PugetSoundPartnership

LEADING PUGET SOUND RECOVERY

Addendum #2

To

RFQQ 2013 – 83

Multi-Scale Soundwide Pressure Assessment

Selection of Core Materials

from

DRAFT Puget Sound Pressures Assessment Methodology

Contents

The material in this document is a slightly modified extract from the June 28, 2013 draft of the Puget Sound Pressures Assessment (PSPA) Methodology Technical Memo. The technical memo is authored by William Labiosa (USGS), Kenneth Currens (NWIFC), Wayne Landis (WWU), Timothy Quinn (WDFW), Scott Redman (PSP), and Richard Anderson (PSI). This extract of core materials was prepared by Scott Redman.

A complete review draft of the technical memo will be completed in mid-July 2013 and PSP Science Panel members will complete a review of the draft in July and August. A final version of the PSPA methodology technical memo may not be available when Task 1 is underway. Task 1 of the contract to conduct the PSPA will use the review draft of the technical memo and reviewer comments on that draft.

Introduction

The Puget Sound Pressures Assessment (PSPA) framework provides a methodology for evaluating, comparing, and ranking the potential impact of stressors associated with common pressure classes on important ecosystem endpoints, chosen to reflect the recovery and management concerns of the Puget Sound Partnership and its many partners. The assessment approach builds on the "vulnerability of marine ecosystems" (VME) approach developed by Halpern et al. (2007), applied at scales ranging from global marine ecosystems to regional coastal waters. We depart from the VME approach in some key ways as discussed below.

Figure 1 presents an overview of the Puget Sound Partnership's conceptualization of ecosystem recovery. The PSPA focuses on the relationships between pressures and ecosystem components as depicted in this model.

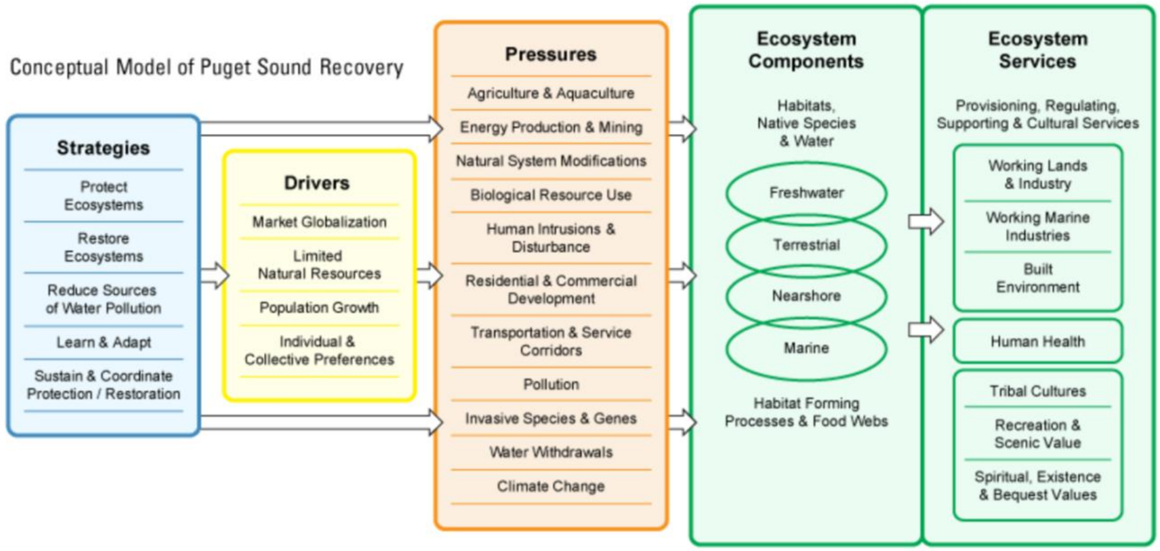

Figure 1. Conceptual model of Puget Sound recovery. From the Puget Sound Partnership Biennial Science Work Plan, 2012.

The pressures to be assessed in the PSPA are identified in PSP's pressure taxonomy (Stiles et al., 2013), which is presented as Addendum 3 to PSP's RFQQ No. 2013-83. (The items included in the "pressures" box in Figure 1 are pressure class categories, the highest level of PSP's pressure taxonomy, including a category for the pressure of climate change) Most of the pressures in the PSP taxonomy represent sources of stress (e.g. development) that act on ecosystems via one or more stressors (e.g. land conversion or pollution). In a few cases, the pressure class represents a stressor (e.g. derelict fishing gear). All sources of pressure act on, or effect change in Puget Sound ecosystem components via one or more stressors. Stressors can also be thought of as the most proximal actors on systems, or the specific structures, compounds and activities that directly impact habitats, species and people.

