Economic Model Predicting Spatial Risk & Cost of Invasive Species Spread: Application to New Zealand Mudsnails

Image from USGS NAS

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1.1. Motivation

- **Why are New Zealand mudsnails problems?**
  - High tolerance to broad range of environmental conditions & reproducing asexually
  - Possible ecological impact
    - Potential impacts on other invertebrates and nutrient levels in water
    - Probable influence on primary producers
    - Effects on prey and predator relationship
  - Possible economic impact (similar to Zebra mussels)
    - Contamination of drinking water
    - Biofouling
    - Recreational disutility

- **How to Minimize their Negative Impact?**
- **Quantitative Models are Necessary ➔ Total Cost Minimization**

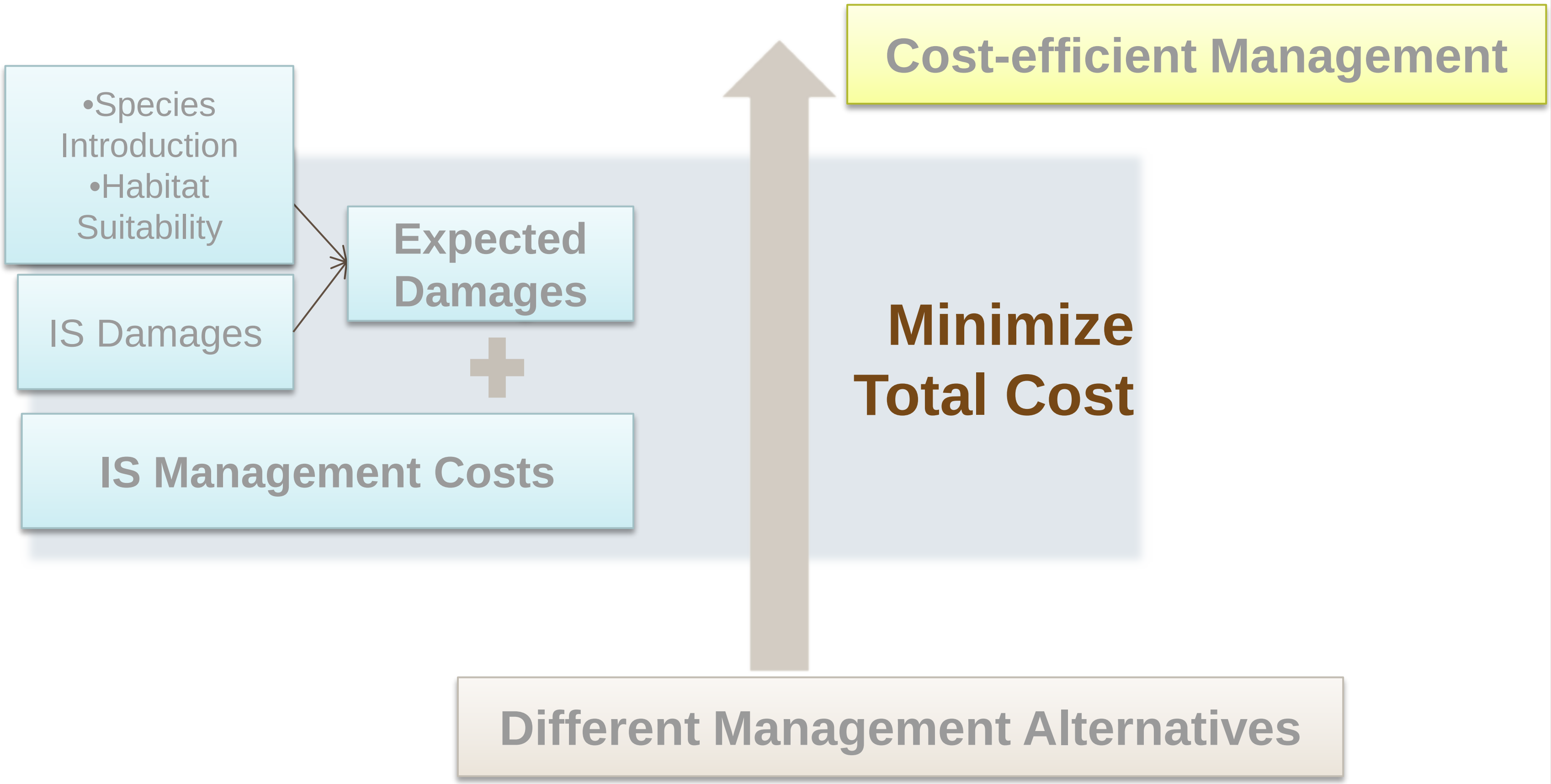
**Small Aquatic Invasive Species:
New Zealand Mudsnials**

