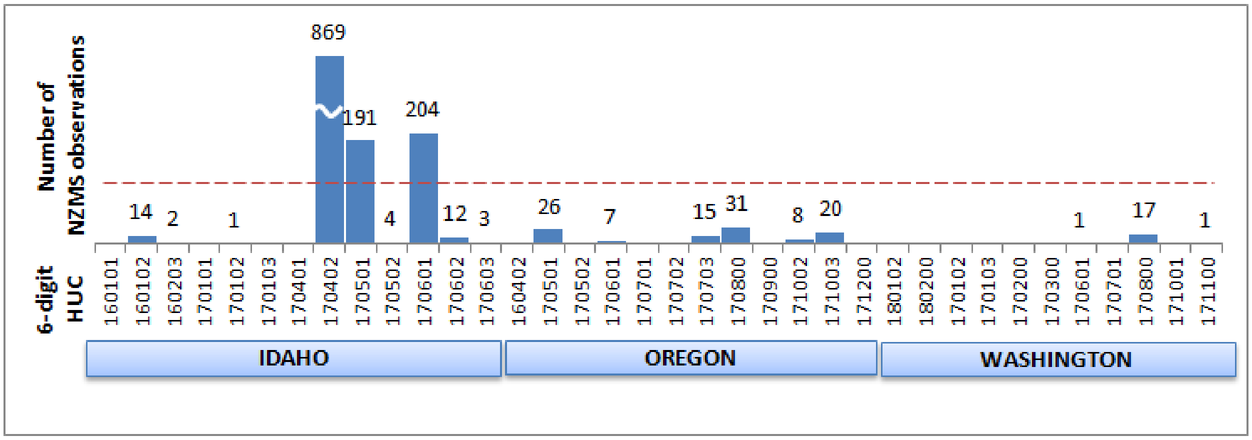



**Table 5.1 Efficacy Parameters in the Binary Model and Base Scenario**

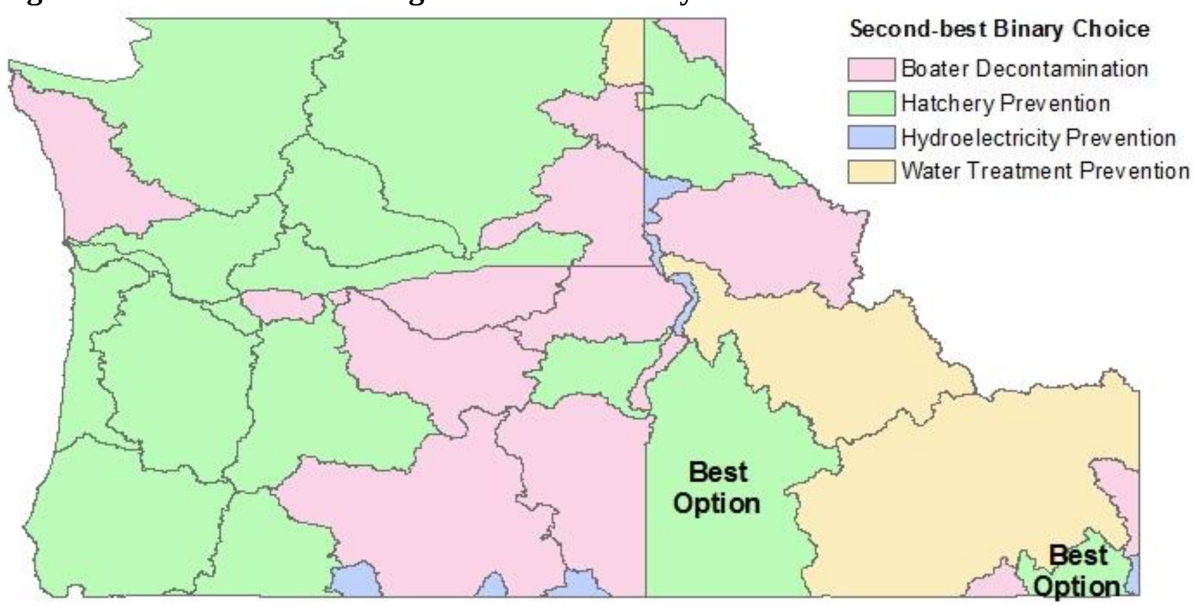
| | Statewide Management | | | Local Management | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | Water Facility | | | Boater Decontamination | Fish Hatchery Prevention |
| | Prevention | EDRR plus | Ex-post | Prevention | EDRR plus | Ex-post | | |
| Uninvaded Region | 0.8 | 0.6 | 0.48 | 1.0 | 0.75 | 0.6 | 0.7 | 0.7 |
| Invaded Region 1 | 0.56 | 0.6 | 0.48 | 0.7 | 0.75 | 0.6 | 0.49 | 0.49 |
| Invaded Region 2 | 0.392 | 0.42 | 0.48 | 0.49 | 0.525 | 0.6 | 0.343 | 0.343 |

### 5.3 Binary Choice Model

As the simplest case, a binary choice model was estimated. The binary choice means that the representative IS manager would choose whether or not to implement the given management strategy with estimated costs in Table 4.3 and Table 4.4. For example, choosing statewide EDRR plus means that all water bodies in the state are monitored and follow-up actions are conducted. If the IS manager chooses to expend his or her budget on boater decontamination, it means that all boaters in that region will decontaminate their boats and gears. Interestingly, most of the best solutions are doing nothing statewide and locally. The most cost-efficient statewide management option is no action in Idaho and Washington and prevention in Oregon. The most cost-efficient local management option is doing nothing in all local regions except two regions in Idaho where fish hatchery prevention is the best action. Figure 5.4 shows these two areas denoted as the best option. Since most of the best actions are doing nothing statewide and locally, the amount of expenditure for the most cost-efficient NZMS management would be less than the values in the Table 4.3 and Table 4.4.

I derive the second-best solution to compare the results with those of the following continuous variable scenarios. As the second-best solution, no statewide management is cost-efficient action in all states. Furthermore, boater decontamination and fish hatchery prevention are efficient local management choices despite prevention of hydroelectricity plants and water treatment plants are also cost-efficient in a small number of areas (Figure 5.4).

**Figure 5.4 Second-Best Management in the Binary Choice Model**



### 5.4. Base Scenario

Based on the relative risk, NZMS damages and management costs, the annual expected damages—total cost in Idaho, Oregon, and Washington are $240,216; $425,748; and $151,012, respectively. Different from the binary choice model, the following scenarios consider management cost as continuous variable (choice variable $x_j^{k,h}$ in Equation 5-2). That is, the IS manager can flexibly choose the amount of money to be invested in each NZMS management strategy. The efficacies are assumed as shown in Table 5.1. As a result, statewide prevention is the cost-efficient option for managing New Zealand mudsnails in all three states, and statewide EDRR plus is also derived as an optimal choice in Washington. This may be because Washington is less invaded than Idaho and Oregon (see Figure 3.1 and Figure 5.3), and EDRR plus would become less cost-efficient in the late phases of bioinvasion.

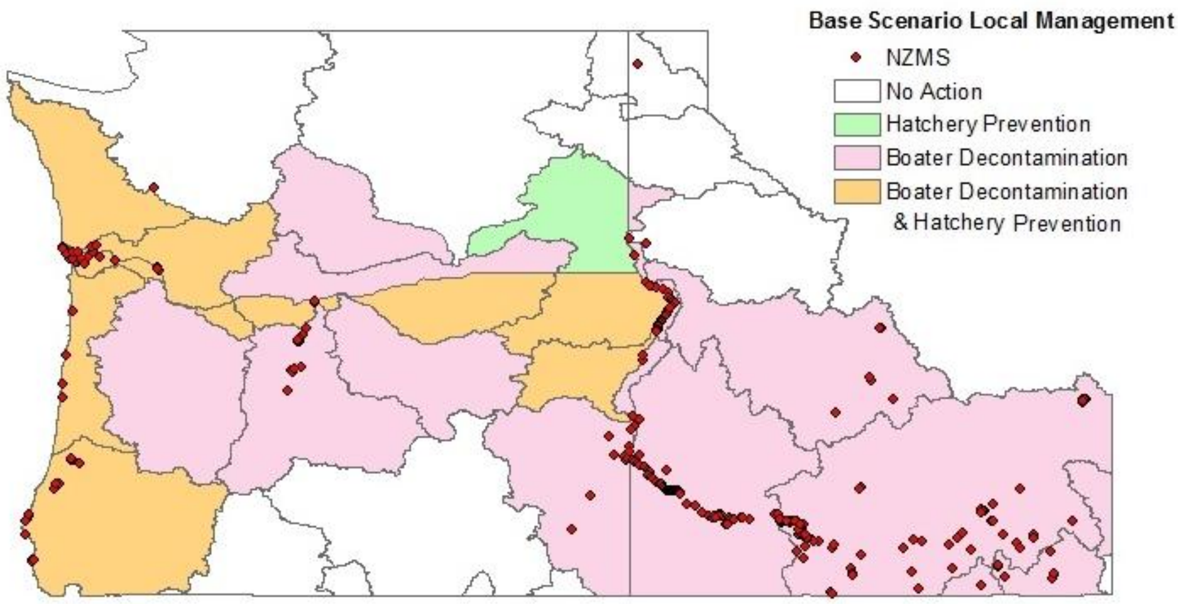
**Table 5.2 Cost-Efficient Statewide Management Strategies in the Base Scenario (USD/Year)**

| State | Total Cost | Expected Damage | Statewide Prevention | Statewide EDRR plus | Statewide Ex-post Actions | Local Management |
|---|---|---|---|---|---|---|
| Idaho | 61,800 | 22,100 | 15,300 | 0 | 0 | Boater Decontamination |
| Oregon | 73,200 | 20,500 | 23,400 | 0 | 0 | Boater Decontamination & Fish Hatchery Prevention |
| Washington | 39,600 | 12,600 | 11,100 | 1,200 | 0 | Boater Decontamination & Fish Hatchery Prevention |

Boater decontamination and fish hatchery prevention are the best local options in Oregon and Washington, while only boater decontamination is the best in Idaho. Figure 5.5 shows that the cost-efficient local actions are more necessary where NZMS have invaded and in adjacent areas. Boater decontamination and fish hatchery prevention would become important where

NZMS have already invaded (Oregon and Washington). In particular, the importance of boater decontamination would increase where NZMS invasion level is relatively high (Idaho), i.e. where more NZMS have been observed (See Figure 5.3), in this base scenario.

**Figure 5.5 Local Management in the Base Scenario**




Note that the cost-efficient management strategies here are derived assuming that managers simultaneously choose statewide and local actions. Let us assume that local managers would only consider their own regions and choose local management independently, given statewide management. In other words, statewide management is decided in advance, and a local manager will then minimize the total cost of their own regions by choosing local options such as boater decontamination, fish hatchery prevention, hydroelectricity plant management, and water treatment plant management. In this case, the cost-efficient local management is doing nothing, in either case that the statewide management is determined as in Table 5.2 or determined not to take any statewide actions.  The result implies that local managers need to determine management strategies in a broader context such as the state or an upper hydrologic unit.  For examples, local IS management authorities such as a county-level invasive species council or a water basin-level invasive species council must coordinate with each other and with statewide agencies to ensure the most cost-efficient IS management.

## 5.4. Various NZMS Damage Levels Compared to Zebra Mussels

In the base scenario, NZMS damages in water facilities and biofouling on boats are supposedly set at 50% of that of zebra mussels.  I extend the base scenario by setting NZMS damages at varying proportion of zebra mussels' damages.  That is, potential damages of water facilities (hydroelectricity plants and drinking water treatment plants) and boat maintenance cost are assumed to be 100%-10% level of those of zebra mussels.

**Table 5.3  The Cost-Efficient Solution with Various NZMS Damages**

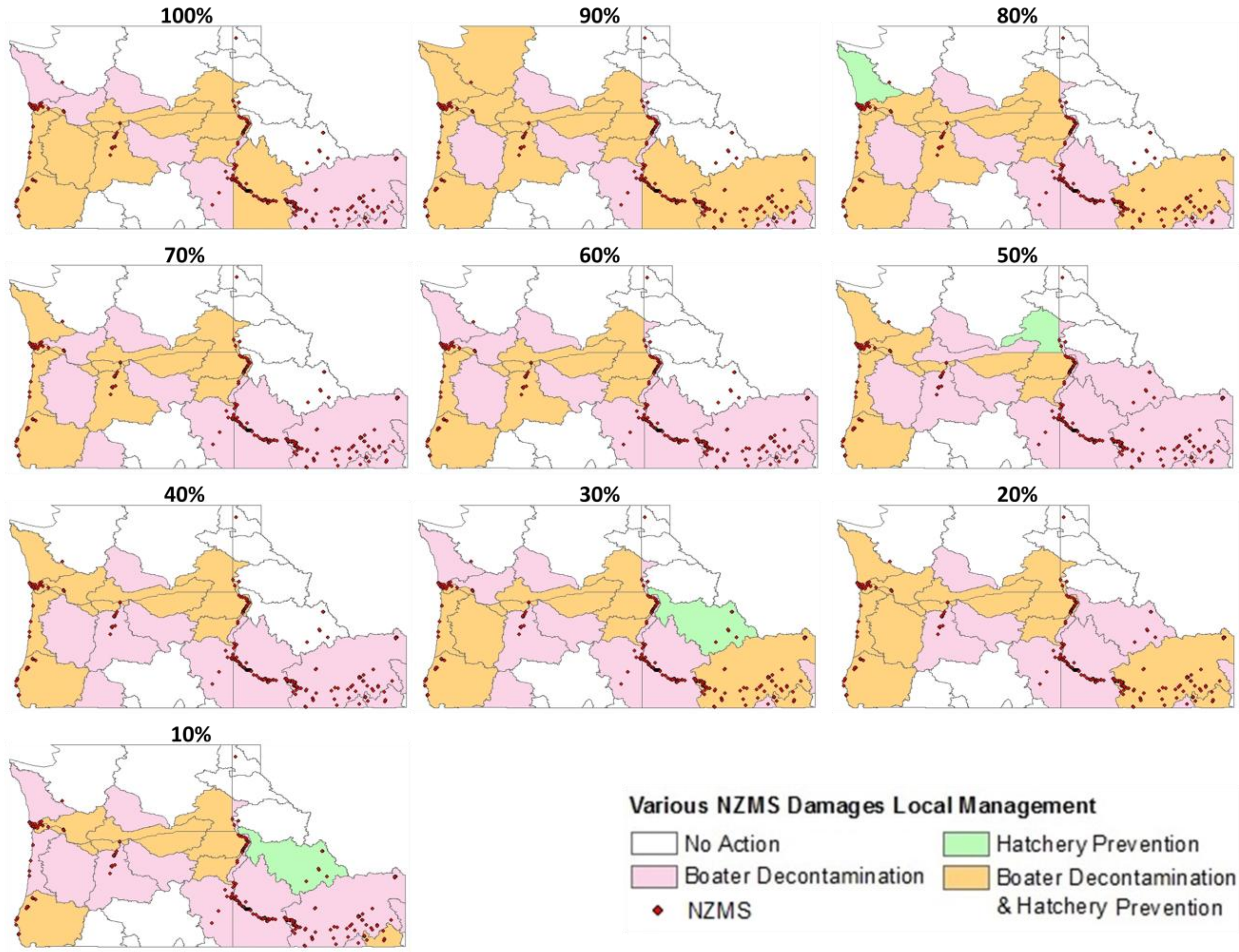
<table>
<tr><th>State</th><th>Management</th><th>100%</th><th>90%</th><th>80%</th><th>70%</th><th>60%</th><th>50%</th><th>40%</th><th>30%</th><th>20%</th><th>10%</th></tr>
<tr><td rowspan="2">Idaho</td><td>Statewide</td><td colspan="10">Prevention</td></tr>
<tr><td>Local</td><td colspan="4">Boater Decontamination & Fish Hatchery Prevention</td><td colspan="2">Boater Decontamination</td><td colspan="4">Boater Decontamination & Fish Hatchery Prevention</td></tr>
<tr><td rowspan="2">Oregon</td><td>Statewide</td><td colspan="10">Prevention</td></tr>
<tr><td>Local</td><td colspan="10">Boater Decontamination & Fish Hatchery Prevention</td></tr>
<tr><td rowspan="2">Washington</td><td>Statewide</td><td>Prevention & EDRR plus</td><td>Pre</td><td colspan="6">Prevention & EDRR plus</td><td colspan="2">Prevention</td></tr>
<tr><td>Local</td><td colspan="10">Boater Decontamination & Fish Hatchery Prevention</td></tr>
</table>

Note: Management written in bold is the cost-efficient strategy in the base scenario.  "Pre" indicates "Prevention."

Regardless of NZMS damage levels, a cost-efficient statewide strategy in Idaho and Oregon is prevention as in the base scenario (Table 5.3). In the case of Washington, prevention and EDRR plus are cost-efficient when NZMS damages are 80%-30% level of zebra mussels' damages while prevention is also cost-efficient when NZMS damages are almost the same as those of zebra mussels (90% level) or relatively small (20%-10% levels). As local management, boater decontamination and fish hatchery prevention are cost-efficient in Oregon and Washington in all cases. In Idaho, boater decontamination and fish hatchery prevention are also cost-efficient in most cases (100%-70% and 40%-10% levels) although boater decontamination is the best local action in the base scenario.

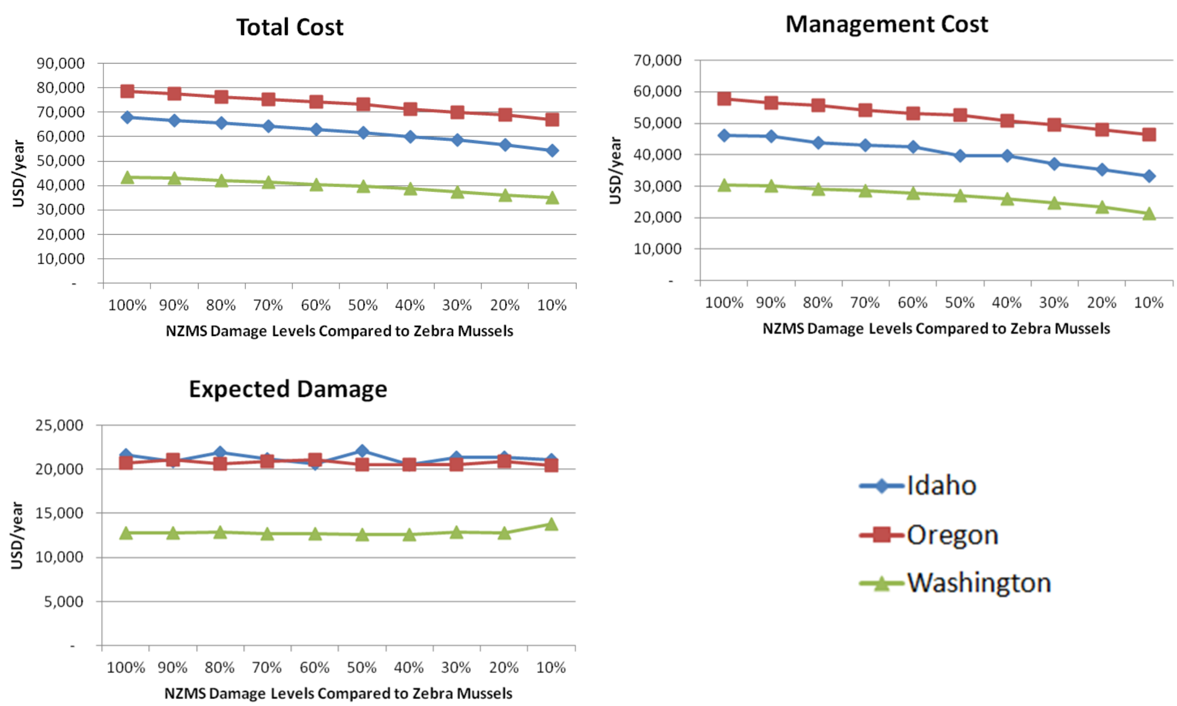
Figure 5.6 illustrates the cost-efficient local management according to NZMS damage levels. Boater decontamination (pink and orange colors) is a more dominant strategy than fish hatchery prevention (green and orange colors) in all three states. This result arises because boaters can visit all hydrologic units (some hydrologic units do not have hatcheries), and utility loss of angers accounts for a large share of NZMS damages. In addition, the cost-efficient local action in each region is stable regardless of NZMS damage levels. Again this arises because anglers' utility loss accounts for a large part of entire NZMS damages, so the influence of assumptions about different NZMS damages related to zebra mussels would diminish in terms of local cost-efficient management.