The ecosystem components box in Figure 1 identifies the major biophysical domains of the Puget Sound ecosystem: freshwater, terrestrial, nearshore, and marine. The PSPA will evaluate the impact of pressures on endpoints for each of these ecosystem components. Preliminary concepts of the endpoints for the PSPA are discussed below.

Proposed pressures assessment approach

The PSPA framework provides a methodology for evaluating, comparing, and ranking the potential impact of stressors associated with common pressure classes on important ecosystem endpoints, chosen to reflect the recovery and management concerns of the Puget Sound Partnership and its many partners. The framework is designed to 1) assess scales of impacts from single species to the ecosystems that make up Puget Sound; 2) span the full suite of stressors and ecosystem endpoints necessary to evaluate and rank stressors across Puget Sound; 3) assess and incorporate uncertainty in the elicited information; and 4) use expert judgment within a transparent and robust process that would support reproducibility and future updates.

The assessment approach builds on the “vulnerability of marine ecosystems” (VME) approach developed by Halpern et al. (2007), applied at scales ranging from global marine ecosystems to regional coastal waters. We depart from the VME approach by including terrestrial and freshwater aquatic ecosystem assessment endpoints, in addition to marine and nearshore endpoints, and extending beyond the VME’s exclusive use of habitat-type endpoints to include habitat-type, species, community, water quality and quantity, and human well-being endpoints, reflecting the Puget Sound Partnership’s recovery goals. In addition, we propose a different approach to assessing and incorporating the uncertainty involved in the assessment and modifications to the aggregation model used to combine the vulnerability criteria into a vulnerability score for a given stressor/endpoint pair. Each of these modifications is detailed below.

Intrinsic vulnerability score (μ)

Ecosystem pressures and stressors are often not directly comparable to one another, since, for example, they may differ in mechanisms of impact, affect distinctly different ecosystem attributes, or operate in very different temporal or spatial scales. Yet, the concept of comparing the degree of threat or potential for change between different pressures and stressors is well accepted in the scientific community, across different disciplines, including both social and natural sciences (Williams and Kapusta, 2000; Turner et al., 2003; Adger, 2006; De Lange et al., 2010). Models of ecological vulnerability typically include various aspects reflecting “exposure” to the stressor, “sensitivity” of the affected endpoint to the stressor, and “recovery potential” of the endpoint from the stress (Suter, 2007; De Lange 2010), with endpoints ranging from organisms to ecosystems.

The intrinsic vulnerability scores (μ_{ijk}) are defined over combinations of stressors (i) and assessment endpoints (j) given an assessment context (k). The scale of the score is relative and the assumptions behind the scores are described in detail below. The score reflects the impact that a given stressor would potentially exhibit on the species/habitat types defined as assessment endpoints. It is important to keep in mind that μ_{ijk} is a model-defined constant (score) aggregated from expert-assessed vulnerability criteria scores, with application at a particular scale of assessment.

The ecosystem vulnerability model

The ecosystem vulnerability model is based on the model underlying the marine ecosystem threats assessments developed at the National Center for Ecological Analysis & Synthesis, NCEAS (Halpern et al., 2007), with significant modifications in the application to marine and nearshore, terrestrial, and freshwater aquatic ecosystems and species as assessment endpoints and the use of Bayesian networks to represent and propagate assessed uncertainty.

The ecosystem vulnerability model (Figure 2) consists of several parts: 1) vulnerability criteria that collectively define vulnerability for a particular stressor/endpoint pair, 2) a scoring system for each of the vulnerability criteria, 3) a probabilistic structure for incorporating uncertainty, and 4) an aggregation model that combines the vulnerability criteria scores into an intrinsic vulnerability score, μ_{ijk}, for stressor “i” and assessment endpoint “j”.

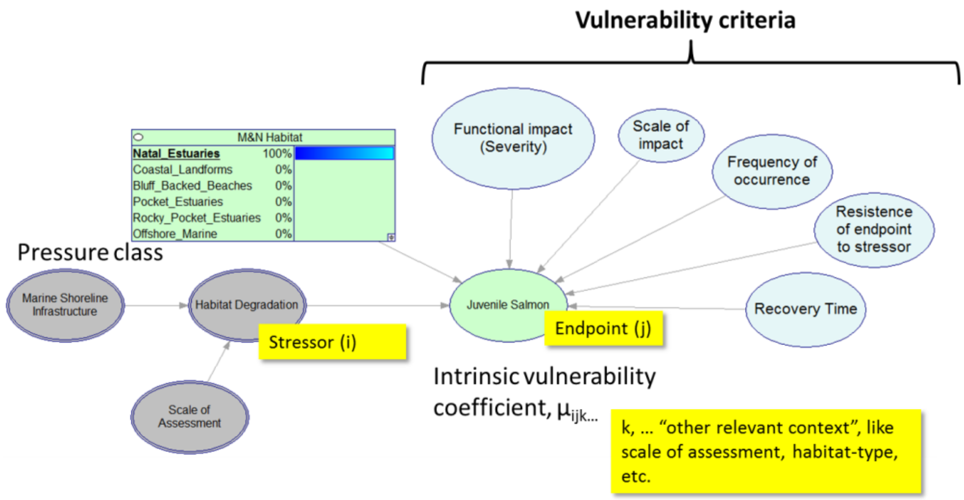

Figure 2. Ecosystem vulnerability model as a Bayesian network.