←NZMS from USGS website
(Accessed April 04, 2011)

**New Zealand Mudsnials
on a Wading Boot**

Photo: D. AcKinney →
from mudsnails.com
(Accessed March 06, 2011)

1.2. Total Cost Minimization Factors



1.2. Total Cost Minimization Factors (cont.)

- **Expected Damage**
  - Risk
    - Introduction Risk (Gravity model)
    - Habitat Suitability (Maximum Entropy)
  - Damages
    - Habitat Degradation (InVEST, Integrated Valuation of Ecosystem Services and Tradeoffs) ➔ Disutility of Anglers (Randum Utility Model)
    - Water Facility Damages (Connelly et al., 2007)
    - Boat Maintenance due to Biofouling
- **Management Cost**
    - Statewide Management: Prevention, EDRR plus & Ex-post management (Survey on Field managers)
    - Water Facility: Prevention, EDRR plus & Ex-post management (Connelly et al., 2007)
    - Boater Decontamination (Chemical Decontamination assumed)
    - Hatchery Prevention (Installing Hydrocyclone)

3. Risk Prediction

- Risk of Invasive Species Introduction
  - Natural spread & host range spread; **Accidental introduction;** or Intentional introduction
  - **Unintentional transportation by humans** is a key IS vector

- Risk of Invasive Species Establishment
  - After introduction, IS may successfully establish in a recipient region, or may fail to establish based on **environmental and biological factors**

- **The relative risk of IS distribution =**

  Pr[risk of anthropogenic introduction] X Pr[habitat suitability]

- Initial study species: New Zealand mudsnails
- Study unit = Hydrologic Unit

3.1. Risk of Invasive Species Introduction: model

- Invasive Species Transported by Humans
  - Based on the propagule pressure concept
    - Propagule number = # of release events
      - ➔ the number of boats from infected regions
    - Propagule size = # of organisms involved in one release event
      - ➔ the level of infection of the donor regions

We cannot estimate it because we don't have density information

- Spatial interaction model (Gravity Model)
  - ➔ parameters = α, β, and δ

$$T_{ij} = f(\alpha w_i;\ \beta w_j;\ \delta d_{ij})$$

the distance between i and j

a flow between i and j (hydrological units)

a level of attractiveness (repulsiveness) of *i* and *j*: e.g. water quality, accessibility

3.2. Risk of Introduction: data & estimation

- Empirical Model (exponential function): Tobit model used

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

  - Spatial unit ➔ hydrologic unit
  - T_{ij} : the number of boats from i to j (censored at 0)
  - HUC size (km^2) : hydrologic area size
  - Herfindahl : water concentration
  - Road density (km/km^2) : accessibility
  - Dummy = 1 if HUC is adjacent to the Pacific Ocean, 0 otherwise
  - $Distance_{ij}$ (m) = distance between i and j

3.3. Risk of Introduction: gravity model results

Independent Variable	Idaho	
	Coefficient	Standardized Coefficient
Constant	-297.59 *** (38.32)	.
$Distance_{ij}$	-4.42 E-4 *** (2.51 E-5)	-80.65
ln(HUC size)$_i$	27.47 *** (2.59)	64.84
ln(HUC size)$_j$	23.03 *** (3.85)	45.89
$Herfindahl_i$	0.01 * (0.01)	11.31
$Herfindahl_j$	0.02 *** (0.01)	18.73
Road $Density_i$	655.59 *** (55.42)	54.61
Road $Density_j$	282.21 *** (60.98)	24.11
Dummy (Ocean)	.	.
Log likelihood	-48178.994	