**Figure 5.6 Local Management with Various NZMS Damages**




Total cost, total management cost, and total expected damage are derived and shown in Figure 5.7. These are final outcomes in each state when choosing the cost-efficient statewide and local actions. As defined earlier, total cost is a sum of total management cost and total expected damage. Also, total management cost is a sum of the statewide management cost and local management cost, and total expected damage is a sum of the expected damages in each regions. As NZMS damages decrease, total cost and management cost also go down while expected damage stays relatively unchanged.

**Figure 5.7 Total Cost, Management Cost, and Expected Damage with Various NZMS Damages**




## 5.5. Various Efficacies of Statewide Management

In the base scenario, statewide management is assumed as 80% effective as local management. To estimate how cost-efficient management would change under alternative assumptions, efficacy of statewide management is also assumed to be at 100% - 10% of the efficacy level of local management. That is, statewide management is considered to be as effective as local management (100% level) or to be less effective than local one (90%-10% levels). As Table 5.4 shows, prevention is a dominant cost-efficient strategy statewide in all three states. Only in Washington, EDRR plus becomes cost-efficient when statewide management is as 90%-80% effective as local management. If the case of 100% is not considered, prevention and EDRR plus are the best solution in Washington when statewide management is sufficiently effective while prevention is the only best option when statewide management efficacy is relatively low. Note that it is less likely that efficacy of statewide management is same as that of local management.

As statewide management efficacy decreases, no action becomes cost-efficient (see Table 5.4). That is, it cannot be always efficient to take statewide actions. IS managers need to be cautious about understanding relative effectiveness between statewide and local management. If the manager overestimates the efficacy of statewide actions, his/her choice of statewide management can be less efficient than doing nothing.

**Table 5.4 The Cost-Efficient Solution with Various Statewide Management Efficacies**

<table>
<tr><th>State</th><th>Management</th><th>100%</th><th>90%</th><th>80%</th><th>70%</th><th>60%</th><th>50%</th><th>40%</th><th>30%</th><th>20%</th><th>10%</th></tr>
<tr><td rowspan="2">Idaho</td><td>Statewide</td><td colspan="3">Prevention</td><td colspan="7">No Action</td></tr>
<tr><td>Local</td><td>B</td><td>B & F</td><td>B</td><td colspan="7">Boater Decontamination<br>& Fish Hatchery Prevention</td></tr>
<tr><td rowspan="2">Oregon</td><td>Statewide</td><td colspan="4">Prevention</td><td colspan="6">No Action</td></tr>
<tr><td>Local</td><td colspan="10">Boater Decontamination & Fish Hatchery Prevention</td></tr>
<tr><td rowspan="2">Washington</td><td>Statewide</td><td>Prevention</td><td colspan="2">Prevention<br>& EDRR plus</td><td>Prevention</td><td colspan="6">No Action</td></tr>
<tr><td>Local</td><td colspan="10">Boater Decontamination & Fish Hatchery Prevention</td></tr>
</table>

Note: Management written in bold is the cost-efficient strategy in the base scenario. "B" denotes "Boater Decontamination," and "F" means "Fish Hatchery Prevention."

Similar to the base scenario, boater decontamination and fish hatchery prevention are cost-efficient local management tools in most cases except the case of Idaho when statewide management efficacy is 100% and 80% levels of local management efficacy. In these cases, boater decontamination is the best local solution in Idaho (Table 5.4). Figure 5.8 shows spatial distribution of the cost-efficient local management strategies according to various statewide management efficacies. As statewide management becomes less effective, the number of regions that needs to do local management increases. Especially when no statewide management is cost-efficient (70%-10%), boater decontamination (pink and orange colors) is a dominant strategy in most local areas. Fish hatchery prevention (green and orange colors) also becomes more important when no action is cost-efficient statewide (see 70% and 60% cases), but the number of areas adopting fish hatchery prevention tends to decline when statewide management becomes less effective.

**Figure 5.8 Local Management with Various Statewide Management Efficacies**

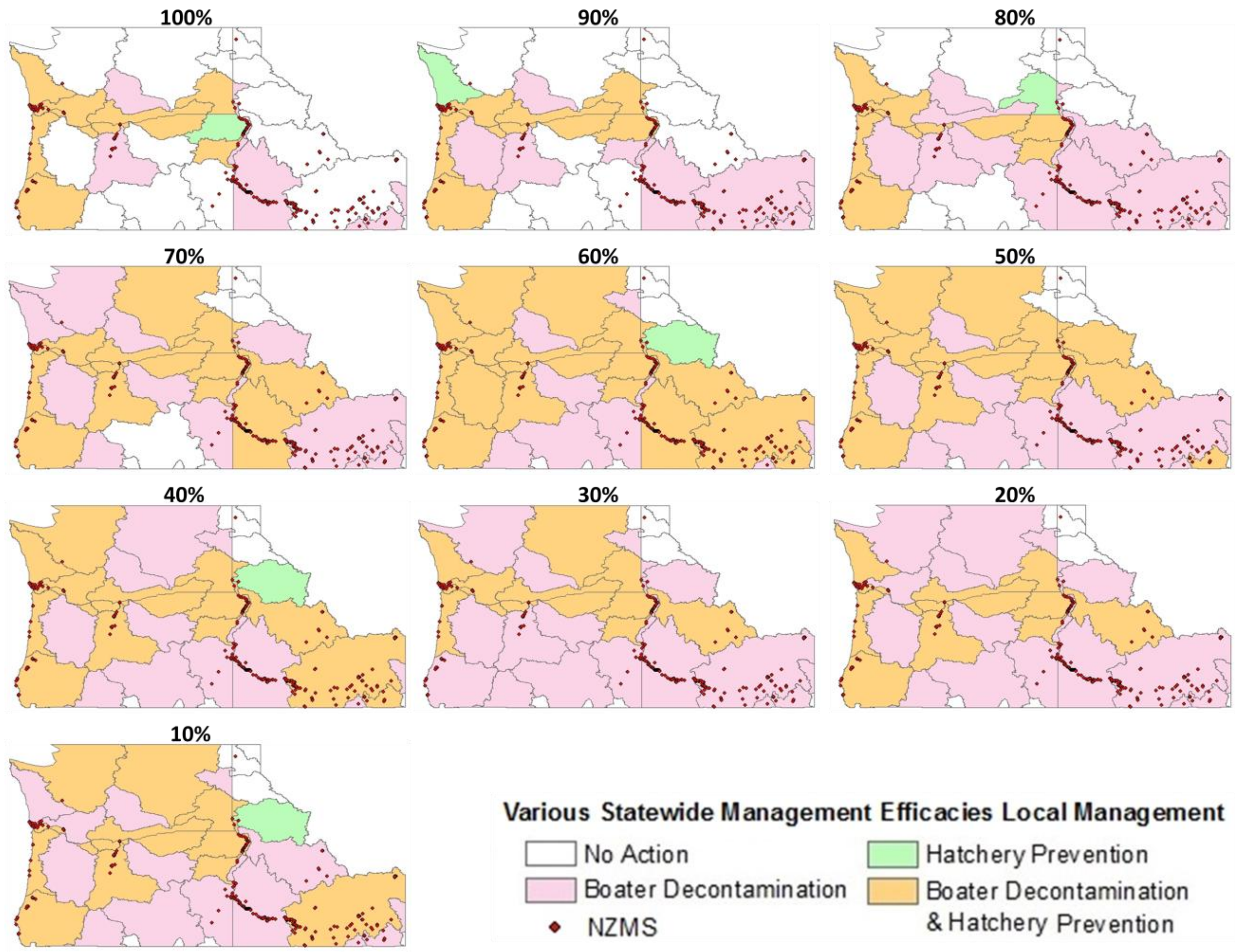
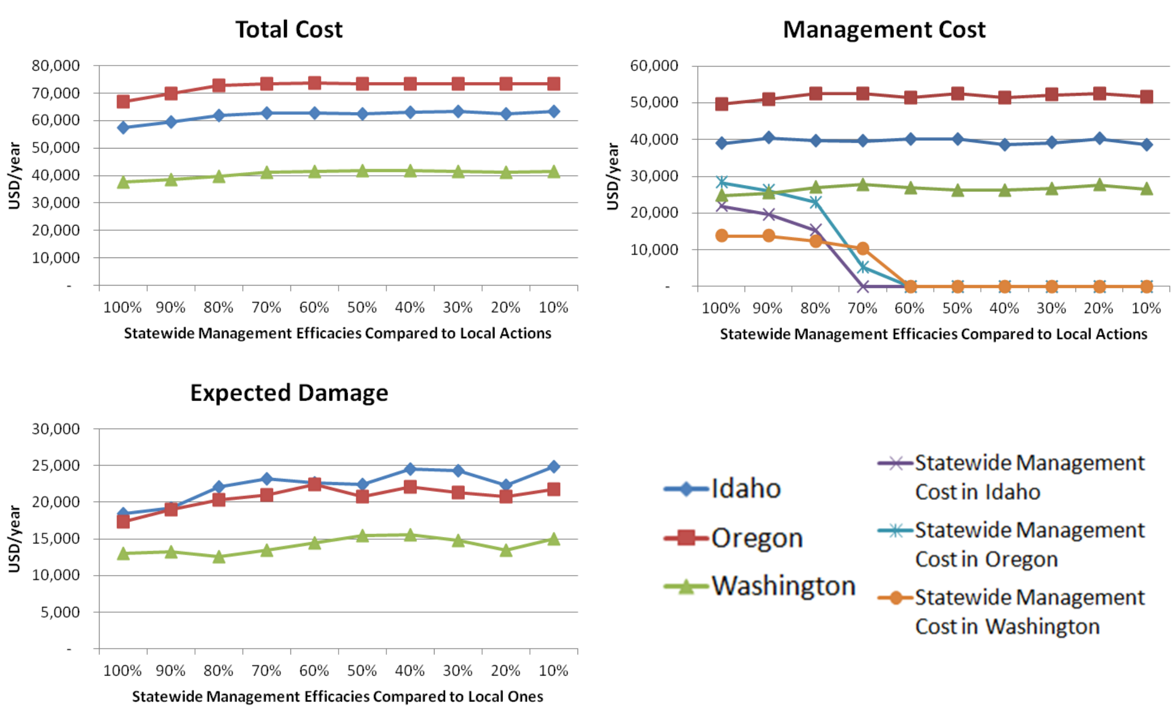


Figure 5.9 shows that total cost goes up when doing statewide management and statewide management becomes less effective (100%-70%). Although total management cost in all three states seems unchanged according to various statewide management efficacies, statewide management cost drops as statewide management gets less effective. That is, local management can replace statewide management when statewide management becomes less effective. Compared to total cost and total management cost, total expected damage fluctuates regardless of statewide management efficacies.

**Figure 5.9 Total Cost, Management Cost and Expected Damage with Various Statewide Management Efficacies**




## 5.6. Various Efficacies of Boater Decontamination and Fish Hatchery Prevention

In the above scenarios, boater decontamination and fish hatchery prevention are the most dominant local management options to minimize total NZMS cost. In order to investigate how the cost-efficient strategies change with alternative effectiveness of these two actions, I assume different efficacies for these two options. The first row of Table 5.5 shows the efficacy parameters imposed in the total cost minimization problems. Recall that this parameter was set to be 0.7 in the base scenario (see Uninvaded Region in Table 5.1).

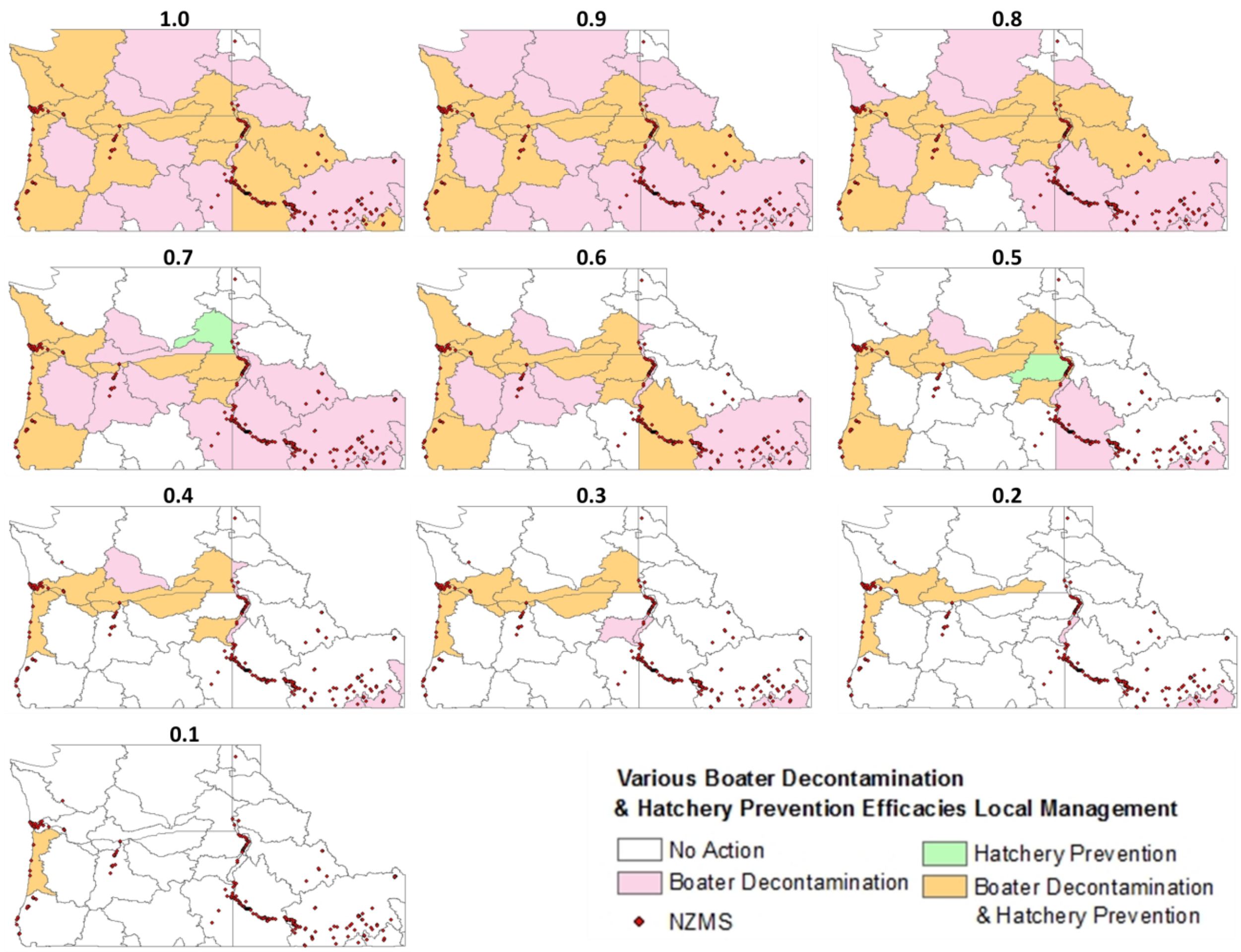
**Table 5.5 The Cost-Efficient Solution with Various Boater Decontamination and Fish Hatchery Prevention Efficacies**

<table>
<tr><th>State</th><th>Management</th><th>1.0</th><th>0.9</th><th>0.8</th><th>0.7</th><th>0.6</th><th>0.5</th><th>0.4</th><th>0.3</th><th>0.2</th><th>0.1</th></tr>
<tr><td rowspan="2">Idaho</td><td>Statewide</td><td colspan="3">No Action</td><td colspan="2">Prevention</td><td colspan="5">Prevention<br>& Ex-post</td></tr>
<tr><td>Local</td><td colspan="3">B<br>& F</td><td>B</td><td colspan="2">B<br>& F</td><td colspan="3">Boater Decontamination</td><td>No<br>Action</td></tr>
<tr><td rowspan="2">Oregon</td><td>Statewide</td><td colspan="2">No Action</td><td colspan="5">Prevention</td><td colspan="3">Prevention<br>& EDRR plus</td></tr>
<tr><td>Local</td><td colspan="10">Boater Decontamination & Hatchery Prevention</td></tr>
<tr><td rowspan="2">Washington</td><td>Statewide</td><td colspan="2">No Action</td><td colspan="3">Prevention<br>& EDRR plus</td><td colspan="5">Prevention</td></tr>
<tr><td>Local</td><td colspan="9">Boater Decontamination & Fish Hatchery Prevention</td><td>No<br>Action</td></tr>
</table>

Note: Management written in bold is the cost-efficient strategy in the base scenario. "B" denotes "Boater Decontamination," and "F" means "Fish Hatchery Prevention."

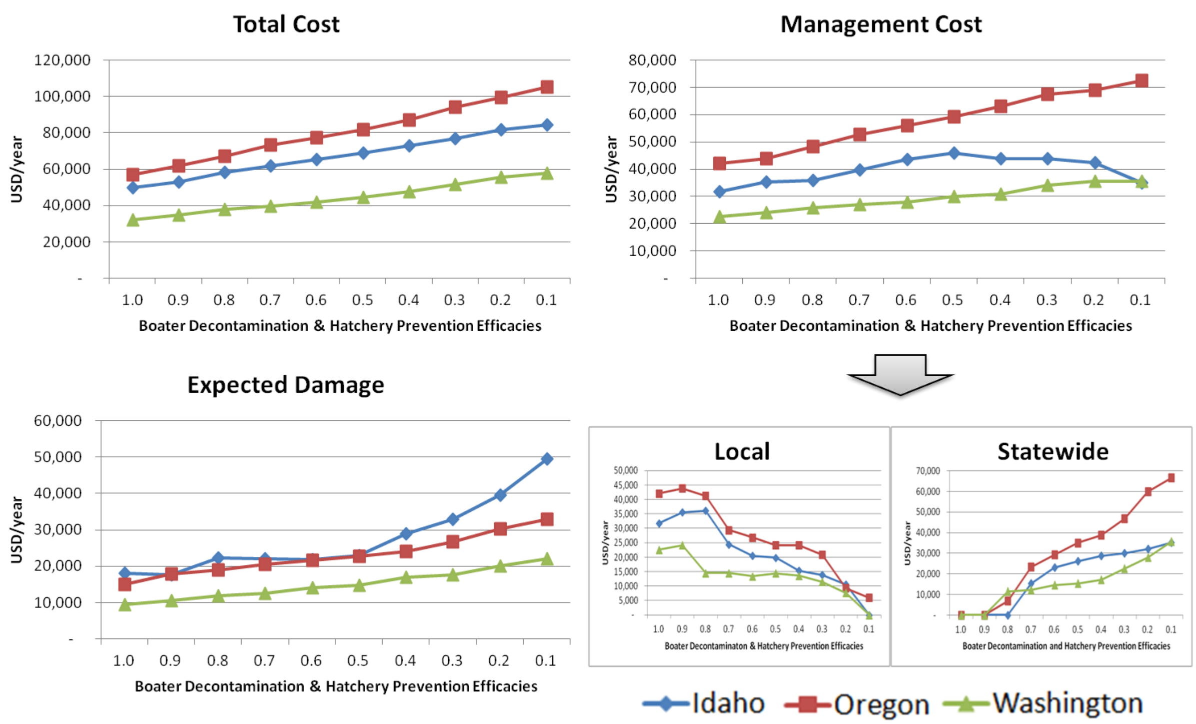
Results show that no statewide action is the most cost-efficient in all states when efficacies of boater decontamination and fish hatchery prevention are sufficiently high (Table 5.5). On the other hand, prevention is a cost-efficient option in all cases when boater decontamination and fish hatchery prevention efficacies are relatively low. In the case of Idaho, the best statewide management options are prevention and ex-post management when the efficacies of boater decontamination and fish hatchery prevention are lower. The cost-efficient statewide management of Oregon is prevention and EDRR plus, and the best statewide management of Washington is prevention when boater decontamination and fish hatchery prevention are relatively ineffective. On the contrary, if boater decontamination and fish hatchery prevention are critically ineffective, then locally no action will be best.