Vulnerability Criteria

The various vulnerability criteria are each defined over states ranging from a negligible outcome to a catastrophic outcome, with interpretations of states being particular to each criterion. It is expected that none of the stressor/endpoint pairs considered would be scored with certainty as having a negligible outcome for any of the vulnerability criteria, since this would indicate that either the endpoint is not exposed to the stressor or that the endpoint is not impacted for one of several reasons, in which case the pair would be irrelevant to the assessment. The rationale for including the “negligible outcome” state is to define the baseline of the relative scoring system for assessing potential impacts. Each of the vulnerability states is now defined. It should be noted that these definitions are subject to refinement during expert workshops, to reduce ambiguity (or more precisely, “linguistic uncertainty”) among the experts and to potentially improve the underlying model based on insights from the experts involved.

- *Scale of impact*

The “scale of impact” vulnerability criterion is defined as the typical scale at which a stressor (associated with a pressure class) affects an assessment endpoint (e.g., an ecosystem component), with scale categories ranging from “no impact” to Puget Sound basin-scale impacts. To reiterate, scale of impact does *not* refer to the scale at which particular pressures or stressors occur (some stressor types with small scales of impact are distributed throughout the entire Puget Sound basin). For example, a stressor like “habitat conversion” associated with the “commercial and residential development” pressure class may impact a particular terrestrial species at a scale of 100s of m^2, while habitat conversions associated with commercial and residential development could occur throughout the entire Puget Sound basin. In this example, the scale of impact vulnerability criterion would be 100s of m^2, capturing the intrinsic vulnerability of the species to a particular land-use change. The scale of impact from habitat losses around Puget Sound could be captured by mapping spatial distributions of the stressor “habitat conversions”. The scale of impact criterion is defined to include both direct and indirect impacts. For example, dredging a channel within the mouth of a delta may directly alter a relatively short stretch of the channel but indirectly affect the entire upstream estuary by altering tidal flow. In this case the scale of impact of the hydromodification stressor acting on an estuary endpoint would encompass the entire estuary.

- *Frequency*

The “frequency” vulnerability criterion describes how often stressor events or activities occur in a given habitat type or impacting a particular species/community. Categories range from “never occurs” to “persistent”. For those stressors that occur as discrete events, frequency refers to how often new events occur, not the duration of a single event. In the case of habitat type endpoints, some stressors may affect only a few species, whereas others affect entire communities or ecosystems. To capture these differences, we define the “functional impact” vulnerability criterion using a four-category ranking scheme ranging from species to ecosystem-level impacts.

- *Functional impact*

Functional impact reflects the magnitude (or severity) of the potential impact that a stressor may have on the assessment endpoint. For endpoints that are habitat-types (ecosystems), functional impact is defined in terms of the level of organization impacted by the stressor, ranging from single species impacts to entire ecosystems. For endpoints that are species, the defined states could range from low abundance/productivity impacts to severe impacts. For other types of endpoints, e.g., working lands, impact states would have to be defined on a case-by-case basis during workshops, with definitions that support comparison across endpoint types.

- *Resistance*

Resistance describes the average tendency of a species, trophic level, community, or ecosystem to resist changing its current state in response to a stressor. Because of the inherent complexity in describing resistance across multiple levels of organization from species to habitat types and across a large number of substantially different stressor/endpoint combinations, qualitative ranks are used for this vulnerability criterion. These ranks referred to the resistance of the ecosystem components that react to the stressor (i.e., the functional level identified above).

- *Recovery time*

Recovery time was the average time required for the affected endpoint to return to its pre-impacted state. Because populations, communities, and ecosystems are dynamic in nature, they need not (and are unlikely to) return to their exact pre-impacted condition to be deemed "recovered" (Beisner et al. 2003). For persistent stressors, we considered recovery time following removal of the stressor.

Suggested definitions for the vulnerability criteria states will be included in the full technical memo on the PSPA methodology.

Assessing and representing uncertainty

In contrast to the "uncertainty factor" approach used by Halpern et al. (2007) to represent uncertainty in the intrinsic vulnerability score, we recommend assessing the uncertainty in each of the assessed vulnerability criteria using an elicited probability approach, and calculating the expected vulnerability score from these probabilistic inputs (Figure 3) using a score aggregation model, described in the next section. In Figure 3, vulnerability criteria are represented probabilistically by discrete probability distributions defined within a score aggregation model expressed as a Bayesian network (defined above). For this illustration, we will assume an elicitation process with a single expert. The probability distributions reflect the expert's uncertain knowledge about each of the vulnerability criteria within the context of a given stressor/endpoint pair, for a defined assessment unit of Puget Sound (assessment scales are described below). The context associated with the assessment will be discussed during expert workshops and the documented assumptions will be an important part of the pressures assessment process. As shown in Figure 3, the probabilistic vulnerability criteria are inputs into the expected (computed) intrinsic vulnerability score for the hypothetical endpoint/stressor pair. The score aggregation approach is described in the next section.