***, ** and * indicate 1%, 5%, and 10% level of significance, respectively

e.g. More boaters would visit

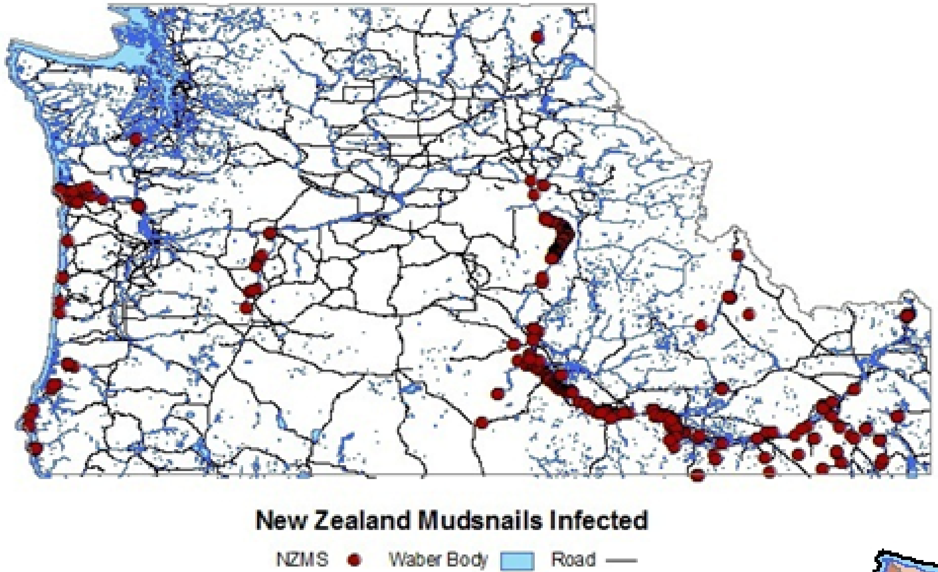
➔ Closer area

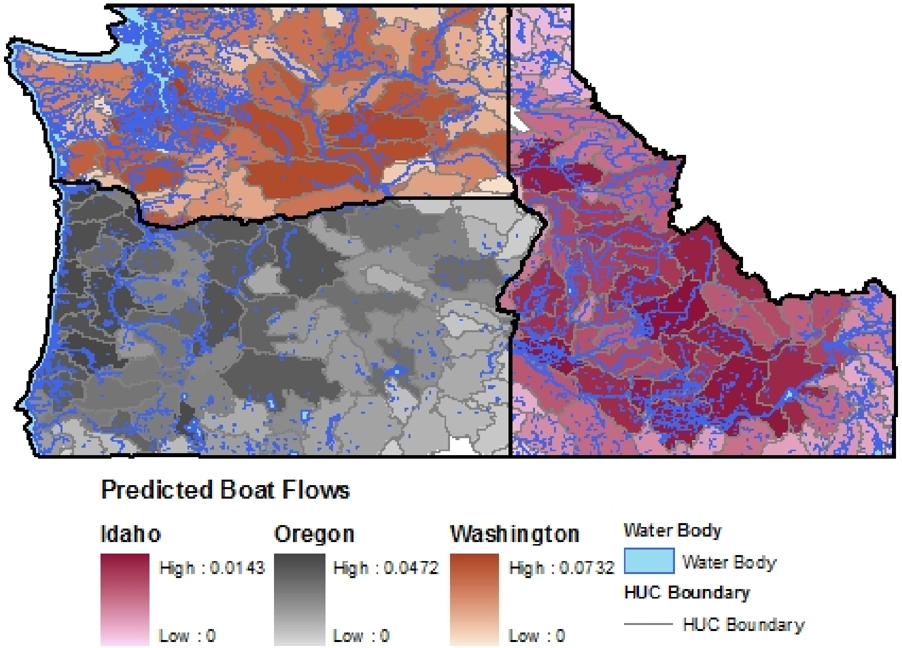
➔ Larger area

➔ More water-concentrated area

➔ More accessible area

3.4. Risk of Introduction (Normalized Boat Flow)





3.5. Species Habitat Suitability: maximum entropy

- Ecological Niche
  - **Joint environmental conditions** which allow 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 & Leibold, 2003)
- Species Distribution Model (Maximum Entropy)
  - Entropy = a measure of information (Shannon, 1948)
  - Assume that π is an unknown probability distribution over a finite set X
  - **X = grids of study area whose elements represent the recorded presence**
  - The entropy of approximated distribution $\hat{\pi}$:

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

the entropy of an approximated distribution

the approximated distribution

3.6. Species Habitat Suitability: model

- *Maxent* Software (developed by Steven Phillips, AT&T Labs)
  - Assume that $f_1, \ldots, f_n$ are known functions of features, **e.g. environmental variables or functions thereof**
  - Let the expectation of features be $\pi[f_j] = \sum_{x \in X} \pi(x) f_j(x)$
  - Then, **the *Maxent* will maximize the entropy under the constraint**:

max $H(\hat{\pi})$

s.t. $\underline{\hat{\pi}[f_j]} = \underline{\tilde{\pi}[f_j]}$ ➔ it can be relaxed as $|\hat{\pi}[f_j] - \tilde{\pi}[f_j]| \le \beta_j$

(Phillips et al. 2006)

the expected features of empirical samples

the expected features of approximate of unknown distribution

- Outcomes will assign **(relative) probability each grid**: $Pr(H_k)$

3.7. Species Habitat Suitability: data & estimation

- Invasive Species Occurrence (presence-only data)
  - USGS NAS database
  - Montana State University database

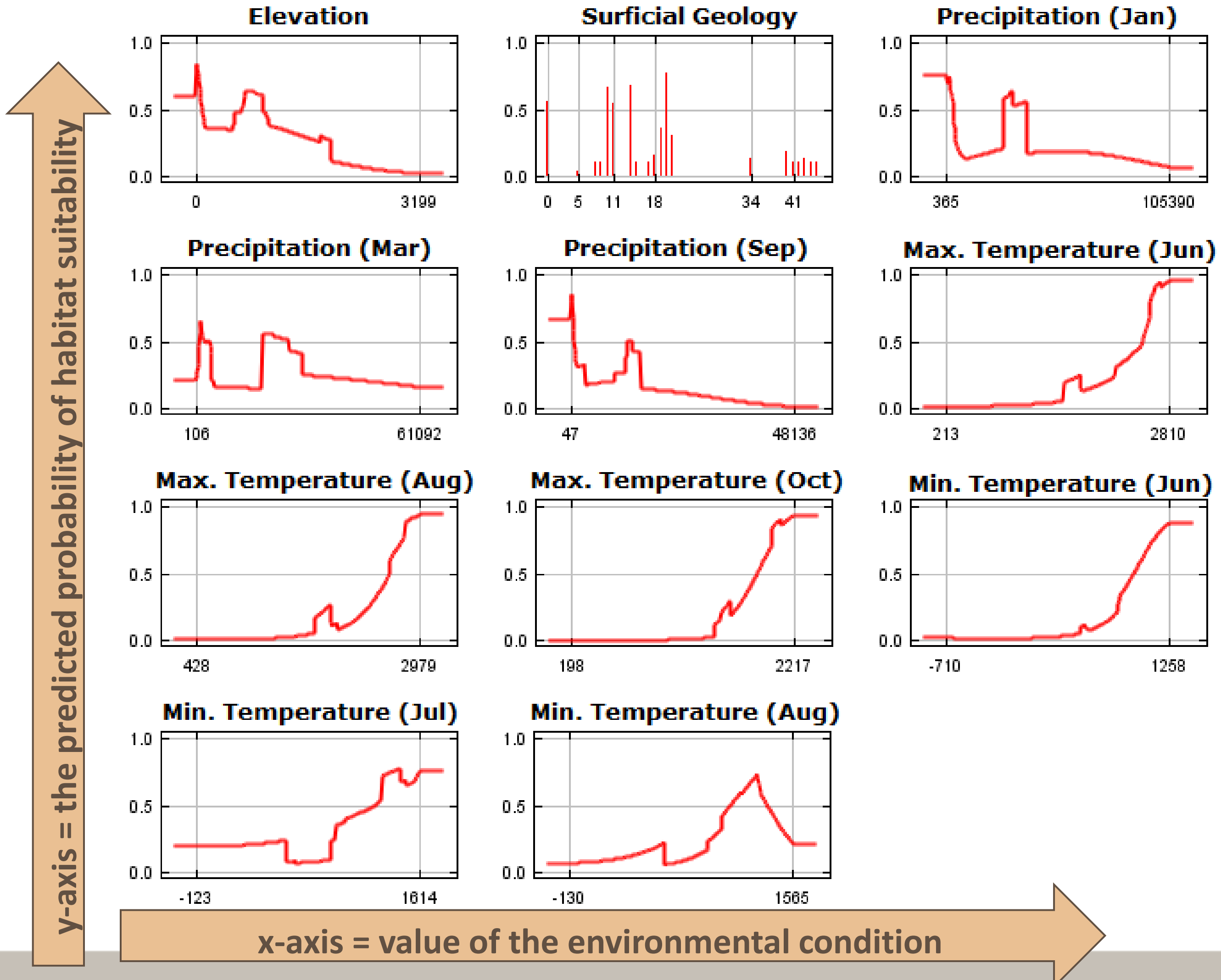
- Environmental Characteristics
  - Elevation (m)
  - Surficial geological features
  - Monthly precipitation (0.01mm)
  - Monthly maximum temperature (0.01 degree Celsius)
  - Monthly minimum temperature (0.01 degree Celsius)
  - City area & its buffer zones