**Figure 5.10 Local Management with Various Boater Decontamination and Fish Hatchery Prevention Efficacies**




More effective boater decontamination and fish hatchery prevention means more regions would choose these two options as the cost-efficient management strategies (Figure 5.10). Despite the number of areas taking local actions decreasing when boater decontamination and fish hatchery prevention are less effective, the cost-efficient actions tends to be taken focusing on NZMS invaded areas. This is consistent with the results of the previous scenario of changing statewide management efficacies (Figure 5.8). In other words, whether to do local management depends on the relative effectiveness between statewide management and local management. However, if Figure 5.8 and Figure 5.10 are compared, efficacy levels of local management have more direct influence on determining whether to take local actions rather than those at the state level.

**Figure 5.11 Total Cost, Management Cost, and Expected Damage with Various Boater Decontamination & Fish Hatchery Prevention Efficacies**




As shown in Figure 5.11, total cost, total management cost, and total expected damage increase as the efficacies of boater decontamination and fish hatchery prevention go down except the case of Idaho when boater decontamination and fish hatchery prevention are less effective (see 0.3, 0.2, and 0.1 cases). Total statewide management cost, i.e. a sum of expenditures in statewide prevention, statewide EDRR plus, and statewide ex-post management in each state, in all three states increase monotonically as boater decontamination and fish hatchery prevention efficacies decrease. When it comes to total local management cost, i.e. a sum of all local management expenditures in each state, it generally goes down with increasing boater decontamination and fish hatchery prevention efficacies.

### 5.7. Cost Minimization Subject to Limited Budget

Recall that the above results are derived under the assumption that local or statewide resource managers do not consider budgets when choosing the cost-efficient strategy. However, most management situations are limited by physical and human resources available to managers. Thus, I introduce budget constraints in the cost minimization.

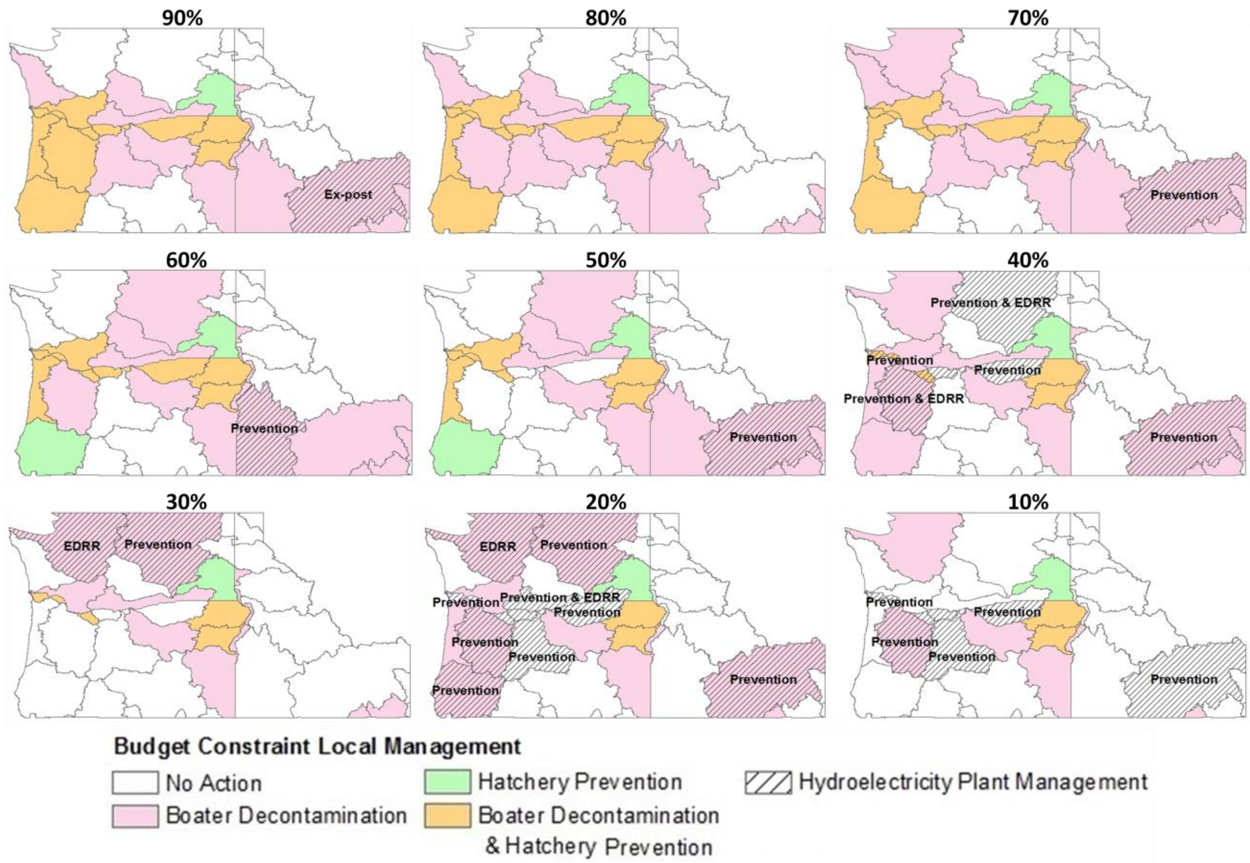
**Table 5.6 The Cost-Efficient Solution with Budget Constraints**

<table>
<tr><th>State</th><th>Management</th><th>90%</th><th>80%</th><th>70%</th><th>60%</th><th>50%</th><th>40%</th><th>30%</th><th>20%</th><th>10%</th></tr>
<tr><td rowspan="3">Idaho</td><td>Statewide</td><td colspan="4">Prevention</td><td colspan="5">No Action</td></tr>
<tr><td>Local</td><td colspan="9">Boater Decontamination</td></tr>
<tr><td>Hydroelectricity Plant Action</td><td>Ex-post</td><td>No Action</td><td colspan="4">Prevention</td><td>No Action</td><td colspan="2">Prevention</td></tr>
<tr><td rowspan="3">Oregon</td><td>Statewide</td><td colspan="7">Prevention</td><td colspan="2">No Action</td></tr>
<tr><td>Local</td><td colspan="9">Boater Decontamination<br>& Fish Hatchery Prevention</td></tr>
<tr><td>Hydroelectricity Plant Action</td><td colspan="5">No Action</td><td>Prevention & EDRR plus</td><td>No Action</td><td colspan="2">Prevention</td></tr>
<tr><td rowspan="3">Washington</td><td>Statewide</td><td>Prevention & EDRR plus</td><td colspan="5">Prevention</td><td colspan="2">No Action</td><td>Ex-post</td></tr>
<tr><td>Local</td><td colspan="9">Boater Decontamination<br>& Fish Hatchery Prevention</td></tr>
<tr><td>Hydroelectricity Plant Action</td><td colspan="5">No Action</td><td colspan="3">Prevention & EDRR plus</td><td>No Action</td></tr>
</table>

As indicated before, the cost minimization problem subject to a budget constraint can be divided into local and global problems (see Equations 5-5-1 and 5-6-1). Recall that local cost-efficient solutions except doing nothing locally could not found when a local resource manager only considers their own region, given statewide management actions chosen as values in Table 5.2 or doing nothing. Accordingly, solving the local cost minimization, i.e. Equation (5-5-1), will be also impossible and result in no local management actions when imposing an additional budget constraint.

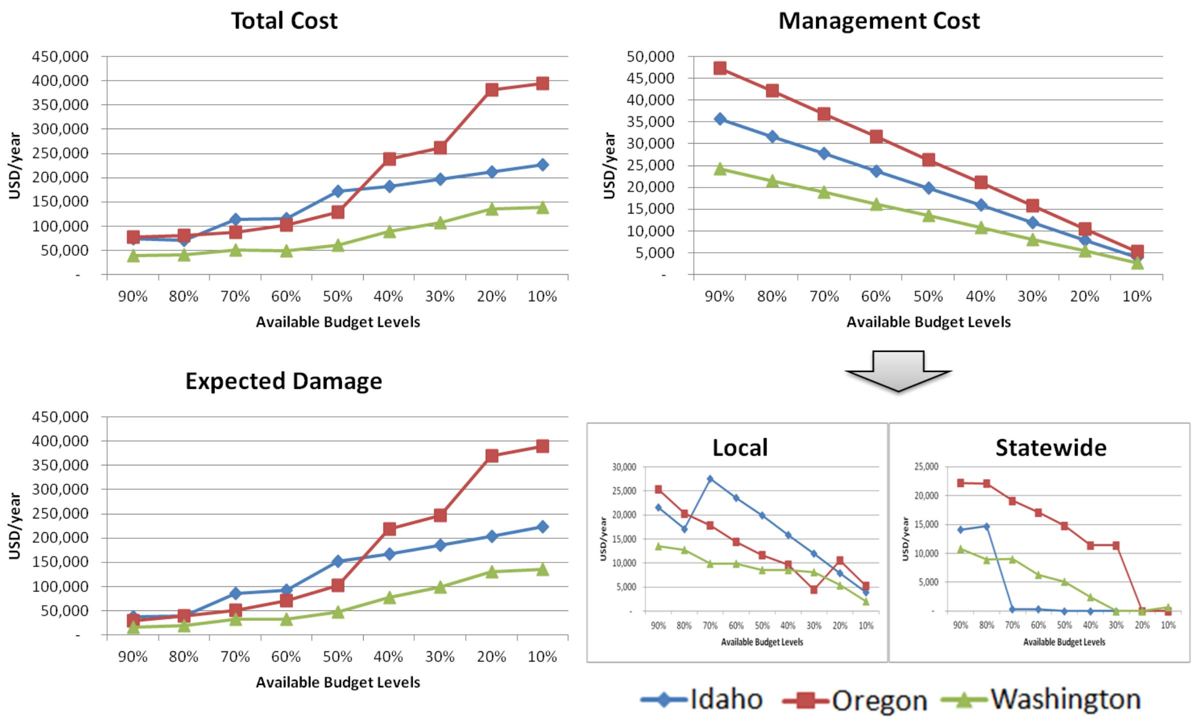
Therefore, the cost minimization here is the global cost minimization subject to a constrained total budget in each state (Equation 5-6-1). After summing up total statewide and local management costs of each state in the base scenario, the total available budget ($\overline{BC}_{total}$) of the state is assumed to be 90%-10% of this sum of all management costs. With respect to cost-efficient statewide strategies, the results are same, prevention in Idaho and Oregon, and prevention and EDRR plus in Washington, with those of the base scenario when available budget is close to the solution of the base scenario (90% level in Table 5.6). Prevention is a dominant statewide strategy in all three states when the budget is relatively unconstrained. When the budget is constrained, no statewide action becomes cost-efficient. Moreover, statewide ex-post management also becomes cost-efficient when the budget is extremely tight (10% level) in Washington. Therefore, the state resource manager needs to consider a level of available budget, in addition to relative effectiveness of statewide management, to choose the most cost-efficient statewide management actions.

**Figure 5.12 Local Management with Budget Constraints**




While boater decontamination and fish hatchery prevention are also cost-efficient local management options in Oregon and Washington, fish hatchery prevention is not cost-efficient in Idaho. Interestingly, hydroelectricity plant management becomes more important as a local management tool under the budget constraint, contrary to other scenarios analyzed earlier. Figure 5.12 illustrates areas where hydroelectricity plant management is cost-efficient (slashed areas). In general, hydroelectricity plant management is added to boater decontamination and fish hatchery prevention when the available budget is small. Figure 5.12 also explains that prevention and EDRR plus are dominant strategies among hydroelectricity management options.

**Figure 5.13 Total Cost, Management Cost, and Expected Damage with Budget Constraints**




Total cost and total expected damage in each state tends to increase as the amount of available budget gets smaller (Figure 5.13). Results explain that the available budget would be completely consumed, so total management cost equals the available budget in all cases in Idaho, Oregon, and Washington. Moreover, both statewide management cost and local management cost decline as the available budget level decreases, and the statewide management cost in Idaho drops more sharply than those of Oregon and Washington. In other words, it would be more important for the resource manager to consider stopping statewide management if the available budget becomes smaller when managing NZMS in Idaho, compared to the resource managers concerned about NZMS in Oregon and Washington.

## 5.8. Cost Minimization Subject to Targeted Risk Level (Targeted Expected Damage)

Targeted risk levels were considered as constraints facing resource managers. That is, the resource manager would plan to reduce the original NZMS risk to the targeted level or lower in the following scenarios. Also, the target area can be local or statewide, depending on the IS manager's interest or purpose. I will introduce two scenarios about targeted risk levels in all individual regions and targeted total expected damage in each state. Recall that expected damages are defined as multiplication of relative risk and potential damages, so the targeted risk level constraint is also expressible as targeted expected damage as in Equations (5-5-2), (5-6-2), and (5-7).

### 5.8.1. Targeted risk level in all individual regions

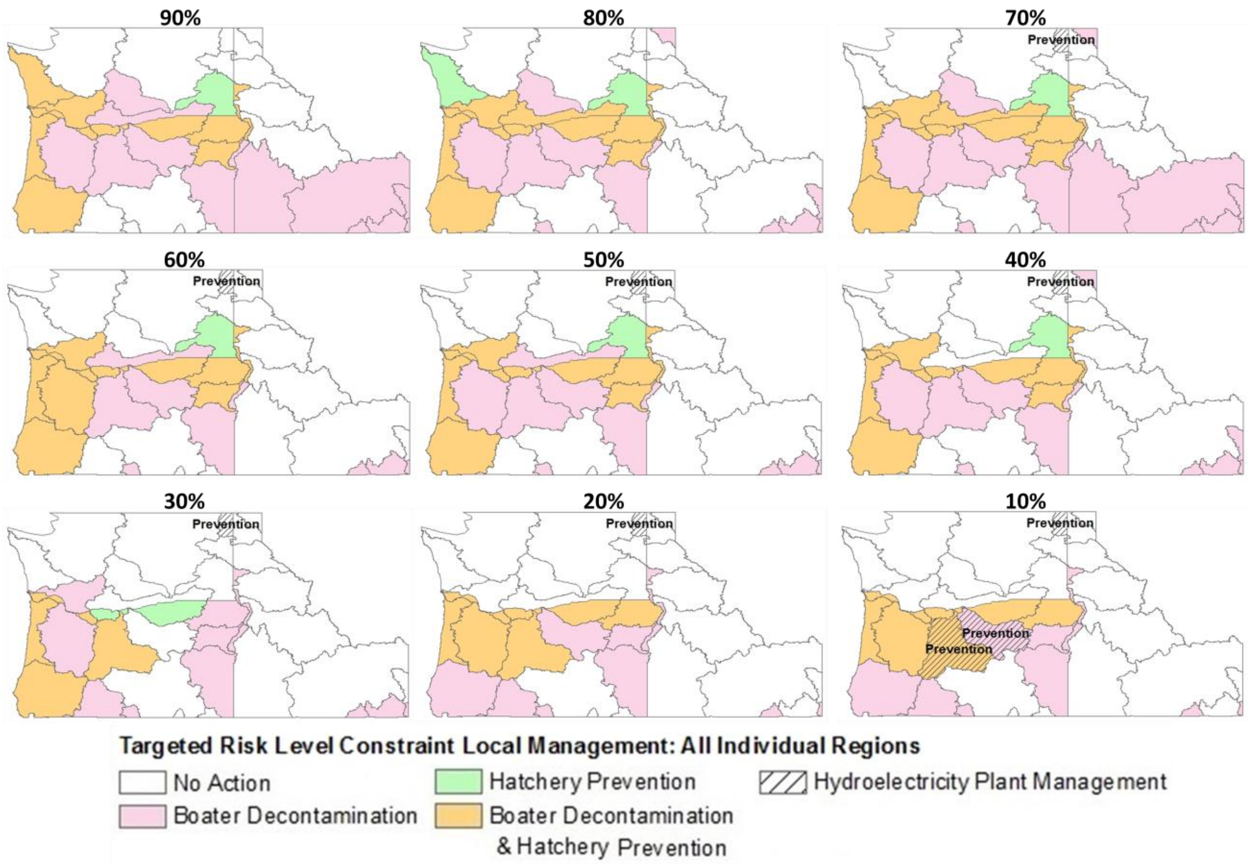
Risk levels in all individual regions are managed to be less than or equal to targeted risk levels, which is denoted as $\overline{ED}_j$ in Equation (5-5-2). Thus, Equation (5-5-2) will be solved for all $j$ regions in this scenario. For example, a 90% targeted risk level indicates that the relative risk in each region after management has to be less than or equal to 90% of original relative risk from Chapter 3. Results show that prevention is the best solution statewide in all cases, and EDRR plus is also the cost-efficient option statewide in some cases (Table 5.7). Fish hatchery prevention becomes more important in Idaho when targeted risk levels are high (90%-40% cases), compared to the results of the base and budget constraint scenarios where fish hatchery prevention is not cost-efficient in Idaho.

**Table 5.7 The Cost-Efficient Solution with Targeted Risk Constraints: All Individual Regions**

<table>
<tr><th>State</th><th>Management</th><th>90%</th><th>80%</th><th>70%</th><th>60%</th><th>50%</th><th>40%</th><th>30%</th><th>20%</th><th>10%</th></tr>
<tr><td rowspan="3">Idaho</td><td>Statewide</td><td colspan="2">Prevention</td><td>Prevention & EDRR plus</td><td colspan="6">Prevention</td></tr>
<tr><td>Local</td><td colspan="6">Boater Decontamination & Fish Hatchery Prevention</td><td colspan="3">Boater Decontamination</td></tr>
<tr><td>Hydroelectricity Plant Action</td><td colspan="9">No Action</td></tr>
<tr><td rowspan="3">Oregon</td><td>Statewide</td><td colspan="6">Prevention</td><td colspan="3">Prevention & EDRR plus</td></tr>
<tr><td>Local</td><td colspan="9">Boater Decontamination & Fish Hatchery Prevention</td></tr>
<tr><td>Hydroelectricity Plant Action</td><td colspan="8">No Action</td><td>Prevention</td></tr>
<tr><td rowspan="3">Washington</td><td>Statewide</td><td>Prevention & EDRR plus</td><td colspan="8">Prevention</td></tr>
<tr><td>Local</td><td colspan="6">Boater Decontamination & Fish Hatchery Prevention</td><td>Boater Deconta-mination</td><td colspan="2">No Action</td></tr>
<tr><td>Hydroelectricity Plant Action</td><td colspan="2">No Action</td><td colspan="7">Prevention</td></tr>
</table>

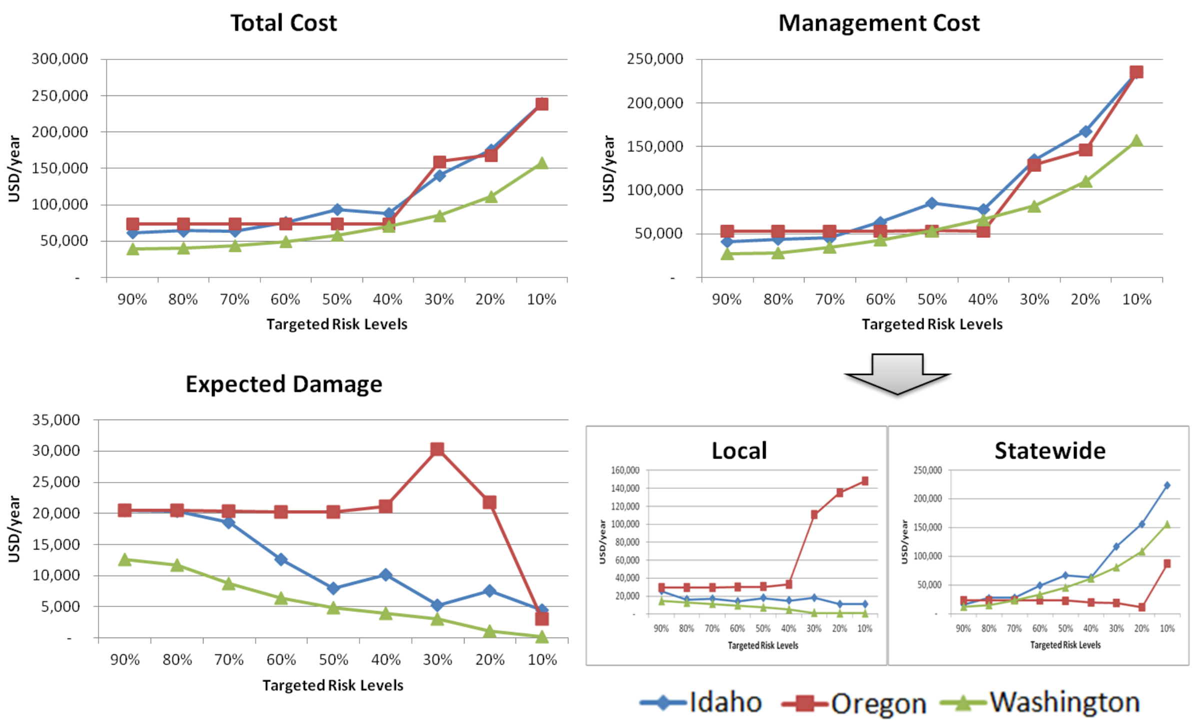
Boater decontamination and fish hatchery prevention play an important role in reducing relative risk levels although hydroelectricity management is also cost-efficient in a small part of regions in Oregon and Washington. To be specific, prevention in hydroelectricity plants is the only cost-efficient option among hydroelectricity plant management actions (Figure 5.14). As shown in Figure 5.15, total cost and total management cost increase as targeted risk level lowers. Different from the results in the budget constraint scenario, total expected damage is not equal to the targeted expected damage (derived from the targeted relative risk). This is because a combination of cost-efficient statewide and local management actions can lower the relative risk below the targeted risk level when the targeted risk levels are high. For example, let us imagine that the resource manager wants to lower NZMS risk in A and B regions to 90% levels of original risk. If $100 and $50 of statewide prevention actions can achieve this goal in region A and B, respectively, then the best statewide solution to satisfy the targeted risk level constraints will be $100 of statewide prevention.