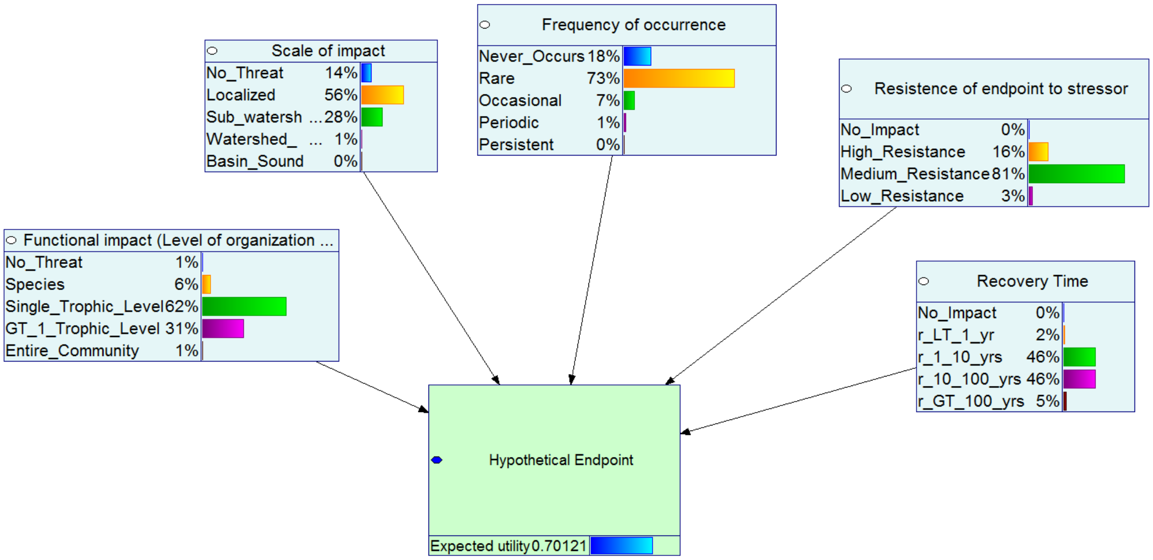

Figure 3. Example of probabilistic calculation of intrinsic vulnerability score from criteria distributions, shown as an "expected utility" here.

The question of how to reconcile different probabilistic assessment responses from different experts for a given vulnerability criterion (for a given endpoint/stressor combination) should be considered carefully (Morgan and Henrion, 1990; Gelman et al., 2003). Halpern et al. (2007) simply averaged across replicate responses, weighting the responses by the certainty factor elicited from the respondent. We recommend assessment reconciliation using a combination of group deliberative techniques during assessment workshops to facilitate discussion of *why* responses are different, with an opportunity for experts to revise their submitted responses if they desire. Once the refined responses have been collected, they could be combined using a number of techniques, including bootstrapping (simulating) the final "reconciled" assessment distribution from the distributions representing the assessed responses from individual experts.

Sources of uncertainty

Uncertainty is, of course, pervasive in ecological management and recovery planning (Maier et al., 2008). There are multiple possible taxonomies of uncertainty relevant to scientific information and environmental decision support with a large multidisciplinary literature to choose from. The taxonomy proposed by Regan et al. (2002) is adopted here because of its useful distinction between epistemic uncertainty, which refers to our uncertainty in the knowledge and information associated with the states and behaviors of systems, and linguistic uncertainty, which refers to our uncertainty arising from the ambiguity, vagueness, and context dependence inherent in natural language. In expert elicitation within complex endeavors like ecosystem pressures assessment, we seek to minimize the linguistic uncertainty (error) introduced due to different experts assuming different contexts, ambiguous or vague terminology, and other sources of indeterminacy and underspecificity. The admittedly ambitious goal is for the uncertainty expressed by experts to reflect epistemic uncertainty due to incomplete knowledge, lack of data, natural variation, and other non-linguistic sources of uncertainty.

Reducing biases in uncertainty elicitations

In a set of landmark studies, Amos Tversky and Daniel Kahneman documented that people use a limited number of imperfect heuristics to reduce the cognitive complexities involved in probabilistic reasoning to simpler operations. Such heuristics are quite useful in sense that they allow people to make quick determinations about complex information, but they lead to predictable (and sometimes severely flawed) biases (Tversky and Kahneman, 1974). Formal studies of the issue of the "predictable biases" involved in judgment under uncertainty have resulted in various approaches being developed to deal with them, including de-anchoring techniques, visual aids, lottery/betting frameworks, scoring rules, etc. The use of demonstrated techniques (Morgan and Henrion, 1990) for reducing biases and fostering useful discussions of uncertainty between experts will be an important part of the model elicitation workshops, as described in the last section.