3.8. Maximum Entropy Results: prediction accuracy

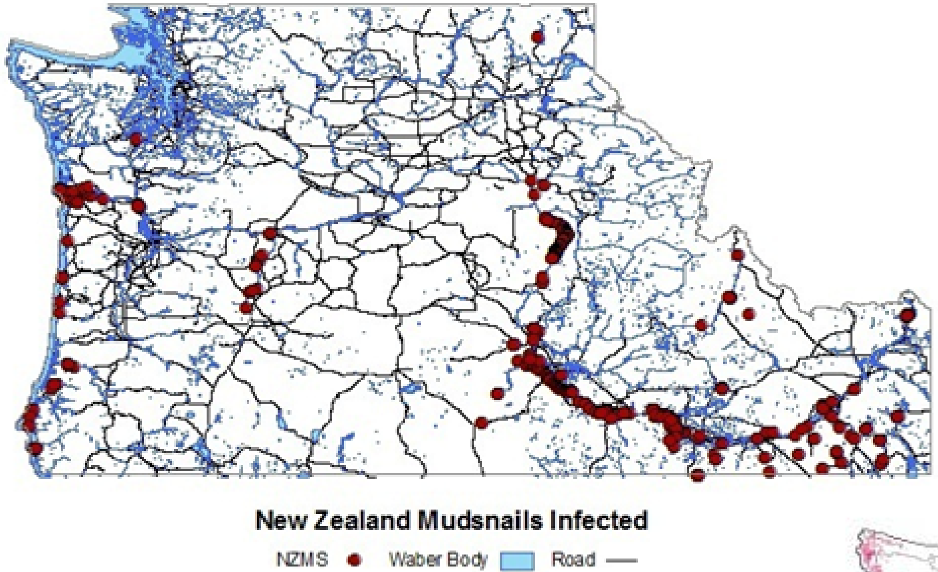
- AUC (area under the receiver-operation characteristic curve) = 0.978

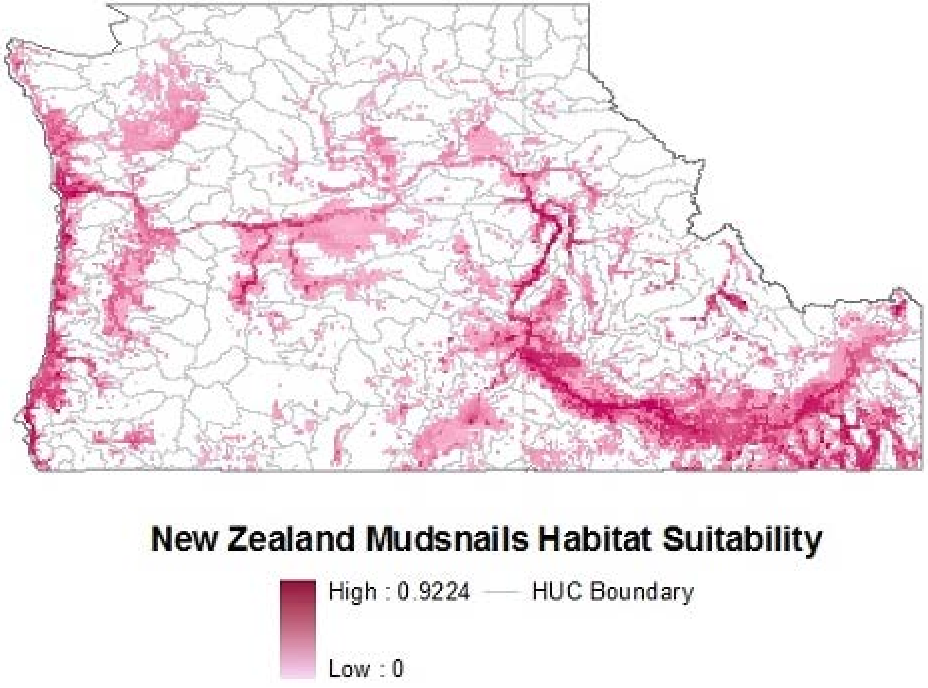
  : If AUC > 0.9, higher predictive performance