**Figure 5.14 Local Management with Targeted Risk Constraints: All Individual Regions**




Accordingly, risk level in region B after management will be lower than the targeted risk level, and related expected damage will also be lower than the targeted expected damage. In conclusion, there is spill-over impact of statewide management when targeting to lower relative risk or expected damage due to statewide management.

**Figure 5.15 Total Cost, Management Cost, and Expected Damage with Targeted Risk Constraints: All Individual Regions**




## 5.8.2. Targeted total expected damage

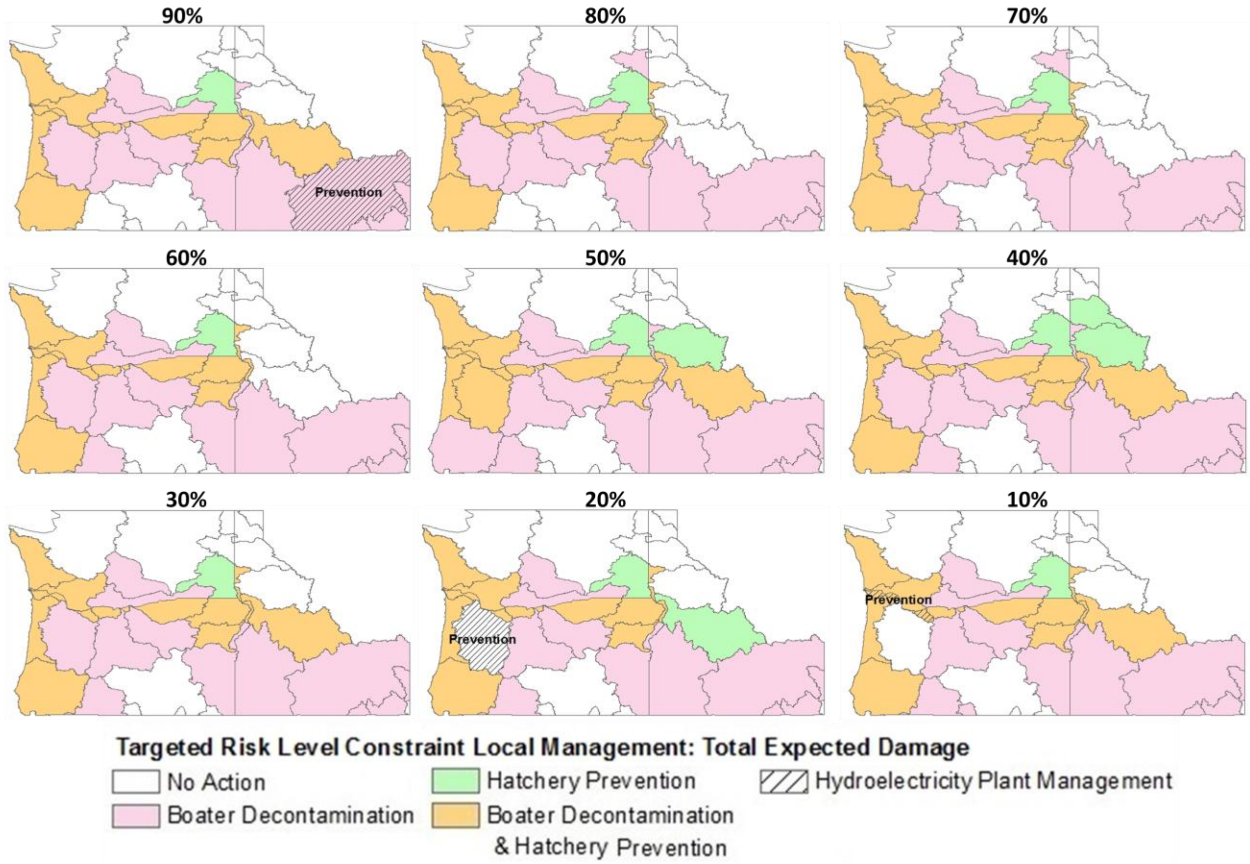
In this scenario, the resource manager would plan to make total expected damages, i.e. a sum of all expected damages ($\sum_j \sum_h ED_j^h$), below the targeted total expected damage ($\overline{ED}_{total}$) like Equation (5-6-2). Different from the previous scenario where the expected damage in each region is proportional to the relative NZMS risk, total expected damage here may or may not be proportional to the relative risk of an individual region since total expected damage is an aggregate value. As I set up the budget constraints as a proportion of total management cost derived from the cost-efficient management of the base scenario, I define the targeted total expected damage as a proportion of the total expected damage resulted from the cost-efficient management of the base scenario. The first column in Table 5.8 represents the targeted total expected damage levels. For example, 90% level means the targeted total expected damage is 90% of the total expected damage after management in the base scenario.

**Table 5.8 The Cost-Efficient Solution with Targeted Risk Constraints: Total Expected Damage**

<table>
<tr><th>State</th><th>Management</th><th>90%</th><th>80%</th><th>70%</th><th>60%</th><th>50%</th><th>40%</th><th>30%</th><th>20%</th><th>10%</th></tr>
<tr><td rowspan="3">Idaho</td><td>Statewide</td><td colspan="5">Prevention</td><td>Prevention & EDRR plus</td><td colspan="3">Prevention</td></tr>
<tr><td>Local</td><td colspan="9">Boater Decontamination & Fish Hatchery Prevention</td></tr>
<tr><td>Hydroelectricity Plant Action</td><td>Prevention</td><td colspan="8">No Action</td></tr>
<tr><td rowspan="3">Oregon</td><td>Statewide</td><td colspan="9">Prevention</td></tr>
<tr><td>Local</td><td colspan="9">Boater Decontamination & Fish Hatchery Prevention</td></tr>
<tr><td>Hydroelectricity Plant Action</td><td colspan="7">No Action</td><td colspan="2">Prevention</td></tr>
<tr><td rowspan="3">Washington</td><td>Statewide</td><td colspan="3">Prevention & EDRR plus</td><td>Prevention</td><td colspan="5">Prevention & EDRR plus</td></tr>
<tr><td>Local</td><td colspan="9">Boater Decontamination & Fish Hatchery Prevention</td></tr>
<tr><td>Hydroelectricity Plant Action</td><td colspan="9">No Action</td></tr>
</table>

Results show that statewide prevention is the cost-efficient management tool in all cases across states, especially in Idaho and Oregon. In Washington, EDRR plus is also a dominant strategy regardless of different target levels except at the 60% level. The results are similar to those of the base scenario where prevention in Idaho and Oregon, and prevention and EDRR plus in Washington are the cost-efficient tools statewide.

**Figure 5.16 Local Management with Targeted Risk Constraints: Total Expected Damage**

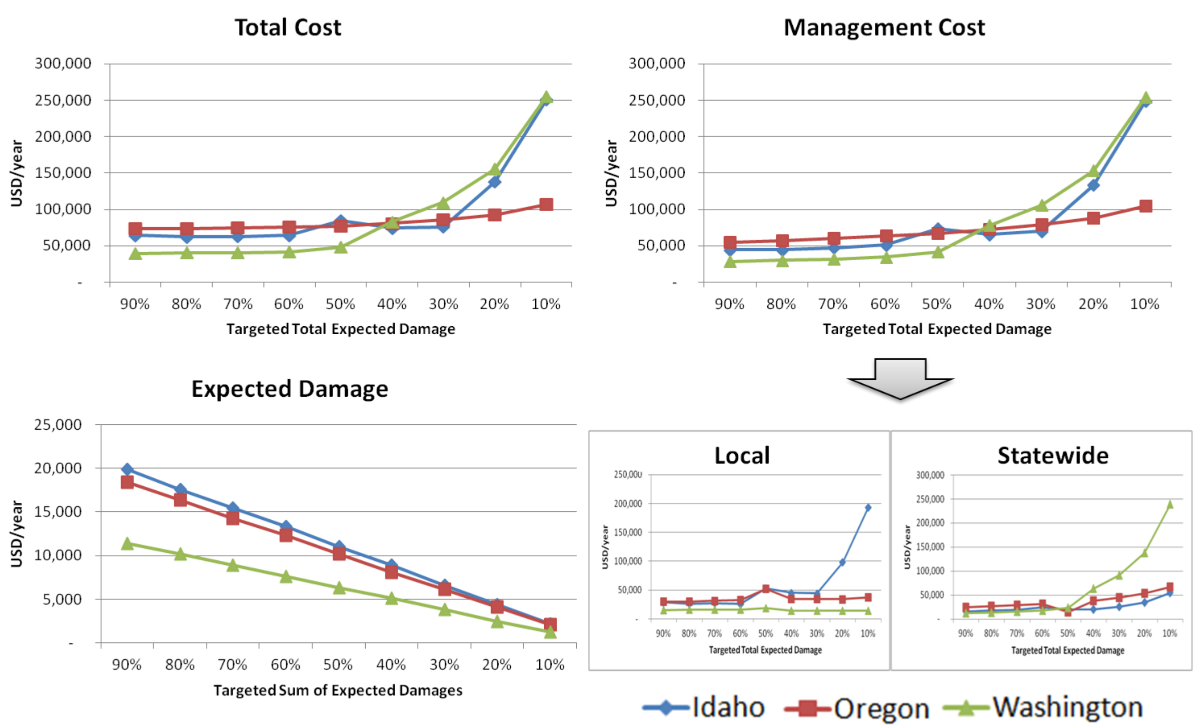



Boater decontamination and fish hatchery prevention are the most cost-efficient local management strategies in all three states. In addition to those, hydroelectricity prevention is also cost-efficient in some cases in Idaho and Oregon as shown in Figure 5.16. In terms of boater decontamination and fish hatchery prevention, the local areas taking both actions as the cost-efficient strategies are almost same regardless of the different targeted total expected damages.

Figure 5.17 illustrates that total cost rises monotonically as the targeted total expected damage and resulted total expected damage after management get lower. Especially, total cost in Idaho and Washington considerably increases when the targeted total expected damage level is low (30%-10% cases), and it is mainly because of substantial increase in total management cost.

Although total management cost in both Idaho and Washington increases, the reason is different. Specifically, the total cost increase in Idaho results from an increase of local management cost while that of Washington is led by increase of statewide management cost.  Since the total cost drastically increases when the targeted total expected damage is relatively lower (30%-10% cases), it implies that the resource managers dealing with introduced IS in Idaho and Washington need to be cautious about defining targeted total expected damage levels to avoid relatively higher total cost.

**Figure 5.17  Total Cost, Management Cost, and Expected Damage with Targeted Risk Constraints: Total Expected Damage**



### 5.9. Targeted risk level in high-risk regions with budget constraints

Finally, I combine the budget constraints and the targeted risk level constraints. In this scenario, the IS resource manager would plan to reduce relative risk in high-risk regions, which are denoted as $j'$ regions in Equation (5-7), to the maximum risk level of low-risk regions. I divide the hydrologic units to high-risk and low-risk groups in two ways: Jenks natural break classification and an average risk value. Jenks natural break classification is to separate groups to minimize a variance in each group (Smith et al., 2013). In terms of the average value, I sort the regions into a high-risk group whose values exceed the average risk level and a low-risk group whose risk values are below the average. As a result, the regions categorized as the high-risk group and low-risk group divided by two different classification manners are the same regardless of the classification methods in Idaho and Washington (Table 5.8). The targeted risk levels are defined as the maximum values in the low-risk groups (values marked by * in Table 5.8).

**Table 5.8 Relative Risk Range in the High-Risk Group and Low-Risk Groups**

| State | Classification | Risk Range | |
|---|---|---|---|
| | | High-Risk Group | Low-Risk Group |
| Idaho | Jenks Break | 0.004490 – 0.001980 | 0.001366* – 0.000017 |
| Oregon | Jenks Break | 0.008075 – 0.005521 | 0.002647* – 0.000090 |
| | Average Risk | 0.008075 – 0.002209 | 0.001937* – 0.000090 |
| Washington | Jenks Break | 0.001789 – 0.000946 | 0.000504* – 0.000019 |

However, the targeted risk level constraints of this scenario are automatically achievable by taking the cost-efficient management actions of the base scenario. In other words, the cost-efficient choices of the base scenario would make the risk of the high-risk regions lower than the targeted risk levels in all three states. Similarly, the targeted risk level constraints are also satisfied despite the limited budget when the budget level is higher than 70% and 40% levels in Idaho and Washington, respectively. If the budget level of Oregon is higher than 40% and 50% levels in the cases of Jenks break classification and average risk classification, respectively, the targeted risk level constraints are accomplished as well.

**Table 5.9 The Cost-Efficient Solution with Targeted Risk Constraints: High-Risk Regions with Budget Constraint**

<table>
<tr><th>State</th><th>Classification</th><th>Management</th><th>70%</th><th>60%</th><th>50%</th><th>40%</th><th>30%</th><th>20%</th><th>10%</th></tr>
<tr><td rowspan="2">Idaho</td><td rowspan="2">Jenks Break</td><td>Statewide</td><td colspan="3">Prevention</td><td colspan="2">No Action</td><td colspan="2" rowspan="2"></td></tr>
<tr><td>Local</td><td colspan="5">Boater Decontamination<br>(70% level, Hydroelectricity Plant Prevention)</td></tr>
<tr><td rowspan="4">Oregon</td><td rowspan="2">Jenks Break</td><td>Statewide</td><td colspan="3" rowspan="2"></td><td>Prevention</td><td colspan="3">No Action</td></tr>
<tr><td>Local</td><td colspan="4">Boater Decontamination<br>& Fish Hatchery Prevention</td></tr>
<tr><td rowspan="2">Average Risk</td><td>Statewide</td><td colspan="2" rowspan="2"></td><td colspan="4">Prevention</td><td rowspan="2"></td></tr>
<tr><td>Local</td><td colspan="4">Boater Decontamination<br>& Fish Hatchery Prevention</td></tr>
<tr><td rowspan="2">Washington</td><td rowspan="2">Jenks Break</td><td>Statewide</td><td colspan="3" rowspan="2"></td><td colspan="2">EDRR plus</td><td colspan="2" rowspan="2"></td></tr>
<tr><td>Local</td><td colspan="2">Boater Decontamination &<br>Fish Hatchery Prevention</td></tr>
</table>

The limited budget levels are defined by the same manner that is applied to the budget constraint scenario (see section 5.7). That is, the percentages in Table 5.9 represents available budget levels as a proportion of total management cost resulted from taking the cost-efficient strategies of the base scenario. However, the total cost minimization, i.e. Equation (5-7), cannot be solved when the budget is relatively tight: at less than a 20% level in Idaho and Washington, and less than a 10% level in the case of average risk classification in Oregon.

In Idaho and Oregon, the most cost-efficient statewide management tool is prevention while EDRR plus is the only cost-efficient statewide tool in Washington. Also, doing nothing statewide is cost-efficient when the available budget is lower in Idaho (40%-30% levels) and in the case of Jenks break classification of Oregon (30%-10% levels). This is consistent with the results of the budget constraint scenario analyzed in section 5.7 (see Table 5.6).

Figure 5.18 shows the cost-efficient local strategies, and the high-risk regions are denoted as "high" on maps. Boater decontamination is the only cost-efficient management action in Idaho while boater decontamination and fish hatchery prevention are dominant local strategies in Oregon and Washington. It is consistent with results of the base scenario and the budget constraint scenario. As shown in Figure 5.18, the areas doing local management are completely matched up with the high-risk regions in Washington while no local actions are cost-efficient in some high-risk regions in Idaho and Oregon. It may explain why EDRR plus is the only cost-efficient statewide strategy in Washington (Table 5.9). Prevention, which is assumed to be more effective than EDRR plus, would become more necessary to reduce the relative risk in target areas, which are the high-risk areas here, if there exist high-risk regions that do not take local management actions. On the other hand, doing local management would sufficiently reduce the relative risk in the high-risk regions, so EDRR plus would be fine as the cost-efficient statewide strategy.