Unfamiliarity with Bayesian (subjective) probability models of uncertainty

Since many natural scientists are not well acquainted with the use of Bayesian (subjective) probability or the use of conditional probability to describe uncertainty, various approaches have been developed to facilitate the elicitation process, dealing with the problems of ease-of-use and well-documented biases. Studies demonstrate that the use of probabilities, odds, log-odds, ranges, etc. in probabilistic assessments converge when administered well, with a widely accepted conclusion that choosing an approach that matches the cognitive style, technical background, and preferences of the experts involved is the more important consideration (Morgan and Henrion, 1990).

Ecosystem Vulnerability Score Aggregation Approach

Vulnerability criteria scores from assessed states

Before potential aggregation models are discussed and the process for choosing a single approach is described, we discuss the scoring system used to assign scores to the individual states defined for each vulnerability criterion. In the Halpern (2007) approach, states were ranked and the ranks themselves used as scores within a relative scoring system. This makes the strong assumption that the marginal change in moving from one state to the next is constant throughout the range of states. We propose that within the expert workshop process used to vet and refine the vulnerability model, the marginal change in scores between vulnerability criteria states are explored and chosen, yielding score/state curves of the type shown in Figure 4. The curves may hold generally for stressor/endpoint pairs that apply to an ecosystem domain, or there may be more than one set, each set applying to a particular grouping of stressor/endpoint pairs within an ecosystem domain. The score for a vulnerability criterion would then come from this curve, based on the ranks associated with the probability distribution over the criterion's states, as elicited during the expert group process.

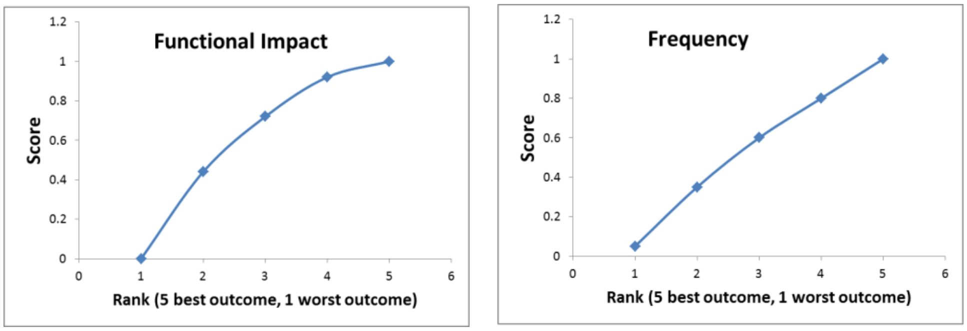

Figure 4. Example of rank/score curves for two vulnerability criteria defined within a single ecosystem domain.

Score aggregation model

An important aspect of the ecosystem vulnerability model is the aggregation approach used to combine the vulnerability criteria inputs into a single vulnerability score that represents, in relative terms, how vulnerable an ecosystem component (or assessment endpoint) is to a particular stressor. Halpern et al. (2007) refer to their aggregation approach as a "modifier model". The Halpern et al. (2007) modifier model averages across replicate survey (assessment) responses to generate a single (assessed) score for each criterion, which are in turn weighted and summed across criteria to generate a weighted-average vulnerability score using a linear-additive model[1]. In the Halpern et al. (2007) approach, the certainty factor is used in the weighting process to inflate the scores of well-documented pressure/endpoint combinations and to depress the scores of poorly-studied combinations. In comparison, a Bayesian probabilistic approach treats uncertainty within a theoretically-robust framework that uses probability to represent and propagate uncertainty. For example, complete ignorance over the states of a vulnerability criterion could be represented as a uniform distribution over the possible states, which would yield a criterion score equal to the average score of the possible states. More precise knowledge could be represented through assigning a higher probability to a particular vulnerability criterion state, which would drive the criterion score toward the score associated with that state, with the exact score depending on the probability distribution that expresses the expert's uncertainty.

A linear additive aggregation model (Figure 5) is the simplest approach and is based on the strong assumption that the vulnerability criteria are independent of one another in the sense that the contribution to vulnerability from one criterion does not interact with the contribution to vulnerability from another criterion. In the context of Bayesian networks and reasoning under uncertainty, this could be referred to as "causal independence" (e.g., Zhang and Poole, 1996). While this is recognized as a strong assumption, the linear-additive model is sometimes justified as a "first order" solution that is supported by a lack of information about interactions.