- Response Curves ➔



3.9. Maximum Entropy Results as Species Habitat Suitability





3.10. Integrated Risk of Invasive Species Distribution

- The Relative Risk of invasive species dispersal
  - **Combination of anthropogenic introduction and habitat suitability**:

$$R_{jk} = \underline{\tau_j} \times \underline{Pr(H_k)}$$

τ_j: the normalized boats movement from the gravity model

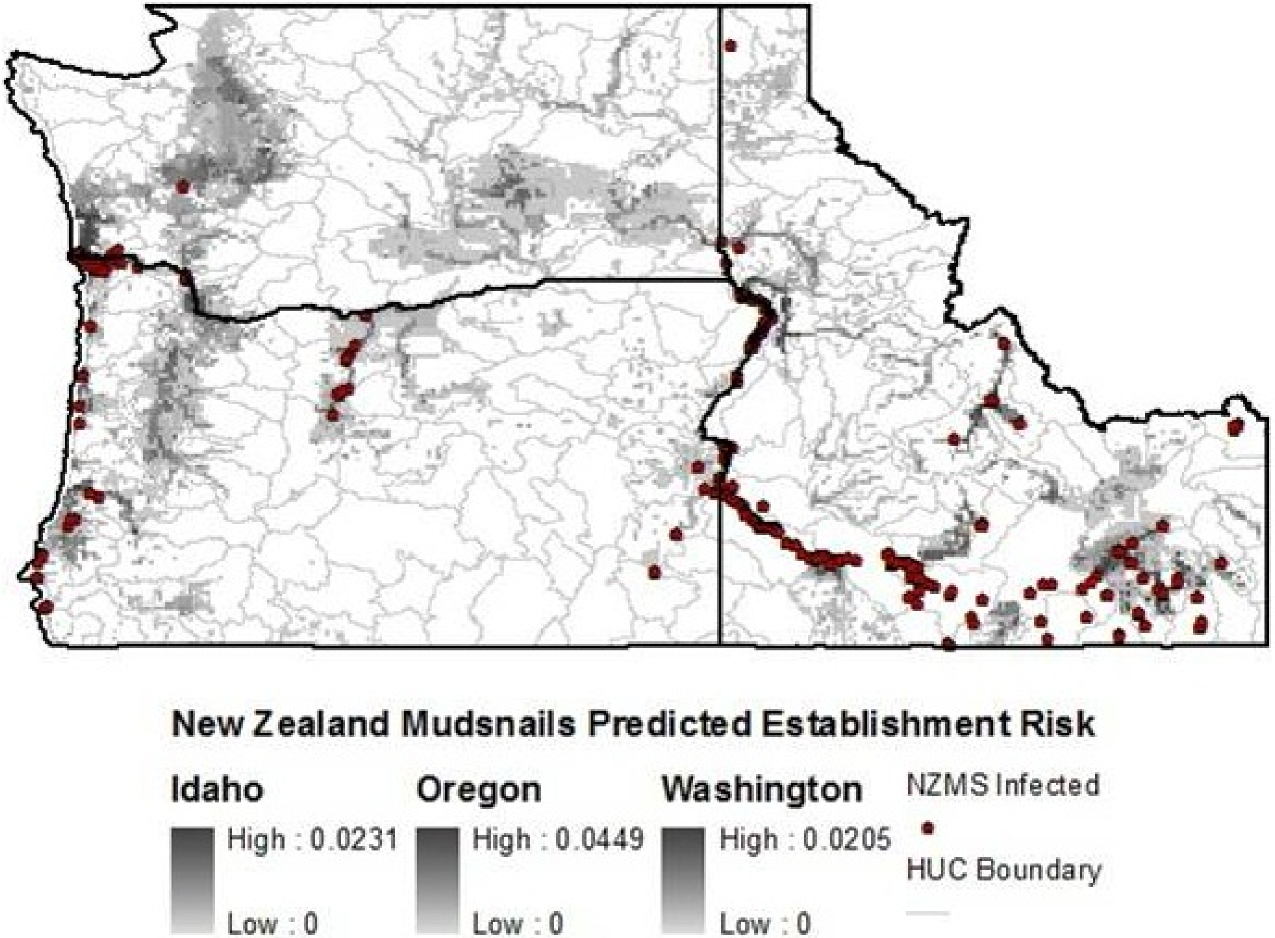
$Pr(H_k)$: the relative probability of species occurrence from maximum entropy method