**Figure 5.18 Local Management with Targeted Risk Constraints: High-Risk Regions with Budget Constraint**

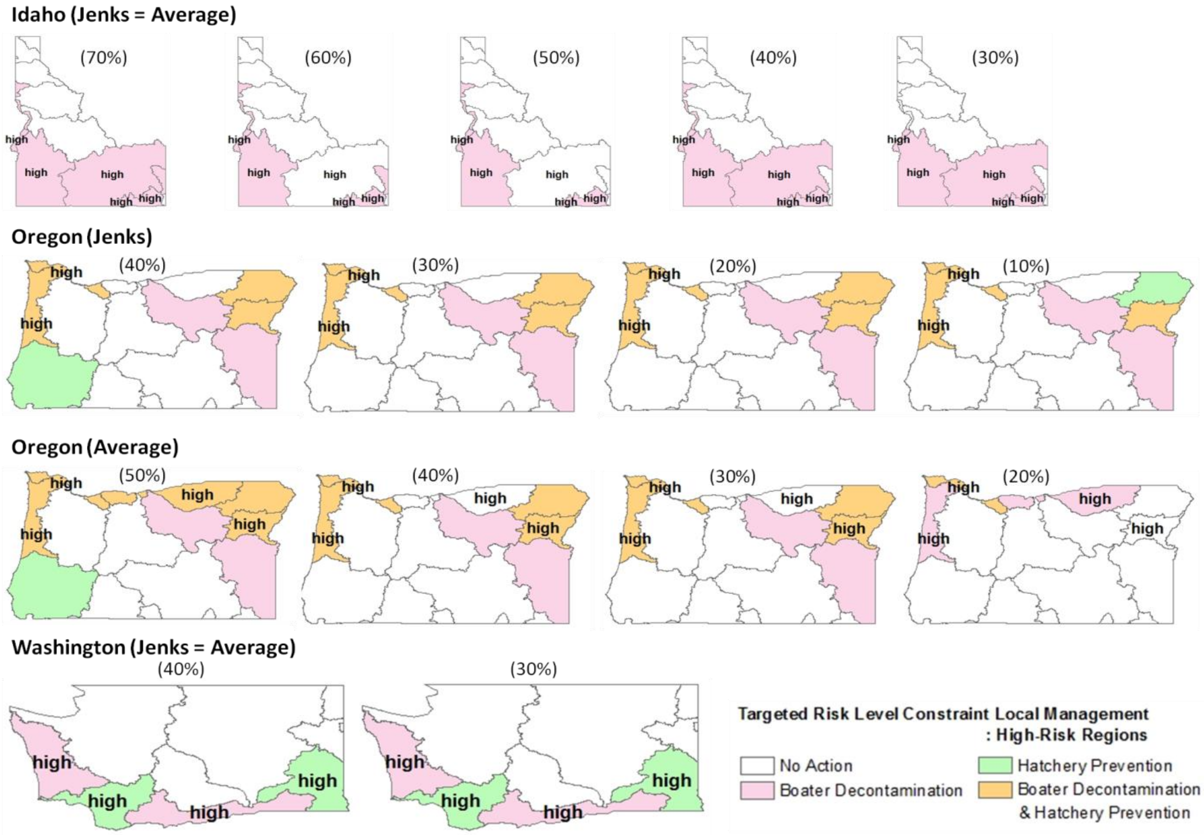



**Figure 5.19 Total Cost, Management Cost, and Expected Damage with Targeted Risk Constraints: High-Risk Regions with Budget Constraint**

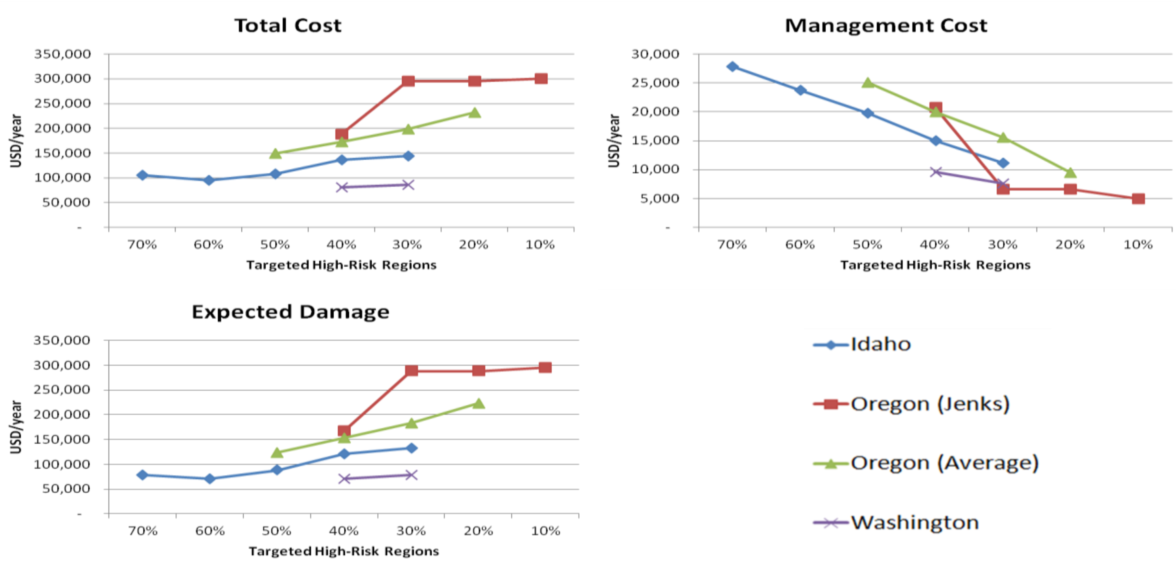


Figure 5.19 shows total cost, total management cost, and total expected damage when aiming to reduce NZMS risk in the high-risk regions under the budget constraints. Similar to the graphs in the budget constraint scenario (see Figure 5.13), total cost and total expected damage increase when the available budget becomes smaller because the limited budget restricts statewide and local management actions. In addition, the budget constraints are binding like the budget constraint scenario in most cases.

# CHAPTER SIX

## Summary and Conclusion

This study developed an integrated spatial framework to measure IS risk and evaluate the cost-efficiency of alternative IS management strategies. For a given spatial unit, the developed framework weighed expected IS damages against the cost of alternative management strategies, i.e. spatial cost minimization. The study then applied the spatial cost minimization framework to the case of New Zealand mudsnails, *Potamopyrgus antipodarum*, (NZMS) in the Pacific Northwest.

Expected damages are defined as a sum of potential IS damages weighted by the IS establishment risk which is estimated as a product of IS introduction risk and habitat suitability. NZMS establishment is a result of two sequential events: NZMS introduction and their survival in the recipient regions. Chapter 2 investigated NZMS introduction risk in the Pacific Northwest. Since recreational boat transportation is a key vector for NZMS dispersal, a gravity model predicted boat flows (the number boat movements) across hydrologic units in each of the three Pacific Northwest states: Idaho, Oregon, and Washington. Results showed that distance between hydrologic units, hydrologic unit sizes, water concentration, and accessibility are major determinants of boat flows. The estimation results are also used to predict boat flows, and their normalized values are considered as a proxy for NZMS introduction risk.

Chapter 3 analyzed ecological niche to identify NZMS habitat suitability in a probability format and estimated the integrated relative NZMS risk. A maximum entropy method was employed to represent the relationship between spatial NZMS distribution (NZMS presence) and environmental features. A combination of low elevation, bedrock and gravel terraces, above average low temperature during summer, and above average precipitation in January, March, and September creates suitable habitats for NZMS. By multiplying the introduction risk and habitat suitability, considering introduction and species' survival as two probabilities of independent sequential events, the final integrated NZMS establishment risk is estimated.

Chapter 4 computed monetized potential NZMS damages and management costs. Potential NZMS damages include anglers' utility loss, which is caused by degradation of aquatic habitat, and biofouling influence of NZMS on hydroelectricity plants, drinking water treatment plants, and boats. The Integrated Valuation of Ecosystem Service and Tradeoffs (InVEST) program is used to calculate habitat quality change due to NZMS invasion, and then the habitat quality index is used to estimate anglers' willingness to pay about habitat quality change. Results of the random utility indicate that willingness to pay of an individual angler for one unit increment in habitat quality is \$363.71, \$350.20, and \$353.02, if visiting Oregon, Idaho, and Washington, respectively. Because the economic damages of NZMS and related management cost are not detailed in the IS literature, the damage and management cost data of zebra mussels are selected as an approximation for those of NZMS. To derive statewide management cost, phone survey of field managers in Idaho, Oregon, and Washington was conducted. Local management cost shown in this chapter is total management cost of each hydrologic region when all local management agents (owners/managers of hydroelectricity plants, drinking water treatment plants, and fish hatcheries, as well as anglers decontaminating their boats and gears) fully undertake management actions.

Chapter 5 integrated the results from the previous chapters and solved for total cost minimization in a spatial context. NZMS expected damages equal to a sum of the potential NZMS damages estimated in Chapter 4, weighted by the integrated NZMS establishment risk in Chapter 3. Given the uncertainties in the relationship between NZMS management and related damages, the total cost minimization is solved for various scenarios. Total cost minimization without any constraints is defined as the base scenario followed by the scenarios about total cost minimization with various NZMS damage levels compared to zebra mussels, total cost minimization with changing efficacies of statewide management as well as boater decontamination and fish hatchery prevention, and total cost minimization subject to budget and/or targeted risk level constraints. Based on model assumptions, the results show that statewide prevention, local boater decontamination and fish hatchery prevention are the most cost-efficient management tools in general; especially boater decontamination is a dominant local strategy. That is, targeted investments based on scientific assessment of IS risk appear to be a guiding principle for managing invaders.

Future studies are needed to improve estimates of management costs as well as efficacy of alternative management strategies. Moreover, monitoring cross-state flows of recreational boats and dynamic assessments of presence and density of invasive species will greatly aid in improved assessment of IS risk.

# BIBLIOGRAPHY

Ben-Akiva, M.E., and S.R. Lerman. 1985. *Discrete choice analysis: theory and application to predict travel demand*. The MIT press.

Anon. 2012. “Boats.net.” Available at: http://www.boats.net/ [Accessed July 20, 2012].

Beerling, D.J., B. Huntley, and J.P. Bailey. 1995. “Climate and the distribution of Fallopia japonica: use of an introduced species to test the predictive capacity of response surfaces.” *Journal of Vegetation Science* 6(2):269–282.

Benson, A.J., R.M. Kipp, J. Larson, and A. Fusaro. 2012. “Potamopyrgus antipodarum.” *Nonindigenous Aquatic Species Database*. Available at: http://nas.er.usgs.gov/queries/factsheet.aspx?SpeciesID=1008 [Accessed July 24, 2013].

Boersma, P.D., S.H. Reichard, and A.N. Van Buren eds. 2006. *Invasive species in the Pacific Northwest*. University of Washington Press.

Ben-Akiva, M.E., and S.R. Lerman. 1985. *Discrete choice analysis: theory and application to predict travel demand*. The MIT press.

Anon. 2012. “Boats.net.” Available at: http://www.boats.net/ [Accessed July 20, 2012].

Beerling, D.J., B. Huntley, and J.P. Bailey. 1995. “Climate and the distribution of Fallopia japonica: use of an introduced species to test the predictive capacity of response surfaces.” *Journal of Vegetation Science* 6(2):269–282.

Benson, A.J., R.M. Kipp, J. Larson, and A. Fusaro. 2012. “Potamopyrgus antipodarum.” *Nonindigenous Aquatic Species Database*. Available at: http://nas.er.usgs.gov/queries/factsheet.aspx?SpeciesID=1008 [Accessed July 24, 2013].

Boersma, P.D., S.H. Reichard, and A.N. Van Buren eds. 2006. *Invasive species in the Pacific Northwest*. University of Washington Press.

Bossenbroek, J., L.E. Johnson, B. Peters, and D.M. Lodge. 2007. “Forecasting the expansion of zebra mussels in the United States.” *Conservation Biology* 21(3):800–810.

Bossenbroek, J.M., C.E. Kraft, and J.C. Nekola. 2001. “Prediction of long-distance dispersal using gravity models: zebra mussel invasion of inland lakes.” *Ecological Applications* 11(6):1778–1788.

Broennimann, O., and A. Guisan. 2008. “Predicting current and future biological invasions: both native and invaded ranges matter.” *Biology Letters* 4(5):585–589.

Bruce, R.L., C.M. Moffitt, and B. Dennis. 2009. "Survival and passage of ingested New Zealand mudsnails through the intestinal tract of rainbow trout." *North American Journal of Aquaculture* 71(4):287–301.

Cabral, L.M.B. 2000. *Introduction to industrial organization*. MIT Press.

Cameron, A.C., and P.K. Trivedi. 2005. *Microeconometrics: Methods and Applications*. Cambridge University Press.

Caraco, N.F., J.J. Cole, P.A. Raymond, D.L. Strayer, M.L. Pace, S.E.G. Findlay, and D.T. Fischer. 1997. "Zebra mussel invasion in a large, turbid river: phytoplankton response to increased grazing." *Ecology* 78(2):588–602.

Carlton, J., and G.M. Ruiz. 2005. "Vector science and integrated vector management in bioinvasion ecology: conceptual frameworks." In H. A. Mooney, R. N. Mack, J. A. McNeely, L. E. Neville, P. J. Schei, and J. K. Waage, eds. *Invasive alien species: a new synthesis*. Island Press, pp. 36–58.

Chang, K.-T. 2010. *Introduction to geographic information systems*. McGraw-Hill Education.

Chase, J.M., and M.A. Leibold. 2003. *Ecological niches: linking classical and contemporary approaches*. University of Chicago Press.

Clout, M.N., and P. Williams. 2009. *Invasive species management: a handbook of techniques*. Oxford Universuty Press.

Connelly, N.A., J.C.R. O'Neill, B.A. Knuth, and T.L. Brown. 2007. "Economic impacts of zebra mussels on drinking water treatment and electric power generation facilities." *Environmental Management* 40(1):105–112.

Dean Runyan Associates. 2009. *Fishing, hunting, wildlife viewing, and shellfishing in Oregon: 2008 state and county expenditure estimates*. Prepared for the Oregon Department of Fish and Wildlife and Travel Oregon.

Dolphin, G., and R. Boatner. 2011. "Oregon aquatic invasive species prevention program: 2010 program report." Oregon State Marine Board & Oregon Department of Fish and Wildlife.

Dybdahl, M.F., and S.L. Kane. 2005. "Adaptation vs. phenotypic plasticity in the success of a clonal invader." *Ecology* 86(6):1592–1601.

Elith, J., and C.H. Graham. 2009. "Do they? How do they? Why do they differ? On finding reasons for differing performances of species distribution models." *Ecography* 32(1):66–77.

Elith, J., C.H. Graham, R.P. Anderson, M. Dud ǩ, S. Ferrier, A. Guisan, R.J. Hijmans, F. Huettmann, J.R. Leathwick, A. Lehmann, Jin Li, L.G. Lohmann, B.A. Loiselle, G. Manion, C. Moritz, M. Nakamura, Y. Nakazawa, J. McC. Overton, A.T. Peterson, and S.J. Phillips. 2006. "Novel methods improve prediction of species' distributions from occurrence data." *Ecography* 29(2):129–151.

Fotheringham, A., and M.E. O'Kelly. 1989. *Spatial interaction models:formulations and applications*. Springer.

Franklin, J. 2009. *Mapping species distributions: spatial inference and prediction*. Cambridge University Press.

Griffiths, R.W., D.W. Schloesser, J.H. Leach, and W.P. Kovalak. 1991. "Distribution and dispersal of the zebra mussel (Dreissena polymorpha) in the Great Lakes region." *Canadian Journal of Fisheries and Aquatic Sciences* 48(8):1381–1388.

Haab, T.C., and K.E. McConnell. 2002. *Valuing environmental and natural resources: the econometrics of non-market valuation*. Edward Elgar Publishing.

Hagerman National Fish Hatchery. "Summer steelhead trout HACCP."

Hall, J.R.O., J.L. Tank, and M.F. Dybdahl. 2003. "Exotic snails dominate nitrogen and carbon cycling in a highly productive stream." *Frontiers in Ecology and the Environment* 1(8):407–411.

Haynes, K.E., and A.S. Fotheringham. 1984. *Gravity and Spatial Interaction Models*. Books on Demand.

Hoddle, M.S. 2013. "CISR: New Zealand mud snail." Available at: http://cisr.ucr.edu/new_zealand_mud_snail.html [Accessed November 22, 2013].

Idaho Department of Environmental Quality. "Source water delineations of Idaho." Available at: http://catalog.data.gov/dataset/source-water-delineations-of-idaho [Accessed November 30, 2012].

ISSG (Invasive Species Specialist Group). 2011. "Global invasive species database: Potamopyrgus antipodarum." Available at: http://www.issg.org/database/species/ecology.asp?si=449 [Accessed July 24, 2013].

Lam, J. 2012. *Invasive species budget survey*. Oregon Sea Grant.

Leung, B., and N.E. Mandrak. 2007. "The risk of establishment of aquatic invasive species: joining invasibility and propagule pressure." *Proceedings of the Royal Society B: Biological Sciences* 274(1625):2603–2609.

Lockwood, J.L., P. Cassey, and T. Blackburn. 2005. “The role of propagule pressure in explaining species invasions.” *Trends in Ecology & Evolution* 20(5):223–228.

Lodge, D.M., S. Williams, H.J. MacIsaac, K.R. Hayes, B. Leung, S. Reichard, R.N. Mack, P.B. Moyle, M. Smith, D.A. Andow, J.T. Carlton, and A. McMichael. 2006. “Biological invasions: recommendations for US policy and management.” *Ecological Applications* 16(6):2035–2054.

Loo, S.E., R.M. Nally, and P.S. Lake. 2007. “Forecasting New Zealand Mudsnail Invasion range: model comparisons using native and invaded ranges.” *Ecological Applications* 17(1):181–189.

Maddala, G.S. 1983. *Limited-dependent and qualitative variables in econometrics*. Cambridge University Press.

Mann, R., H. Radtke, D.D. Huppert, J.R. Hamilton, S.S. Hanna, J. Duffield, and N.R. Netusil. 2010. “Economic risk associated with the potential establishment of zebra and quagga mussels in the Columbia River Basin.”

Maynard, G., and D. Nowell. 2009. “Biosecurity and quarantine for preventing invasive species.” In M. N. Clout and P. Williams, eds. *Invasive species management: a handbook of techniques*. Oxford Universuty Press, pp. 1–18.

Montana State University. 2007. “New Zealand mudsnails in the western USA.” Available at: http://www.esg.montana.edu/aim/mollusca/nzms/index.html [Accessed February 28, 2011].

Muirhead, J.R., M.A. Lewis, and H.J. MacIsaac. 2011. “Prediction and error in multi-stage models for spread of aquatic non-indigenous species.” *Diversity and Distributions* 17(2):323–337.

Murihead, J.R., A.M. Bobeldyk, J.M. Bossenbroek, K.J. Egan, and C.L. Jerde. 2009. “Estimating dispersal and predicting spread of nonindigenous species.” In R. P. Keller, D. M. Lodge, M. A. Lewis, and J. F. Shogren, eds. *Bioeconomics of invasive species: integrating ecology, economics, policy, and management*. Oxford University Press, pp. 103–125.

Natural Capital Project. “InVEST: ES project database.” Available at: http://www.naturalcapitalproject.org/InVEST.html [Accessed October 18, 2013].

Nielson, R.J., C.M. Moffitt, and B.J. Watten. 2008. “Feasibility of two step system for removing New Zealand mudsnails from infested hatchery inflow waters.” Presentation file.

Nielson, R.J., C.M. Moffitt, and B.J. Watten. 2012. “Hydrocyclonic separation of invasive New Zealand mudsnails from an aquaculture water source.” *Aquaculture* 326-329:156–162.

NNSS (Non-native Species Secretariat in U.K.). "Risk assessments - GB non-native species secretariat." Available at: https://secure.fera.defra.gov.uk/nonnativespecies/index.cfm?sectionid=51 [Accessed October 18, 2013].

Oregon Department of Environmental Quality. "Water quality - Oregon drinking water protection program." Available at: http://www.deq.state.or.us/wq/dwp/results.htm [Accessed November 30, 2012].

Ortúzar, J. de D., and L.G. Willumsen. 2011. *Modelling transport*. John Wiley & Sons.

Park, K. 2004. "Assessment and management of invasive alien predators." *Ecology and Society* 9(2).

Perrings, C., M. Williamson, E.B. Barbier, and D. Delfino. 2002. "Biological invasion risks and the public good: an economic perspective." *Conservation Ecology* 6(1).

Peterson, A.T. 2003. "Predicting the geography of species' invasions via ecological niche modeling." *The Quarterly Review of Biology* 78(4):419–433.

Phillips, S. 2011. "A brief tutorial on Maxent." Available at: http://www.cs.princeton.edu/~schapire/maxent/tutorial/tutorial.doc [Accessed March 5, 2011].

Phillips, S.J., R.P. Anderson, and R.E. Schapire. 2006. "Maximum entropy modeling of species geographic distributions." *Ecological Modelling* 190(3–4):231–259.

Phillips, S.J., and M. Dud k. 2008. "Modeling of species distributions with Maxent: new extensions and a comprehensive evaluation." *Ecography* 31(2):161–175.

Pimentel, D., R. Zuniga, and D. Morrison. 2005. "Update on the environmental and economic costs associated with alien-invasive species in the United States." *Ecological Economics* 52(3):273–288.

Potapov, A.B., and M.A. Lewis. 2008. "Allee effect and control of lake system invasion." *Bulletin of Mathematical Biology* 70(5):1371–1397.

Proctor, T., B. Kerans, P. Clancey, E. Ryce, M. Dybdahl, D. Gustafson, R. Hall, F. Pickett, D. Richards, R. Draheim, J. Chapman, R.H. Wiltshire, D. Becker, M. Anderson, B. Pitman, D. Lassuy, P. Heimowitz, P. Dwyer, and E. Levri. 2007. "National management and control plan for the New Zealand mudsnail (Potamopyrgus antipodarum)." *Aquatic Nuisance Species Task Force, USA*:1–52.

Ramcharan, C.W., D.K. Padilla, and S.I. Dodson. 1992. "Models to predict potential occurrence and density of the zebra mussel, Dreissena polymorpha." *Canadian Journal of Fisheries and Aquatic Sciences* 49(12):2611–2620.