Linear additive model: $U(x_1,\ldots,x_m) = c_1U_1(x_1) + \ldots + c_mU_m(x_m)$, where c_i is the weight for the "ith" attribute and $U_i(x_i)$ is the utility of attribute x_i .

[1] For the analogy between the linear additive vulnerability model and a linear additive multi-attribute utility model, in which vulnerability criteria scores act as utilities and the score aggregation model acts as a utility model, see Nelso et al. (2009).

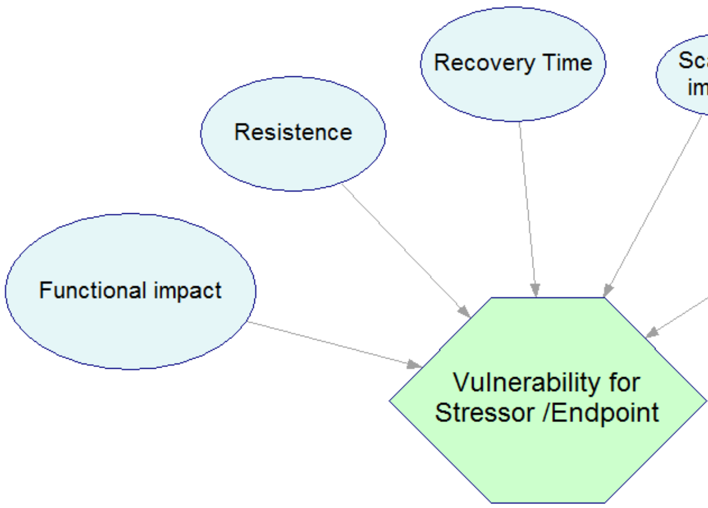

Figure 5. Aggregation scoring function as a utility function with vulnerability criteria as inputs.

A more general model based on multiattribute utility models with interactions is also a possible approach, but requires more attention (Clemen, 1996). With a relatively small number of attribute/state combinations, perhaps the simplest way to think about this approach is to think in terms of scoring exceptions from the score obtained from the linear additive model.

Linear additive model with exceptions: $U(x_1,\ldots,x_m) = c_1U_1(x_1) + \ldots + c_mU_m(x_m) + E_1(x_1) + \ldots + E_m(x_m)$, where $E_i(x_i)$ is an exception term (e.g., a penalty) that is non-zero for some states, but zero for most states.

For example, if we decide that a score of “0” for vulnerability criteria conceptually related to the sensitivity of an assessment endpoint to a stressor should be penalized beyond the contribution of a score of “0” for that criterion, to reflect the severity of the catastrophic outcome, a penalty could be applied for those situations. Table 1 shows the situation where a penalty in score is applied since the “Resistance” score is 0 (corresponding to low resistance of the endpoint to the stressor). Of course, Table 1 is a small part of a much larger table (with 5 criteria, each with 5 states, the table would have 3125 combinations represented as columns), so the number of situations with exceptions could become unwieldy when exceptions are considered on a case-by-case basis. However, if exceptions could be codified using a manageable number of rules, the size of the table is less pertinent.

Table 1. Use of exceptions to modify linear additive aggregation function.

STATES→ / CRITERIA↓	No Threat No Threat Never occurs Low Resistance No Impact	No Threat No Threat Never occurs Low Resistance LT 1 yr	No Threat No Threat Never occurs Low Resistance 1 - 10 yrs
Functional Impact	1	1	1
Scale of Impact	1	1	1
Frequency	1	1	1
Resistance	0	0	0
Recovery Time	1	0.94	0.79
Linear additive score	0.8	0.788	0.758
Exceptions	-0.5	-0.5	-0.5
Adjusted score	0.3	0.288	0.258

Another approach is the use of a nested multi-attribute model that decomposes the dimensionality of the utility model into smaller sub-utility models that become inputs into a new utility model. Although the number of variables increases, the size of the new utility table is considerably smaller (Figure 6; with 5 states for each criterion, the Sensitivity Score table would have 125 columns and the Exposure Score table would have 25 columns, for a total of 150 columns). In addition to the decrease in the dimensionality of the new utility table, the consideration of exceptions becomes simpler. We could define algorithms for identifying exceptions within the "sensitivity" sub-utility function (Figure 6), for example, shifting the task to identifying the algorithm rather than searching for exceptions through a large number of possible combinations. For example, a multiplicative "sensitivity" sub-utility could be defined, which would mean that any occurrence of "0" in any of the vulnerability criteria would generate a "0" in the aggregated sensitivity utility score.