  - *j* = hydrologic unit region; and *k* = each grid in the raster map layers
  - The estimate $\widetilde{T_{ij}}$ is normalized as $\tau_j = \frac{\sum_i \widetilde{T_{ij}}}{\sum_i \sum_j \widetilde{T_{ij}}}$ ranging between 0 and 1

    ➔ **It will be a scalar to represent the probability of the anthropogenic species introduction**

  - Anthropogenic introduction = normalized boat flows
  - Habitat suitability = probabilistic format of species occurrence

3.11. Integrated Risk of New Zealand Mudsnails Invasion



4.1. Potential Damage Estimation

- Utility Loss of Anglers
  - Idaho: $\Delta \textit{Habitat quality} \times \$363.71$
  - Oregon: $\Delta \textit{Habitat quality} \times \$350.20$
  - Washington: $\Delta \textit{Habitat quality} \times \$353.02$

- Hydroelectricity plant damage: $124,110/facility (Connelly et al., 2007; USEIA, 2010)
- Water treatment plant damage: $726.5/facility (< 2MGD), $1453/facility (>= 2MGD) (Connelly et al., 2007; Idaho DEQ, Oregon DEQ, and Washington DOH)
- Boat motor replacement: $118/boat (< 16 feet) or $235/boat (16-26 feet) (Recreational Boating Statistics 2010 & motor price web search)
- Boat paint cost: $107/boat (< 16 feet) or $184/boat (16-26 feet) (Recreational Boating Statistics 2010 & motor price web search)