Rothlisberger, J.D., and D.M. Lodge. 2011. "Limitations of gravity models in predicting the spread of Eurasian watermilfoil." *Conservation Biology* 25(1):64–72.

Rouget, M., and D.M. Richardson. 2003. "Inferring process from pattern in plant invasions: a semimechanistic model incorporating propagule pressure and environmental factors." *The American Naturalist* 162(6):713–724.

Sala, O.E., F.S. Chapin, Iii, J.J. Armesto, E. Berlow, J. Bloomfield, R. Dirzo, E. Huber-Sanwald, L.F. Huenneke, R.B. Jackson, A. Kinzig, R. Leemans, D.M. Lodge, H.A. Mooney, M. Oesterheld, N.L. Poff, M.T. Sykes, B.H. Walker, M. Walker, and D.H. Wall. 2000. "Global biodiversity scenarios for the year 2100." *Science* 287(5459):1770–1774.

Schapire, R.E. "Maxent software and datasets." Available at: http://www.cs.princeton.edu/~schapire/maxent/ [Accessed March 4, 2011].

Schisler, G.J., N.K.M. Vieira, and P.G. Walker. 2008. "Application of household disinfectants to control New Zealand mudsnails." *North American Journal of Fisheries Management* 28(4):1172–1176.

Schneider, D.W., C.D. Ellis, and K.S. Cummings. 1998. "A transportation model assessment of the risk to native mussel communities from zebra mussel spread." *Conservation Biology* 12(4):788–800.

Schreiber, E.S.G., G.P. Quinn, and P.S. Lake. 2003. "Distribution of an alien aquatic snail in relation to flow variability, human activities and water quality." *Freshwater Biology* 48(6):951–961.

Segurado, P., and M.B. Araújo. 2004. "An evaluation of methods for modelling species distributions." *Journal of Biogeography* 31(10):1555–1568.

Shannon, C.E. 1948. "A mathematical theory of communication." *Bell System Technical Journal* 27(3):379–423.

Smith, M. de, M.F. Goodchild, and P. Longley. 2013. *Geospatial analysis - a comprehensive guide to principles, techniques and software tools (web version)*. The Winchelsea Press. Available at: http://www.spatialanalysisonline.com/output/index.html [Accessed November 20, 2013].

StreamNet. "StreamNet - fish data for the Northwest." Available at: http://www.streamnet.org/ [Accessed November 20, 2012].

Tallis, H., A. Guerry, E. Nelson, D. Ennaanay, S. Wolny, N. Olwero, K. Vigerstol, D. Pennington, G. Mendoza, J. Aukema, J. Foster, J. Forrest, D. Cameron, K. Arkema, E. Lonsdorf, C. Kennedy, G. Verutes, C.-K. Kim, G. Guannel, M. Papenfus, J. Toft, M. Marsik, J. Bernhardt, S. Wood, and R. Sharp. "InVEST 2.1 beta user's guide."

Taylor, C.M., and A. Hastings. 2005. "Allee effects in biological invasions." *Ecology Letters* 8(8):895–908.

U.S. Census Bureau. 2011. "2010 TIGER/Line® Shapefiles." Available at: http://www.census.gov/cgi-bin/geo/shapefiles2010/main [Accessed July 24, 2012].

U.S. Department of Homeland Security, and U.S. Coast Guard Office of Auxiliary and Boating Safety. 2012. "Recreational boating statistics 2011." Available at: http://www.safeboatingcampaign.com/statistics/2011-statistics.pdf [Accessed July 25, 2013].

U.S. Energy Information Administration. 2011. "Existing electric generating units." Available at: http://www.eia.gov/electricity/capacity/ [Accessed October 19, 2011].

U.S. Environmental Protection Agency. 2011. "SDWISFED drinking water data." Available at: http://water.epa.gov/scitech/datait/databases/drink/sdwisfed/pivottables.cfm [Accessed November 30, 2012].

U.S. Geological Survey. 2013. "USGS: Data files for estimated use of water in the United States, 2005." Available at: http://water.usgs.gov/watuse/data/2005/ [Accessed November 20, 2012].

UCSB RIVRLab (University of California, Santa Barbara, Riparian Invasion Research Laboratory). "New Zealand mud snail." Available at: http://rivrlab.msi.ucsb.edu/NZMS/index.php [Accessed July 24, 2013].

Veltman, C.J., S. Nee, and M.J. Crawley. 1996. "Correlates of introduction success in exotic New Zealand birds." *The American Naturalist* 147(4):542–557.

Vinson, M., T. Harju, and E. Dinger. 2007. "Status of the New Zealand mudsnail (Potamopyrgus antipodarum) in the Green River downstream from Flaming Gorge Dam: current distribution; habitat preferences and invertebrate changes; food web and fish effects; and predicted distributions. US Bureau of Land Management, Final Report." *Final Reports for Project Agreements: USFWS-601815G405, NPS-J1242050058. BLM-JSA041003*.

Vinson, M.R., and M.A. Baker. 2008. "Poor growth of rainbow trout fed New Zealand mud snails Potamopyrgus antipodarum." *North American Journal of Fisheries Management* 28(3):701–709.

Washington State Department of Health. “Washington’s source water assessment program maps.” Available at: https://fortress.wa.gov/doh/eh/dw/swap/maps/ [Accessed November 30, 2012].

Wooldridge, J.M. 2002. *Econometric analysis of cross section and panel data*. The MIT press.

# APPENDICES

## Appendix 2.1 Gravity Model: Summary Statistics of Variables

| Variable | Mean | Std. Dev. | Minimum | Maximum |
|---|---|---|---|---|
| OREGON | | | | |
| Boat Flow | 21.72 | 181.33 | 0.00 | 10679.74 |
| Distance (m) | 303018.40 | 151057.40 | 0.00 | 707973.9 |
| Hydrologic Unit Size ($km^2$) | 2734.35 | 1889.14 | 0.10 | 10727.10 |
| Herfindahl Index[a] | 164.44 | 334.43 | 0.00 | 2307.81 |
| Road Density ($km/km^2$) | 0.06 | 0.05 | 0.00 | 0.33 |
| Water Quality Index (WQI) | 80.19 | 7.89 | 56.78 | 95.55 |
| Dummy (Ocean) | 0.16 | 0.36 | 0.00 | 1.00 |
| WASHINGTON | | | | |
| Boat Flow | 42.83 | 315.17 | 0.00 | 12223.53 |
| Distance (m) | 245165.50 | 127247.40 | 0.00 | 572318.70 |
| Hydrologic Unit Size ($km^2$) | 2575.74 | 1605.42 | 6.25 | 7596.03 |
| Herfindahl Index[a] | 197.16 | 758.62 | 0.00 | 5171.06 |
| Road Density ($km/km^2$) | 0.07 | 0.06 | 0.00 | 0.33 |
| Water Quality Index (WQI) | 74.71 | 8.10 | 47.43 | 91.26 |
| Dummy (Ocean) | 0.13 | 0,33 | 0.00 | 1.00 |
| IDAHO | | | | |
| Boat Flow | 27.20 | 349.66 | 0.00 | 21249.06 |
| Distance (m) | 325778.90 | 182663.70 | 0.00 | 839864.30 |
| Hydrologic Unit Size ($km^2$) | 3278.50 | 1879.21 | 0.26 | 9521.40 |
| Herfindahl Index[a] | 17.31 | 127.48 | 0.00 | 1215.34 |
| Road Density ($km/km^2$) | 0.05 | 0.08 | 0.00 | 0.74 |
| Stream Fish Index (SFI) | 72.24 | 17.01 | 20.76 | 98.76 |

[a] Herfindahl Index = 10,000 Absent sum of (water body / hydrologic unit size)$^2$.

## Appendix 2.2 Gravity Model: Data Sources

| Data | Source | | |
|---|---|---|---|
| | Idaho | Oregon | Washington |
| Boat Registration | Idaho Dept. of Parks & Recreation | Oregon State Marine Board | Dept. of Licensing |
| Boater Survey | Idaho Dept. of Parks & Recreation | OSU survey center | Dept. of Fish & Wildlife |
| Water Quality | Idaho Dept. of Environmental Quality | Oregon Dept. of Environmental Quality - LASAR | Washington Dept. of Ecology |
| Hydrologic Unit | U.S. Geological Survey – 1:250,000-scale Hydrologic Units of the United States | | |
| 5-digit ZIP Code Tabulation Areas | U.S. Census Bureau – ZIP Code Tabulation Areas | | |
| Counties | U.S. Census Bureau – Counties (and equivalent) | | |
| Cartographic boundary | U.S. Census Bureau – 2000 Incorporated Places/Census Designated Places | | |
| Population Estimates | U.S. Census Bureau – All Incorporated Places: 2000 to 2009; Preliminary Vintage 2010 Population Estimates and 2010 Census Counts | | |
| Waterbody | U.S. Census Bureau – Area Hydrography | | |
| Road | U.S. Census Bureau – Primary and Secondary Roads | | |

**Appendix 3.1 Maximum Entropy Method: Data Sources**

| **Data** **(Variable)** | **Description** **(Unit)** | **Source** |
|---|---|---|
| Elevation | Digital elevation grid (m) | PRISM Climate Group – 2.5 minute Digital Elevation Model (DEM) for the Conterminous U.S. |
| Surficial Geology | 1:7500000-scale map of surficial geology with geologic unit categories (category) | U.S. Geological Survey – Surficial geology in the conterminous U.S. |
| City Area | Area considered as cities, boroughs, towns, and villages (category) | U.S. Census Bureau – 2000 Incorporated Places/Census Designated Places |
| Monthly Precipitation | 2010 monthly precipitation (0.01mm) | PRISM Climate Group – Near-Real-Time Monthly High-Resolution Precipitation Climate Data Set for the Conterminous U.S. |
| Monthly Maximum Temperature | 2010 monthly average maximum temperature (0.01 ℃) | PRISM Climate Group – Near-Real-Time Monthly Average Maximum/Minimum Temperature for the Conterminous U.S. |
| Monthly Minimum Temperature | 2010 monthly average minimum temperature (0.01 ℃) | PRISM Climate Group – Near-Real-Time Monthly Average Maximum/Minimum Temperature for the Conterminous U.S. |
| Water Body | Water bodies in each state (category) | U.S. Census Bureau – Area Hydrography |

Note: City area and water area are originally vector data, and they are converted to the raster data.

## Appendix 5.1 Cost-Efficient Local Management Strategies in the Base Scenario (USD/Year)

| 6-digit Hydrologic Unit | | Hydroelectricity Plants | | | Drinking Water Treatment Plants | | | Boater Deconta-mination | Fish Hatchery Prevention |
|---|---|---|---|---|---|---|---|---|---|
| | | Prevention | EDRR plus | EX-post | Prevention | EDRR plus | EX-post | | |
| ID | 160101 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 160102 | 0 | 0 | 0 | 0 | 0 | 0 | 5,200 | 0 |
| | 160203 | 0 | 0 | 0 | 0 | 0 | 0 | 2,700 | 0 |
| | 170101 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170103 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170401 | 0 | 0 | 0 | 0 | 0 | 0 | 1,500 | 0 |
| | 170402 | 0 | 0 | 0 | 0 | 0 | 0 | 4,100 | 0 |
| | 170501 | 0 | 0 | 0 | 0 | 0 | 0 | 5,100 | 0 |
| | 170502 | 0 | 0 | 0 | 0 | 0 | 0 | 3,700 | 0 |
| | 170601 | 0 | 0 | 0 | 0 | 0 | 0 | 2,000 | 0 |
| | 170602 | 0 | 0 | 0 | 0 | 0 | 0 | 100 | 0 |
| | 170603 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| OR | 170501 | 0 | 0 | 0 | 0 | 0 | 0 | 300 | 0 |
| | 170502 | 0 | 0 | 0 | 0 | 0 | 0 | 2,600 | 300 |
| | 170601 | 0 | 0 | 0 | 0 | 0 | 0 | 200 | 1,300 |
| | 170701 | 0 | 0 | 0 | 0 | 0 | 0 | 800 | 2,100 |
| | 170702 | 0 | 0 | 0 | 0 | 0 | 0 | 200 | 0 |
| | 170703 | 0 | 0 | 0 | 0 | 0 | 0 | 2,100 | 0 |
| | 170800 | 0 | 0 | 0 | 0 | 0 | 0 | 6,000 | 1,200 |
| | 170900 | 0 | 0 | 0 | 0 | 0 | 0 | 1,600 | 0 |
| | 171002 | 0 | 0 | 0 | 0 | 0 | 0 | 6,200 | 1,100 |
| | 171003 | 0 | 0 | 0 | 0 | 0 | 0 | 3,000 | 400 |
| | 171200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 180102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 180200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| WA | 170102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170103 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170300 | 0 | 0 | 0 | 0 | 0 | 0 | 1,500 | 0 |
| | 170601 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3,200 |
| | 170701 | 0 | 0 | 0 | 0 | 0 | 0 | 3,600 | 0 |
| | 170800 | 0 | 0 | 0 | 0 | 0 | 0 | 4,000 | 1,500 |
| | 171001 | 0 | 0 | 0 | 0 | 0 | 0 | 600 | 100 |
| | 171100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

## Appendix 5.2 Cost-Efficient Local Management Strategies with Various NZMS Damages: Boater Decontamination (USD/Year)

| 6-digit Hydrologic Unit | | 100% | 90% | 80% | 70% | 60% | 50% | 40% | 30% | 20% | 10% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ID | 160101 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 160102 | 5,500 | 5,500 | 5,500 | 5,500 | 5,400 | 5,200 | 5,300 | 5,200 | 5,000 | 5,200 |
| | 160203 | 3,000 | 3,200 | 2,500 | 2,900 | 3,100 | 2,700 | 3,100 | 2,600 | 2,300 | 2,400 |
| | 170101 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170103 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170401 | 1,600 | 1,600 | 1,600 | 1,400 | 1,400 | 1,500 | 1,300 | 1,400 | 1,300 | 1,200 |
| | 170402 | 4,000 | 3,900 | 4,100 | 4,100 | 4,100 | 4,100 | 4,000 | 4,700 | 3,800 | 3,500 |
| | 170501 | 4,100 | 1,900 | 5,500 | 5,300 | 5,100 | 5,100 | 4,800 | 5,200 | 4,300 | 3,900 |
| | 170502 | 3,800 | 4,100 | 4,000 | 3,900 | 4,000 | 3,700 | 3,900 | 3,700 | 3,600 | 3,400 |
| | 170601 | 2,700 | 2,900 | 2,900 | 2,400 | 2,600 | 2,000 | 2,100 | 2,200 | 1,400 | 2,000 |
| | 170602 | 0 | 0 | 0 | 0 | 0 | 100 | 0 | 0 | 200 | 0 |
| | 170603 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| OR | 170501 | 300 | 200 | 700 | 1,400 | 400 | 300 | 1,300 | 1,500 | 300 | 200 |
| | 170502 | 2,700 | 2,600 | 2,800 | 2,800 | 2,600 | 2,600 | 2,800 | 2,700 | 2,300 | 2,500 |
| | 170601 | 300 | 200 | 300 | 300 | 200 | 200 | 200 | 300 | 300 | 100 |
| | 170701 | 1,000 | 900 | 1,000 | 1,100 | 900 | 800 | 900 | 1,000 | 600 | 800 |
| | 170702 | 200 | 400 | 700 | 1,300 | 400 | 200 | 1,100 | 800 | 100 | 100 |
| | 170703 | 2,700 | 2,600 | 2,500 | 3,200 | 2,000 | 2,100 | 2,900 | 2,700 | 1,500 | 1,100 |
| | 170800 | 6,700 | 6,600 | 6,300 | 6,300 | 6,300 | 6,000 | 5,900 | 5,700 | 5,500 | 5,000 |
| | 170900 | 2,000 | 2,100 | 2,400 | 3,000 | 1,900 | 1,600 | 2,400 | 2,100 | 800 | 700 |
| | 171002 | 7,000 | 6,800 | 6,900 | 7,300 | 6,800 | 6,200 | 6,800 | 7,300 | 6,000 | 6,700 |
| | 171003 | 3,700 | 3,700 | 3,800 | 4,400 | 2,900 | 3,000 | 4,200 | 3,900 | 2,800 | 2,600 |
| | 171200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 180102 | 0 | 0 | 100 | 500 | 0 | 0 | 300 | 200 | 0 | 0 |
| | 180200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| WA | 170102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170103 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170300 | 1,600 | 1,400 | 1,500 | 1,500 | 1,500 | 1,500 | 1,500 | 1,300 | 1,500 | 1,700 |
| | 170601 | 1,100 | 1,000 | 1,000 | 1,100 | 1,100 | 0 | 1,100 | 1,000 | 800 | 600 |
| | 170701 | 2,100 | 2,200 | 2,200 | 2,600 | 2,300 | 3,600 | 2,200 | 2,100 | 2,200 | 2,200 |
| | 170800 | 5,800 | 4,900 | 4,600 | 5,700 | 5,600 | 4,000 | 4,900 | 5,400 | 4,900 | 4,200 |
| | 171001 | 1,200 | 500 | 0 | 200 | 900 | 600 | 400 | 400 | 100 | 100 |
| | 171100 | 0 | 1,000 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

## Appendix 5.3 Cost-Efficient Local Management Strategies with Various NZMS Damages: Fish Hatchery Prevention (USD/Year)

| 6-digit Hydrologic Unit | | 100% | 90% | 80% | 70% | 60% | 50% | 40% | 30% | 20% | 10% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ID | 160101 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 160102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 100 | 100 | 100 |
| | 160203 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170101 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170103 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170401 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170402 | 0 | 100 | 200 | 0 | 0 | 0 | 0 | 200 | 100 | 0 |
| | 170501 | 1,300 | 3,500 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170502 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170601 | 300 | 0 | 0 | 400 | 0 | 0 | 300 | 0 | 800 | 0 |
| | 170602 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 500 | 0 | 100 |
| | 170603 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| OR | 170501 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170502 | 300 | 300 | 300 | 300 | 300 | 300 | 300 | 300 | 300 | 300 |
| | 170601 | 1,400 | 1,200 | 1,400 | 1,600 | 1,100 | 1,300 | 1,600 | 1,600 | 1,100 | 1,200 |
| | 170701 | 2,200 | 2,300 | 2,300 | 2,700 | 2,300 | 2,100 | 2,600 | 2,300 | 2,300 | 1,900 |
| | 170702 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170703 | 100 | 100 | 400 | 400 | 500 | 0 | 0 | 0 | 0 | 0 |
| | 170800 | 1,300 | 1,300 | 1,400 | 1,400 | 1,100 | 1,200 | 1,100 | 1,000 | 800 | 900 |
| | 170900 | 100 | 0 | 0 | 0 | 0 | 0 | 0 | 200 | 300 | 0 |
| | 171002 | 800 | 900 | 900 | 700 | 700 | 1,100 | 700 | 100 | 900 | 0 |
| | 171003 | 100 | 200 | 400 | 500 | 900 | 400 | 200 | 400 | 400 | 300 |
| | 171200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 180102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 180200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| WA | 170102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170103 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170300 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170601 | 2,000 | 2,000 | 1,800 | 2,100 | 2,100 | 3,200 | 2,100 | 2,100 | 1,800 | 1,200 |
| | 170701 | 1,600 | 1,400 | 1,400 | 1,100 | 1,400 | 0 | 1,500 | 1,600 | 1,600 | 1,700 |
| | 170800 | 0 | 800 | 1,000 | 0 | 0 | 1,500 | 700 | 0 | 600 | 1,400 |
| | 171001 | 0 | 700 | 1,100 | 700 | 0 | 100 | 200 | 0 | 200 | 0 |
| | 171100 | 0 | 200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