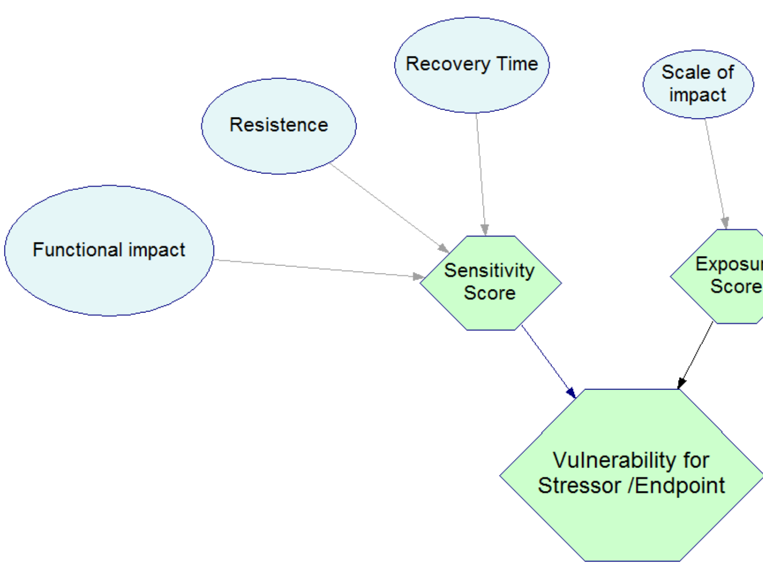

Figure 6. Multiattribute utility model with sub-utility models for “sensitivity” and “exposure”.

The task would be to work with the team of experts charged with refining and vetting the vulnerability model to agree upon an aggregation scoring function that exhibits properties matching our intuitions about exceptions, while remaining simple enough to be tractable and easy to communicate.

Ecosystem (assessment) endpoints

The assessment endpoints for an ecological risk assessment explicitly express the ecological values that are being managed or recovered, often operationally defined in terms of ecosystem components and their attributes (EPA, 1992; Suter, 2007). The choice of assessment endpoints is the process by which ecosystem recovery and management planning goals are translated into specific attributes of the ecosystem that is being recovered and managed. Narrowing down the possible choice of components and attributes into a tractable set is an important part of the process of evaluating and comparing ecosystem pressures, since the chosen set should reflect the biophysical components and processes within the linked natural and human systems being managed, as well as the goals and values of the ecosystem managers. The complexity of this task necessitates the use of conceptual models to ground the choice of assessment endpoints and clear consideration of scale, driving processes, and the different levels of organization that make up the ecosystem (organism, population, community, and ecosystem). For this reason, clear criteria should be used when choosing assessment endpoints (Table 2). Suter (2007) counsels risk assessors to focus on the levels of organization at which the endpoint entities are defined and to look both above and below these levels when considering the meaning of assessment.

Three sets of endpoints will be finalized during initial expert workshops conducted as part of the pressures assessment, each set corresponding to one of the three ecosystem domains within the Puget Sound Partnership’s conceptual model of Puget Sound ecosystem recovery: marine & nearshore, terrestrial, and freshwater aquatic. The PSPA technical memorandum offers draft lists of assessment endpoints for each of the domains, for refinement during expert workshops (Table 3.)

Table 2. Criteria for selection of assessment endpoints (Based on Box 16.2 from Suter et al., 2007, p. 164)

Criteria	Definition
Policy goals and societal values	Because the action of pressures and stressors on the assessment endpoint are the basis for management, the choice of the endpoint should reflect the goals and values that managers seek to protect, recover, and manage.
Ecological relevance	Components and attributes that are significant determinants of the attributes of the system of which they are a part should be considered above components and attributes that could be augmented or degraded without significant ecosystem-level consequences. Keystone species that influence community composition or species that are consumed by multiple species at multiple levels of a food web are examples of endpoints with high ecological relevance.
Susceptibility (sensitivity to stressors)	Components and attributes that are potentially highly exposed to and/or highly responsive to exposure to the stressors being evaluated are more relevant.
Operationally definable	An operationally definable endpoint is one that corresponds to aspects of the system that can be directly observed, monitored through surrogates, and/or modeled within the adaptive management framework being used to manage the system.
Appropriate scale	Endpoints should be chosen with scales corresponding to the management actions being evaluated and implemented and/or at the scale of the activities corresponding to pressure classes associated with the stressors being evaluated.
Practicality	Endpoints should be chosen such that a strong technical basis exists for evaluating the relations between stressors and potential impacts to endpoints.

Table 3. Suggested assessment endpoints for consideration and refinement during expert workshops. Notes: a) Valued Ecosystem Components from the Puget Sound Nearshore Restoration Project (PSNERP), as listed in Schlenger et al., 2011; b) Examples of possible endpoints for the terrestrial domain; c) Examples of possible endpoints for the freshwater aquatic domain. [Note: Scott Redman has modified entries in the terrestrial and freshwater aquatic columns so that these core materials provide example endpoints in each category]