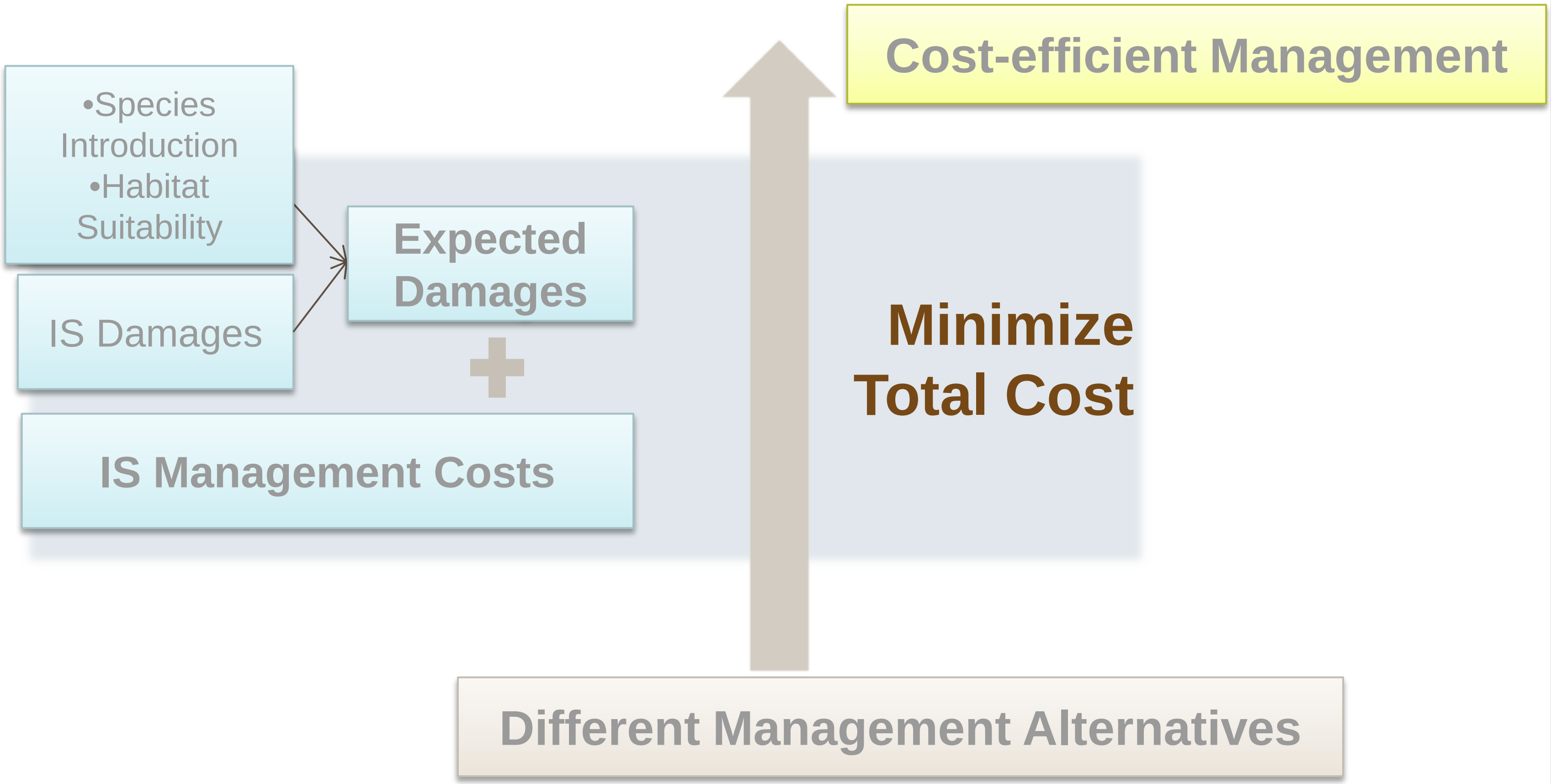
4.2. Management Cost Estimation

- Statewide Management

State	Prevention	EDRR + other management	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

- Water Facility Management (Connelly et al., 2007)
- Boater Decontamination: Washing a boat $3, and Chemical use per boat $16
- Hatchery Prevention: $12,000 per hatchery (6-unit hydrocyclone)

5. Total Cost Minimization: Next Step

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Appendix 1. HUC with high risk of NZMS introduction

Hydrologic Unit Name	Normalized Boat Inflow (τ_j)		Observed NZMS
Idaho			
Upper Salmon	0.0143	1.43%	○
Lower Boise	0.0142	1.42%	○
Lake Walcott	0.0139	1.39%	○
Upper Snake-Rock	0.0139	1.39%	○
Clearwater	0.0138	1.38%	○
Oregon			
Lower Willamette	0.0472	4.72%	×
Lower Columbia	0.0400	4.00%	○
Umpqua	0.0261	2.61%	○
Siletz-Yaquina	0.0258	2.58%	○
Upper Klamath Lake	0.0234	2.34%	×
Washington			
Lake Washington	0.0732	7.32%	×
Puget Sound	0.0485	4.85%	○
Duwamish	0.0365	3.65%	×
Lower Crab	0.0345	3.45%	×
Lower Yakima, Washington	0.0301	3.01%	×

Appendix 2. HUC with high risk of NZMS establishment

Invasion Status	Hydrologic Unit Name with High Risk Percentile
NZMS Observed	10% 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% Little Wood, Crooked-Rattlesnake, Lower Owyhee, Bully, Pahsimeroi, Lower Deschutes, Lower Columbia-Clatskanie, Umpqua, Coos, and Sixes
	30% Upper Henrys, Salmon Falls, Big Wood, Bruneau, and Alsea
NZMS Not-Observed	10% Willapa Bay and Siltcoos
	20% 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% 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

Appendix 3. HUC with high risk of NZMS invasion

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