## Appendix 5.4 Cost-Efficient Local Management Strategies in the Various Statewide Management Efficacies: Boater Decontamination (USD/Year)

| 6-digit Hydrologic Unit | | 100% | 90% | 80% | 70% | 60% | 50% | 40% | 30% | 20% | 10% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ID | 160101 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 160102 | 5,000 | 5,200 | 5,200 | 6,000 | 6,100 | 5,800 | 5,800 | 6,200 | 5,900 | 6,200 |
| | 160203 | 2,700 | 3,100 | 2,700 | 2,500 | 2,600 | 3,200 | 2,200 | 1,700 | 3,300 | 1,600 |
| | 170101 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170103 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170401 | 1,200 | 1,300 | 1,500 | 1,600 | 1,800 | 1,700 | 1,700 | 1,600 | 1,700 | 1,500 |
| | 170402 | 0 | 1,600 | 4,100 | 9,900 | 9,300 | 10,000 | 9,800 | 10,000 | 9,900 | 9,800 |
| | 170501 | 2,000 | 3,400 | 5,100 | 7,000 | 8,800 | 9,000 | 9,000 | 9,000 | 9,000 | 9,000 |
| | 170502 | 3,700 | 3,900 | 3,700 | 4,400 | 4,100 | 4,100 | 3,500 | 4,500 | 4,100 | 4,000 |
| | 170601 | 2,400 | 1,900 | 2,000 | 2,000 | 2,500 | 2,200 | 2,300 | 2,700 | 2,700 | 2,400 |
| | 170602 | 0 | 0 | 100 | 300 | 2,500 | 1,400 | 1,600 | 1,000 | 300 | 2,900 |
| | 170603 | 0 | 0 | 0 | 600 | 0 | 500 | 0 | 500 | 600 | 0 |
| OR | 170501 | 0 | 0 | 300 | 2,900 | 3,600 | 3,400 | 3,000 | 3,300 | 3,500 | 3,100 |
| | 170502 | 2,100 | 2,500 | 2,500 | 3,200 | 3,400 | 3,400 | 3,400 | 3,400 | 3,400 | 3,400 |
| | 170601 | 0 | 100 | 100 | 400 | 400 | 500 | 400 | 500 | 500 | 500 |
| | 170701 | 500 | 700 | 900 | 1,300 | 1,500 | 1,400 | 1,300 | 1,000 | 1,300 | 1,300 |
| | 170702 | 0 | 0 | 200 | 2,300 | 2,500 | 2,700 | 2,300 | 2,400 | 2,700 | 2,400 |
| | 170703 | 600 | 1,300 | 2,200 | 4,200 | 4,200 | 4,400 | 4,700 | 5,000 | 4,800 | 4,900 |
| | 170800 | 6,200 | 5,800 | 6,300 | 6,200 | 5,100 | 6,300 | 6,300 | 6,900 | 6,000 | 6,200 |
| | 170900 | 0 | 800 | 1,600 | 4,100 | 4,600 | 4,700 | 4,700 | 4,700 | 4,700 | 4,700 |
| | 171002 | 6,400 | 6,600 | 5,900 | 7,900 | 7,800 | 7,400 | 7,600 | 8,100 | 7,900 | 7,700 |
| | 171003 | 900 | 2,100 | 3,100 | 6,100 | 6,200 | 6,400 | 6,700 | 6,900 | 6,800 | 6,800 |
| | 171200 | 0 | 0 | 0 | 0 | 200 | 1,000 | 900 | 1,000 | 1,000 | 1,000 |
| | 180102 | 0 | 0 | 0 | 1,000 | 1,400 | 1,400 | 1,300 | 1,400 | 1,300 | 1,400 |
| | 180200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| WA | 170102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170103 | 0 | 0 | 0 | 0 | 100 | 0 | 200 | 200 | 200 | 100 |
| | 170200 | 0 | 0 | 0 | 400 | 3,700 | 3,500 | 3,700 | 3,400 | 3,700 | 3,600 |
| | 170300 | 900 | 1,000 | 1,500 | 1,700 | 2,700 | 2,700 | 2,600 | 2,600 | 2,600 | 2,700 |
| | 170601 | 400 | 700 | 0 | 1,200 | 1,100 | 1,000 | 900 | 1,100 | 1,400 | 1,100 |
| | 170701 | 1,900 | 1,800 | 3,600 | 200 | 2,700 | 2,600 | 2,700 | 2,800 | 2,600 | 2,100 |
| | 170800 | 4,500 | 4,200 | 4,000 | 2,300 | 6,000 | 5,400 | 5,900 | 6,100 | 6,500 | 6,500 |
| | 171001 | 200 | 0 | 600 | 1,000 | 600 | 1,000 | 700 | 700 | 600 | 1,900 |
| | 171100 | 0 | 0 | 0 | 1,300 | 1,600 | 1,300 | 3,700 | 3,700 | 3,800 | 1,500 |

## Appendix 5.5 Cost-Efficient Local Management Strategies in the Various Statewide Management Efficacies: Fish Hatchery Prevention (USD/Year)

| 6-digit Hydrologic Unit | | 100% | 90% | 80% | 70% | 60% | 50% | 40% | 30% | 20% | 10% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ID | 160101 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 160102 | 0 | 0 | 0 | 0 | 100 | 100 | 100 | 0 | 0 | 0 |
| | 160203 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170101 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170103 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170401 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170402 | 0 | 0 | 0 | 0 | 600 | 0 | 100 | 0 | 0 | 100 |
| | 170501 | 0 | 0 | 0 | 1,900 | 200 | 0 | 0 | 0 | 0 | 0 |
| | 170502 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170601 | 0 | 500 | 0 | 700 | 500 | 500 | 500 | 0 | 0 | 400 |
| | 170602 | 0 | 0 | 0 | 2,600 | 500 | 1,600 | 1,300 | 1,900 | 2,700 | 0 |
| | 170603 | 0 | 0 | 0 | 0 | 600 | 100 | 500 | 0 | 0 | 600 |
| OR | 170501 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170502 | 200 | 0 | 300 | 400 | 300 | 400 | 400 | 400 | 400 | 400 |
| | 170601 | 1,000 | 1,000 | 1,400 | 2,200 | 2,200 | 2,500 | 2,400 | 2,500 | 2,400 | 2,400 |
| | 170701 | 1,600 | 1,800 | 2,100 | 3,000 | 3,200 | 3,300 | 3,200 | 3,600 | 3,300 | 3,300 |
| | 170702 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170703 | 0 | 0 | 0 | 300 | 800 | 700 | 300 | 0 | 300 | 200 |
| | 170800 | 700 | 1,100 | 800 | 1,300 | 2,300 | 1,200 | 1,200 | 600 | 1,500 | 1,300 |
| | 170900 | 0 | 0 | 0 | 0 | 100 | 0 | 0 | 0 | 0 | 0 |
| | 171002 | 300 | 400 | 1,400 | 300 | 700 | 1,100 | 800 | 400 | 600 | 800 |
| | 171003 | 700 | 400 | 400 | 100 | 600 | 500 | 200 | 0 | 100 | 100 |
| | 171200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 180102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 180200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| WA | 170102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170103 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170200 | 0 | 0 | 0 | 100 | 100 | 200 | 0 | 300 | 0 | 200 |
| | 170300 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170601 | 800 | 1,200 | 3,200 | 2,100 | 2,100 | 1,900 | 1,800 | 2,200 | 2,800 | 2,000 |
| | 170701 | 1,400 | 1,500 | 0 | 3,700 | 2,000 | 2,000 | 1,900 | 1,900 | 2,000 | 2,500 |
| | 170800 | 700 | 1,000 | 1,500 | 3,400 | 600 | 1,100 | 600 | 400 | 0 | 0 |
| | 171001 | 300 | 300 | 100 | 0 | 1,500 | 1,000 | 1,200 | 1,100 | 1,300 | 0 |
| | 171100 | 0 | 0 | 0 | 0 | 2,200 | 2,500 | 100 | 0 | 0 | 2,200 |

## Appendix 5.6 Cost-Efficient Local Management Strategies with Various Boater Decontamination & Fish Hatchery Prevention Efficacies: Boater Decontamination (USD/Year)

| 6-digit Hydrologic Unit | | 100% | 90% | 80% | 70% | 60% | 50% | 40% | 30% | 20% | 10% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ID | 160101 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 160102 | 4,500 | 5,000 | 5,300 | 5,200 | 5,600 | 6,200 | 6,400 | 5,800 | 4,000 | 0 |
| | 160203 | 1,700 | 2,900 | 1,600 | 2,700 | 3,000 | 2,700 | 2,300 | 3,200 | 2,100 | 0 |
| | 170101 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170103 | 300 | 200 | 100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170401 | 1,500 | 1,600 | 1,500 | 1,500 | 1,400 | 1,300 | 700 | 0 | 0 | 0 |
| | 170402 | 7,700 | 8,300 | 9,000 | 4,100 | 1,000 | 0 | 0 | 0 | 0 | 0 |
| | 170501 | 6,700 | 7,600 | 8,200 | 5,100 | 2,700 | 1,900 | 0 | 0 | 0 | 0 |
| | 170502 | 2,900 | 3,600 | 3,800 | 3,700 | 4,100 | 4,900 | 4,500 | 4,900 | 4,400 | 0 |
| | 170601 | 2,200 | 2,300 | 2,500 | 2,000 | 2,300 | 2,200 | 1,400 | 0 | 0 | 0 |
| | 170602 | 1,300 | 800 | 800 | 100 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170603 | 900 | 900 | 400 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| OR | 170501 | 2,900 | 2,600 | 2,400 | 300 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170502 | 2,800 | 2,900 | 2,900 | 2,600 | 2,500 | 2,500 | 2,500 | 2,100 | 0 | 0 |
| | 170601 | 400 | 400 | 400 | 200 | 200 | 0 | 0 | 0 | 0 | 0 |
| | 170701 | 1,100 | 1,100 | 1,200 | 800 | 1,300 | 700 | 500 | 400 | 0 | 0 |
| | 170702 | 2,300 | 2,100 | 1,800 | 200 | 100 | 0 | 0 | 0 | 0 | 0 |
| | 170703 | 4,000 | 3,800 | 3,400 | 2,100 | 1,200 | 0 | 0 | 0 | 0 | 0 |
| | 170800 | 4,900 | 5,200 | 6,100 | 6,000 | 6,400 | 8,500 | 7,200 | 6,500 | 0 | 0 |
| | 170900 | 3,700 | 4,000 | 3,500 | 1,600 | 700 | 0 | 0 | 0 | 0 | 0 |
| | 171002 | 5,600 | 6,200 | 6,500 | 6,200 | 6,600 | 7,000 | 7,800 | 5,100 | 3,900 | 4,600 |
| | 171003 | 5,000 | 5,400 | 5,100 | 3,000 | 2,200 | 700 | 0 | 0 | 0 | 0 |
| | 171200 | 1,000 | 800 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 180102 | 1,400 | 1,300 | 900 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 180200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| WA | 170102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170103 | 500 | 500 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170200 | 3,000 | 3,200 | 200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170300 | 2,300 | 2,300 | 1,600 | 1,500 | 1,100 | 900 | 200 | 0 | 0 | 0 |
| | 170601 | 1,200 | 1,700 | 1,200 | 0 | 800 | 1,100 | 800 | 300 | 0 | 0 |
| | 170701 | 2,400 | 2,800 | 2,300 | 3,600 | 2,200 | 2,200 | 3,300 | 1,800 | 800 | 0 |
| | 170800 | 4,700 | 3,900 | 4,900 | 4,000 | 5,700 | 3,500 | 6,400 | 5,900 | 5,900 | 0 |
| | 171001 | 900 | 500 | 900 | 600 | 100 | 0 | 0 | 0 | 0 | 0 |
| | 171100 | 2,900 | 3,300 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

## Appendix 5.7 Cost-Efficient Local Management Strategies with Various Boater Decontamination & Fish Hatchery Prevention Efficacies: Fish Hatchery Prevention (USD/Year)

| 6-digit Hydrologic Unit | | 100% | 90% | 80% | 70% | 60% | 50% | 40% | 30% | 20% | 10% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ID | 160101 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 160102 | 100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 160203 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170101 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170103 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170401 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170402 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170501 | 300 | 0 | 0 | 0 | 400 | 0 | 0 | 0 | 0 | 0 |
| | 170502 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170601 | 400 | 400 | 300 | 0 | 0 | 600 | 0 | 0 | 0 | 0 |
| | 170602 | 1,300 | 1,900 | 2,100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170603 | 0 | 0 | 500 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| OR | 170501 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170502 | 300 | 300 | 300 | 300 | 300 | 300 | 200 | 0 | 0 | 0 |
| | 170601 | 2,100 | 2,200 | 1,900 | 1,300 | 900 | 600 | 0 | 0 | 0 | 0 |
| | 170701 | 2,500 | 2,800 | 2,600 | 2,100 | 1,500 | 1,700 | 1,400 | 500 | 0 | 0 |
| | 170702 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170703 | 100 | 500 | 500 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170800 | 800 | 1,100 | 600 | 1,200 | 1,300 | 100 | 2,900 | 1,300 | 0 | 0 |
| | 170900 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 171002 | 900 | 800 | 900 | 1,100 | 1,200 | 1,400 | 1,700 | 4,900 | 5,300 | 1,300 |
| | 171003 | 300 | 300 | 300 | 400 | 400 | 700 | 0 | 0 | 0 | 0 |
| | 171200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 180102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 180200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| WA | 170102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170103 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170300 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170601 | 2,200 | 2,000 | 1,900 | 3,200 | 1,600 | 1,900 | 1,500 | 700 | 0 | 0 |
| | 170701 | 1,200 | 1,100 | 1,200 | 0 | 1,500 | 1,700 | 800 | 1,700 | 700 | 0 |
| | 170800 | 300 | 1,600 | 300 | 1,500 | 300 | 3,100 | 600 | 1,100 | 200 | 0 |
| | 171001 | 800 | 1,200 | 0 | 100 | 100 | 0 | 0 | 0 | 0 | 0 |
| | 171100 | 200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

## Appendix 5.8 Cost-Efficient Local Management Strategies with Budget Constraints: Boater Decontamination (USD/Year)

| 6-digit Hydrologic Unit | | 90% | 80% | 70% | 60% | 50% | 40% | 30% | 20% | 10% |
|---|---|---|---|---|---|---|---|---|---|---|
| ID | 160101 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 160102 | 5,200 | 5,200 | 4,900 | 4,900 | 4,900 | 4,900 | 4,300 | 0 | 0 |
| | 160203 | 2,700 | 2,700 | 2,700 | 2,700 | 2,700 | 2,700 | 2,700 | 2,600 | 2,300 |
| | 170101 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170103 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170401 | 1,400 | 1,400 | 1,000 | 1,000 | 1,000 | 1,000 | 0 | 0 | 0 |
| | 170402 | 1,500 | 0 | 1,000 | 1,000 | 500 | 100 | 0 | 200 | 0 |
| | 170501 | 800 | 2,100 | 11,900 | 8,300 | 100 | 0 | 0 | 0 | 0 |
| | 170502 | 3,700 | 3,700 | 3,600 | 3,600 | 3,600 | 3,600 | 3,600 | 3,000 | 1,400 |
| | 170601 | 2,000 | 2,000 | 1,800 | 1,800 | 1,800 | 1,800 | 1,400 | 0 | 0 |
| | 170602 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170603 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| OR | 170501 | 300 | 300 | 200 | 200 | 200 | 200 | 200 | 200 | 200 |
| | 170502 | 2,500 | 2,500 | 2,400 | 2,300 | 2,200 | 2,200 | 2,200 | 1,800 | 1,800 |
| | 170601 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 100 | 100 |
| | 170701 | 700 | 700 | 400 | 200 | 0 | 0 | 0 | 0 | 0 |
| | 170702 | 200 | 200 | 200 | 200 | 200 | 200 | 200 | 100 | 100 |
| | 170703 | 600 | 200 | 200 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170800 | 5,300 | 5,300 | 5,200 | 3,000 | 1,900 | 500 | 400 | 0 | 0 |
| | 170900 | 3,300 | 500 | 0 | 100 | 0 | 300 | 0 | 400 | 300 |
| | 171002 | 4,800 | 4,400 | 3,500 | 5,000 | 5,000 | 300 | 0 | 200 | 0 |
| | 171003 | 1,500 | 200 | 1,100 | 0 | 0 | 100 | 0 | 100 | 0 |
| | 171200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 180102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 180200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| WA | 170102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170103 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170200 | 0 | 0 | 0 | 400 | 300 | 0 | 200 | 200 | 0 |
| | 170300 | 1,200 | 1,000 | 1,100 | 400 | 400 | 0 | 0 | 0 | 0 |
| | 170601 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170701 | 3,400 | 3,400 | 3,500 | 3,100 | 3,100 | 2,900 | 2,700 | 0 | 0 |
| | 170800 | 3,700 | 3,500 | 400 | 2,500 | 1,300 | 300 | 100 | 100 | 0 |
| | 171001 | 500 | 300 | 400 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 171100 | 0 | 0 | 200 | 0 | 0 | 200 | 300 | 300 | 100 |

**Appendix 5.9 Cost-Efficient Local Management Strategies with Budget Constraints: Fish Hatchery Prevention (USD/Year)**

| 6-digit Hydrologic Unit | | 90% | 80% | 70% | 60% | 50% | 40% | 30% | 20% | 10% |
|---|---|---|---|---|---|---|---|---|---|---|
| ID | 160101 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 160102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 160203 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170101 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170103 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170401 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170402 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170501 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170502 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170601 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170602 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170603 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| OR | 170501 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170502 | 300 | 300 | 200 | 200 | 200 | 200 | 200 | 200 | 200 |
| | 170601 | 1,300 | 1,300 | 1,200 | 1,100 | 1,100 | 1,000 | 1,000 | 800 | 800 |
| | 170701 | 1,800 | 1,800 | 1,100 | 600 | 0 | 0 | 0 | 0 | 0 |
| | 170702 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170703 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170800 | 1,100 | 1,100 | 800 | 600 | 400 | 100 | 100 | 0 | 0 |
| | 170900 | 100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 171002 | 900 | 900 | 800 | 500 | 100 | 0 | 0 | 0 | 0 |
| | 171003 | 400 | 400 | 300 | 200 | 100 | 0 | 0 | 0 | 0 |
| | 171200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 180102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 180200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| WA | 170102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170103 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170300 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170601 | 3,200 | 3,200 | 3,200 | 3,200 | 3,200 | 3,200 | 3,200 | 3,100 | 1,900 |
| | 170701 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170800 | 1,500 | 1,300 | 1,100 | 300 | 200 | 0 | 0 | 0 | 0 |
| | 171001 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 171100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

## Appendix 5.10 Cost-Efficient Local Management Strategies with Budget Constraints: Sum of Hydroelectricity Plant Management (USD/Year)

| 6-digit Hydrologic Unit | | 90% | 80% | 70% | 60% | 50% | 40% | 30% | 20% | 10% |
|---|---|---|---|---|---|---|---|---|---|---|
| ID | 160101 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 160102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 160203 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170101 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170103 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170401 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170402 | 4,300 | 0 | 600 | 0 | 5,300 | 1,700 | 0 | 2,100 | 200 |
| | 170501 | 0 | 0 | 0 | 200 | 0 | 0 | 0 | 0 | 0 |
| | 170502 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170601 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170602 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170603 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| OR | 170501 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170502 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170601 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170701 | 0 | 0 | 0 | 0 | 0 | 1,100 | 0 | 900 | 200 |
| | 170702 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170703 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 500 | 100 |
| | 170800 | 0 | 0 | 0 | 0 | 0 | 1,300 | 0 | 800 | 200 |
| | 170900 | 0 | 0 | 0 | 0 | 0 | 1,900 | 0 | 4,300 | 1,200 |
| | 171002 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 171003 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 100 | 0 |
| | 171200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 180102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 180200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| WA | 170102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170103 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170200 | 0 | 0 | 0 | 0 | 0 | 1,900 | 1,500 | 1,400 | 0 |
| | 170300 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170601 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170701 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 200 | 0 |
| | 170800 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 171001 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 171100 | 0 | 0 | 0 | 0 | 0 | 0 | 100 | 100 | 0 |

## Appendix 5.11 Cost-Efficient Local Management Strategies with Targeted Risk Constraints (All Individual Regions): Boater Decontamination (USD/Year)

| 6-digit Hydrologic Unit | | 90% | 80% | 70% | 60% | 50% | 40% | 30% | 20% | 10% |
|---|---|---|---|---|---|---|---|---|---|---|
| ID | 160101 | 100 | 200 | 500 | 600 | 800 | 1,100 | 1,400 | 1,800 | 2,600 |
| | 160102 | 5,400 | 5,000 | 5,000 | 4,400 | 6,600 | 3,900 | 6,000 | 0 | 0 |
| | 160203 | 3,100 | 3,100 | 3,100 | 3,100 | 3,100 | 2,800 | 3,100 | 1,700 | 2,500 |
| | 170101 | 0 | 300 | 100 | 0 | 0 | 400 | 0 | 0 | 0 |
| | 170102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170103 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170401 | 1,400 | 1,100 | 1,100 | 0 | 0 | 1,100 | 0 | 0 | 0 |
| | 170402 | 4,000 | 0 | 100 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170501 | 5,000 | 0 | 800 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170502 | 4,000 | 4,000 | 4,000 | 3,900 | 4,200 | 3,600 | 4,200 | 5,300 | 2,700 |
| | 170601 | 2,200 | 2,100 | 2,100 | 1,700 | 2,700 | 1,800 | 3,500 | 2,400 | 3,400 |
| | 170602 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170603 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| OR | 170501 | 300 | 300 | 300 | 300 | 300 | 600 | 100 | 3,600 | 3,600 |
| | 170502 | 2,600 | 2,600 | 2,600 | 2,600 | 2,600 | 2,700 | 2,800 | 1,800 | 1,900 |
| | 170601 | 200 | 200 | 200 | 200 | 200 | 200 | 1,400 | 2,200 | 2,200 |
| | 170701 | 800 | 900 | 900 | 900 | 900 | 900 | 0 | 2,200 | 2,200 |
| | 170702 | 200 | 200 | 200 | 200 | 200 | 400 | 0 | 1,300 | 1,700 |
| | 170703 | 2,100 | 2,000 | 2,100 | 2,100 | 2,100 | 2,500 | 11,900 | 3,100 | 4,300 |
| | 170800 | 6,000 | 5,900 | 5,900 | 5,900 | 5,900 | 6,000 | 3,800 | 2,400 | 2,400 |
| | 170900 | 1,600 | 1,600 | 1,500 | 1,500 | 1,600 | 2,100 | 3,000 | 1,200 | 200 |
| | 171002 | 6,200 | 6,200 | 6,200 | 6,200 | 6,200 | 6,400 | 4,800 | 6,800 | 6,600 |
| | 171003 | 3,000 | 3,000 | 3,000 | 3,100 | 3,100 | 3,600 | 4,800 | 3,900 | 3,600 |
| | 171200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 180102 | 0 | 0 | 0 | 0 | 0 | 0 | 72,600 | 80,500 | 80,500 |
| | 180200 | 0 | 100 | 300 | 500 | 800 | 1,100 | 1,500 | 2,200 | 2,100 |
| WA | 170102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170103 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170300 | 1,500 | 1,100 | 500 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170601 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170701 | 3,600 | 2,800 | 2,500 | 2,100 | 1,200 | 0 | 0 | 0 | 0 |
| | 170800 | 4,000 | 2,500 | 2,000 | 1,600 | 1,300 | 800 | 200 | 0 | 0 |
| | 171001 | 600 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 171100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Appendix 5.12 Cost-Efficient Local Management Strategies with Targeted Risk Constraints (All Individual Regions): Fish Hatchery Prevention (USD/Year)**

| 6-digit Hydrologic Unit | | 90% | 80% | 70% | 60% | 50% | 40% | 30% | 20% | 10% |
|---|---|---|---|---|---|---|---|---|---|---|
| ID | 160101 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 160102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 160203 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170101 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170103 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170401 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170402 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170501 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170502 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170601 | 300 | 300 | 300 | 200 | 500 | 300 | 0 | 0 | 0 |
| | 170602 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170603 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| OR | 170501 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170502 | 300 | 300 | 300 | 300 | 300 | 300 | 0 | 0 | 0 |
| | 170601 | 1,300 | 1,300 | 1,300 | 1,300 | 1,300 | 1,300 | 0 | 14,100 | 14,100 |
| | 170701 | 2,100 | 2,100 | 2,100 | 2,100 | 2,200 | 2,300 | 1,400 | 1,700 | 1,600 |
| | 170702 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170703 | 0 | 0 | 0 | 0 | 0 | 0 | 300 | 100 | 100 |
| | 170800 | 1,200 | 1,200 | 1,200 | 1,200 | 1,200 | 1,200 | 1,300 | 5,700 | 5,600 |
| | 170900 | 0 | 0 | 0 | 100 | 0 | 0 | 0 | 700 | 700 |
| | 171002 | 1,100 | 1,100 | 1,100 | 1,100 | 1,100 | 1,100 | 400 | 1,300 | 1,200 |
| | 171003 | 400 | 400 | 400 | 300 | 400 | 400 | 200 | 0 | 0 |
| | 171200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 180102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 180200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| WA | 170102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170103 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170300 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170601 | 3,200 | 2,800 | 2,800 | 2,800 | 2,700 | 2,600 | 0 | 0 | 0 |
| | 170701 | 0 | 500 | 300 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170800 | 1,500 | 2,900 | 2,700 | 2,300 | 1,600 | 900 | 0 | 0 | 0 |
| | 171001 | 100 | 400 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 171100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

## Appendix 5.13 Cost-Efficient Local Management Strategies with Targeted Risk Constraints (All Individual Regions): Sum of Hydroelectricity Plant Management (USD/Year)

| 6-digit Hydrologic Unit | | 90% | 80% | 70% | 60% | 50% | 40% | 30% | 20% | 10% |
|---|---|---|---|---|---|---|---|---|---|---|
| ID | 160101 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 160102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 160203 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170101 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170103 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170401 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170402 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170501 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170502 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170601 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170602 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170603 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| OR | 170501 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170502 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170601 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170701 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170702 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3,000 |
| | 170703 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 10,400 |
| | 170800 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170900 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 171002 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 171003 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 171200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 180102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 180200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| WA | 170102 | 0 | 0 | 500 | 700 | 800 | 900 | 1,000 | 1,100 | 1,100 |
| | 170103 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170300 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170601 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170701 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170800 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 171001 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 171100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

## Appendix 5.14 Cost-Efficient Local Management Strategies with Targeted Risk Constraints (Total Expected Damage): Boater Decontamination (USD/Year)

| 6-digit Hydrologic Unit | | 90% | 80% | 70% | 60% | 50% | 40% | 30% | 20% | 10% |
|---|---|---|---|---|---|---|---|---|---|---|
| ID | 160101 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 160102 | 5,200 | 5,600 | 5,800 | 6,900 | 5,900 | 7,300 | 7,500 | 7,900 | 7,500 |
| | 160203 | 2,700 | 2,900 | 3,700 | 2,900 | 3,400 | 4,200 | 3,800 | 5,800 | 6,700 |
| | 170101 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170103 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170401 | 1,500 | 1,600 | 1,700 | 2,000 | 1,900 | 2,100 | 2,300 | 2,500 | 3,400 |
| | 170402 | 5,000 | 3,600 | 3,500 | 2,100 | 12,000 | 9,400 | 7,400 | 26,100 | 59,800 |
| | 170501 | 6,000 | 4,900 | 4,900 | 4,400 | 21,300 | 11,100 | 9,900 | 42,100 | 96,200 |
| | 170502 | 3,700 | 4,300 | 4,500 | 4,700 | 4,700 | 5,700 | 6,800 | 6,500 | 8,900 |
| | 170601 | 2,000 | 3,000 | 3,200 | 2,700 | 2,300 | 2,800 | 5,800 | 4,600 | 6,000 |
| | 170602 | 100 | 0 | 0 | 0 | 700 | 700 | 200 | 0 | 1,700 |
| | 170603 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| OR | 170501 | 300 | 300 | 300 | 300 | 3,000 | 300 | 400 | 400 | 400 |
| | 170502 | 2,600 | 2,800 | 2,800 | 3,200 | 3,700 | 2,900 | 3,200 | 3,700 | 3,900 |
| | 170601 | 200 | 300 | 200 | 200 | 300 | 300 | 300 | 300 | 400 |
| | 170701 | 900 | 900 | 900 | 1,000 | 1,300 | 1,200 | 1,300 | 1,100 | 1,200 |
| | 170702 | 200 | 200 | 200 | 200 | 2,600 | 200 | 200 | 200 | 200 |
| | 170703 | 2,200 | 2,000 | 2,300 | 2,300 | 5,200 | 2,500 | 2,200 | 1,800 | 1,500 |
| | 170800 | 6,300 | 6,300 | 6,700 | 6,900 | 7,600 | 7,600 | 7,900 | 8,000 | 9,600 |
| | 170900 | 1,500 | 1,400 | 1,500 | 1,300 | 2,800 | 900 | 400 | 0 | 0 |
| | 171002 | 6,400 | 6,500 | 6,700 | 6,900 | 8,400 | 7,100 | 6,700 | 7,800 | 8,600 |
| | 171003 | 3,100 | 2,900 | 3,000 | 3,100 | 6,500 | 3,000 | 3,000 | 1,800 | 1,400 |
| | 171200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 180102 | 0 | 0 | 100 | 200 | 1,600 | 800 | 1,100 | 900 | 1,100 |
| | 180200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 100 |
| WA | 170102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170103 | 0 | 100 | 100 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170300 | 1,600 | 1,700 | 1,700 | 1,300 | 1,500 | 1,500 | 1,500 | 1,500 | 1,500 |
| | 170601 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170701 | 3,800 | 3,900 | 3,900 | 3,700 | 3,900 | 3,600 | 3,600 | 3,600 | 3,600 |
| | 170800 | 4,700 | 4,900 | 4,400 | 5,100 | 6,600 | 4,000 | 4,000 | 4,100 | 4,100 |
| | 171001 | 600 | 700 | 800 | 800 | 900 | 600 | 600 | 600 | 600 |
| | 171100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

## Appendix 5.15 Cost-Efficient Local Management Strategies with Targeted Risk Constraints (Total Expected Damage): Fish Hatchery Prevention (USD/Year)

| 6-digit Hydrologic Unit | | 90% | 80% | 70% | 60% | 50% | 40% | 30% | 20% | 10% |
|---|---|---|---|---|---|---|---|---|---|---|
| ID | 160101 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 160102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 160203 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170101 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170103 | 0 | 0 | 0 | 0 | 0 | 900 | 0 | 0 | 0 |
| | 170401 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170402 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170501 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170502 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170601 | 0 | 100 | 100 | 100 | 0 | 0 | 300 | 100 | 700 |
| | 170602 | 100 | 0 | 0 | 0 | 900 | 900 | 200 | 2,800 | 2,500 |
| | 170603 | 0 | 0 | 0 | 0 | 100 | 100 | 0 | 0 | 0 |
| OR | 170501 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170502 | 300 | 300 | 300 | 300 | 400 | 300 | 300 | 300 | 400 |
| | 170601 | 1,300 | 1,500 | 1,300 | 1,400 | 2,100 | 1,500 | 1,700 | 1,700 | 2,200 |
| | 170701 | 2,100 | 2,100 | 2,300 | 2,400 | 3,600 | 2,900 | 3,100 | 2,900 | 3,000 |
| | 170702 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170703 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170800 | 1,200 | 1,200 | 1,200 | 1,300 | 1,400 | 1,500 | 1,600 | 1,700 | 2,000 |
| | 170900 | 0 | 0 | 0 | 0 | 700 | 0 | 0 | 0 | 0 |
| | 171002 | 1,100 | 1,100 | 1,100 | 1,200 | 1,100 | 1,200 | 1,100 | 1,100 | 1,200 |
| | 171003 | 400 | 400 | 400 | 400 | 0 | 400 | 400 | 400 | 300 |
| | 171200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 180102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 180200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| WA | 170102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170103 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170300 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170601 | 3,600 | 3,600 | 3,200 | 3,300 | 3,200 | 3,200 | 3,200 | 3,200 | 3,200 |
| | 170701 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170800 | 1,100 | 1,100 | 1,800 | 1,800 | 1,900 | 1,500 | 1,500 | 1,500 | 1,500 |
| | 171001 | 100 | 300 | 100 | 300 | 600 | 100 | 100 | 100 | 100 |
| | 171100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

## Appendix 5.16 Cost-Efficient Local Management Strategies with Targeted Risk Constraints (Total Expected Damage): Sum of Hydroelectricity Plant Management (USD/Year)

| 6-digit Hydrologic Unit | | 90% | 80% | 70% | 60% | 50% | 40% | 30% | 20% | 10% |
|---|---|---|---|---|---|---|---|---|---|---|
| ID | 160101 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 160102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 160203 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170101 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170103 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170401 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170402 | 2,400 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170501 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170502 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170601 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170602 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170603 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| OR | 170501 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170502 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170601 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170701 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170702 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170703 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170800 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 100 |
| | 170900 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 100 | 0 |
| | 171002 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 171003 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 171200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 180102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 180200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| WA | 170102 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170103 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170200 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170300 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170601 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170701 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 170800 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 171001 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 171100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Appendix 5.17 Cost-Efficient Local Management Strategies With Targeted Risk Constraints (High-Risk Regions with Budget Constraint): Boater Decontamination (USD/Year)**

| 6-digit Hydrologic Unit | | 70% | 60% | 50% | 40% | 30% | 20% | 10% |
|---|---|---|---|---|---|---|---|---|
| ID (Jenks Break) | 160101 | 0 | 0 | 0 | 0 | 0 | | |
| | 160102 | 5,000 | 5,000 | 4,300 | 4,300 | 2,100 | | |
| | 160203 | 2,700 | 2,700 | 2,700 | 2,700 | 2,600 | | |
| | 170101 | 0 | 0 | 0 | 0 | 0 | | |
| | 170102 | 0 | 0 | 0 | 0 | 0 | | |
| | 170103 | 0 | 0 | 0 | 0 | 0 | | |
| | 170401 | 1,200 | 1,100 | 0 | 0 | 0 | | |
| | 170402 | 300 | 0 | 0 | 2,000 | 2,000 | | |
| | 170501 | 500 | 1,500 | 2,600 | 1,100 | 1,100 | | |
| | 170502 | 3,700 | 3,600 | 3,600 | 3,600 | 3,300 | | |
| | 170601 | 1,900 | 1,800 | 1,400 | 1,400 | 0 | | |
| | 170602 | 0 | 0 | 0 | 0 | 0 | | |
| | 170603 | 0 | 0 | 0 | 0 | 0 | | |
| OR (Jenks Break) | 170501 | | | | 200 | 200 | 200 | 100 |
| | 170502 | | | | 2,200 | 1,700 | 1,700 | 900 |
| | 170601 | | | | 200 | 100 | 100 | 0 |
| | 170701 | | | | 0 | 0 | 0 | 0 |
| | 170702 | | | | 200 | 100 | 100 | 100 |
| | 170703 | | | | 0 | 0 | 0 | 0 |
| | 170800 | | | | 1,500 | 1,700 | 1,700 | 1,700 |
| | 170900 | | | | 0 | 0 | 0 | 0 |
| | 171002 | | | | 400 | 1,100 | 1,100 | 1,100 |
| | 171003 | | | | 0 | 0 | 0 | 0 |
| | 171200 | | | | 0 | 0 | 0 | 0 |
| | 180102 | | | | 0 | 0 | 0 | 0 |
| | 180200 | | | | 0 | 0 | 0 | 0 |
| OR (Average Risk) | 170501 | | | 200 | 200 | 200 | 0 | |
| | 170502 | | | 2,300 | 2,200 | 2,000 | 0 | |
| | 170601 | | | 200 | 200 | 100 | 0 | |
| | 170701 | | | 100 | 0 | 0 | 100 | |
| | 170702 | | | 200 | 200 | 200 | 0 | |
| | 170703 | | | 0 | 0 | 0 | 0 | |
| | 170800 | | | 2,400 | 2,300 | 2,300 | 2,600 | |
| | 170900 | | | 0 | 0 | 0 | 0 | |
| | 171002 | | | 900 | 1,100 | 1,300 | 1,900 | |
| | 171003 | | | 0 | 0 | 0 | 0 | |
| | 171200 | | | 0 | 0 | 0 | 0 | |
| | 180102 | | | 0 | 0 | 0 | 0 | |
| | 180200 | | | 0 | 0 | 0 | 0 | |
| WA (Jenks Break) | 170102 | | | | 0 | 0 | | |
| | 170103 | | | | 0 | 0 | | |
| | 170200 | | | | 0 | 0 | | |
| | 170300 | | | | 0 | 0 | | |
| | 170601 | | | | 0 | 0 | | |
| | 170701 | | | | 2,500 | 1,800 | | |
| | 170800 | | | | 0 | 0 | | |
| | 171001 | | | | 1,200 | 1,200 | | |
| | 171100 | | | | 0 | 0 | | |

**Appendix 5.18 Cost-Efficient Local Management Strategies with Targeted Risk Constraints (High-Risk Regions with Budget Constraint): Fish Hatchery Prevention (USD/Year)**

| 6-digit Hydrologic Unit | | 70% | 60% | 50% | 40% | 30% | 20% | 10% |
|---|---|---|---|---|---|---|---|---|
| ID (Jenks Break) | 160101 | 0 | 0 | 0 | 0 | 0 | | |
| | 160102 | 0 | 0 | 0 | 0 | 0 | | |
| | 160203 | 0 | 0 | 0 | 0 | 0 | | |
| | 170101 | 0 | 0 | 0 | 0 | 0 | | |
| | 170102 | 0 | 0 | 0 | 0 | 0 | | |
| | 170103 | 0 | 0 | 0 | 0 | 0 | | |
| | 170401 | 0 | 0 | 0 | 0 | 0 | | |
| | 170402 | 0 | 0 | 0 | 0 | 0 | | |
| | 170501 | 0 | 0 | 0 | 0 | 0 | | |
| | 170502 | 0 | 0 | 0 | 0 | 0 | | |
| | 170601 | 0 | 0 | 0 | 0 | 0 | | |
| | 170602 | 0 | 0 | 0 | 0 | 0 | | |
| | 170603 | 0 | 0 | 0 | 0 | 0 | | |
| OR (Jenks Break) | 170501 | | | | 0 | 0 | 0 | 0 |
| | 170502 | | | | 200 | 200 | 200 | 100 |
| | 170601 | | | | 1,100 | 700 | 700 | 200 |
| | 170701 | | | | 0 | 0 | 0 | 0 |
| | 170702 | | | | 0 | 0 | 0 | 0 |
| | 170703 | | | | 0 | 0 | 0 | 0 |
| | 170800 | | | | 300 | 300 | 300 | 300 |
| | 170900 | | | | 0 | 0 | 0 | 0 |
| | 171002 | | | | 400 | 400 | 400 | 400 |
| | 171003 | | | | 100 | 0 | 0 | 0 |
| | 171200 | | | | 0 | 0 | 0 | 0 |
| | 180102 | | | | 0 | 0 | 0 | 0 |
| | 180200 | | | | 0 | 0 | 0 | 0 |
| OR (Average Risk) | 170501 | | | 0 | 0 | 0 | 0 | |
| | 170502 | | | 200 | 200 | 200 | 0 | |
| | 170601 | | | 1,100 | 1,000 | 900 | 0 | |
| | 170701 | | | 300 | 0 | 0 | 0 | |
| | 170702 | | | 0 | 0 | 0 | 0 | |
| | 170703 | | | 0 | 0 | 0 | 0 | |
| | 170800 | | | 500 | 500 | 500 | 200 | |
| | 170900 | | | 0 | 0 | 0 | 0 | |
| | 171002 | | | 500 | 500 | 500 | 0 | |
| | 171003 | | | 100 | 0 | 0 | 0 | |
| | 171200 | | | 0 | 0 | 0 | 0 | |
| | 180102 | | | 0 | 0 | 0 | 0 | |
| | 180200 | | | 0 | 0 | 0 | 0 | |
| WA (Jenks Break) | 170102 | | | | 0 | 0 | | |
| | 170103 | | | | 0 | 0 | | |
| | 170200 | | | | 0 | 0 | | |
| | 170300 | | | | 0 | 0 | | |
| | 170601 | | | | 3,100 | 1,900 | | |
| | 170701 | | | | 0 | 0 | | |
| | 170800 | | | | 1,500 | 1,500 | | |
| | 171001 | | | | 0 | 0 | | |
| | 171100 | | | | 0 | 0 | | |