Marine & Nearshore[a]	Terrestrial[b]	Freshwater Aquatic[c]
Coastal forests (marine riparian vegetation)	Major river flood plains	Small stream systems (water and sediment quality, flows, and habitat conditions)
Beaches and bluffs	Old growth forests	Major rivers (water and sediment quality, flows, and habitat conditions)
Eelgrass and kelp	Marine and riverine riparian habitat	Riverine and lake riparian habitat
Forage fish	Westside Prairies and Oregon White Oak Woodlands	Lakes (water and sediment quality, trophic and habitat conditions)
Great blue heron	Working forestlands	Groundwater (water quality and levels)
Juvenile salmon	Working farmlands	Water provision
Orca whales	Wetlands	Wetlands (water quality and habitat conditions)
Native shellfish	Land base under conservation protection	
Nearshore birds	Parks and green space	
Embayments	~~Water provision and quality~~	
Tidal wetlands	Functional Diversity (Pollinators, seed dispersers, Predators)	
	Ecosystem diversity	Invertebrate communities
	~~Fish and game~~Wildlife species	Fish species

Pressures and Stressors Taxonomy Used in the Assessment

As described in the Introduction, we make use of an updated taxonomy of pressures, as developed and revised by the Puget Sound Partnership and its partners, through a progression of workshops, projects, workgroup efforts, and associated publications over the past several years (Neuman et al., 2009; Stiles et al., 2013). Where necessary, we depart from the 2013 pressures taxonomy, as described below.

At the highest level, the pressures taxonomy includes 29 pressure classes grouped into ten pressure categories (Table 4). We include an eleventh pressure category to account for climate change-related pressures and stressors, generating at total of 32 pressure classes.

Most of the 32 pressure classes represent sources of stress. In effect, the taxonomy represents a classification of sources, with nested taxonomies of stressors and mechanisms of action used to further define a source's specific pathways of effects on Puget Sound ecosystems. Sources of stress are not the most proximal actors on ecosystem components but rather act on the ecosystem via one or more stressors, or agents of change. For example, the pressure *Residential & Commercial Development* acts directly on ecosystem components via habitat conversion and pollution (air, noise, and light), as well as indirectly via increasing the need for other pressures, or sources of stress, including *Transportation & Service Corridors* and *Runoff from the Built Environment* (Stiles et al., 2013).

Table 4. Pressure class categories (1 – 11) and their associated pressure classes, based on the 2013 PSP 2013 Pressure Taxonomy (Stiles et al., 2013 draft), modified to include climate change pressures.

1. **Residential & Commercial Development**
   1.1 Residential & Commercial Development
2. **Agriculture & Aquaculture**
   2.1 Agriculture
   2.2 Livestock Grazing
   2.3 Fin Fish Aquaculture
   2.4 Shellfish Aquaculture
   2.5 Timer Harvesting
3. **Energy Production & Mining**
   3.1 Energy Production & Energy Emissions
   3.2 Mineral & Gravel Mining
4. **Transportation & Service Corridors**
   4.1 Transportation & Service Corridors
   4.2 Dredging & Dredged Materials
5. **Biological Resource Use**
   5.1 Animal Harvesting (Aquatic)
   5.2 Animal Harvesting (Terrestrial)
6. **Human Intrusions & Disturbances**
   6.1 Recreational Activities
   6.2 Military Exercises
   6.3 Derelict Fishing Gear
7. **Natural System Modifications**
   7.1 Dams
   7.2 Culverts
   7.3 Freshwater Levees & Floodgates
   7.4 Marine Water Levees & Tidegates
   7.5 Freshwater Shoreline Infrastructure
   7.6 Marine Shoreline Infrastructure
8. **Invasive & Other Problematic Species**
   8.1 Invasive Species (Aquatic, Terrestrial)
9. **Pollution**
   9.1 Runoff from the Built Environment
   9.2 Industrial, Domestic & Municipal Wastewater
   9.3 Onsite Sewage Systems (OSS)
   9.4 Combined Sewer Overflows (CSOs)
   9.5 Toxics & Legacy Contaminants
   9.6 Oil & Hazardous Spills
10. **Water Withdrawals & Diversions**
   10.1 Water Withdrawals & Diversions
11. **Climate Change**
   11.1 Physicochemical changes to marine waters
   11.2 Sea level rise
   11.3 Shifts in temperature/precipitation patterns

Table 5 presents a list of common stressors in Puget Sound, as presented in the Puget Sound pressures taxonomy. See Stiles et al. (2013) for a complete list of stressors with definitions and additional information about their primary sources and common ecological effects, or stresses to ecosystem components.

	Table 5. List of stressors from Puget Sound pressures taxonomy (Stiles et al., 2013).
a.	Bycatch (unintended harvest)
b.	Derelict fishing gear and vessels
c.	Disease introduction
d.	Fish passage barriers
e.	Habitat conversion due to human land-use change
f.	Habitat degradation
g.	Defoliation
h.	Habitat destruction due to altered hydrology
i.	Harvest
j.	Hydromodification - altered volume and timing of runoff
k.	Hydromodification - ditching
l.	Hydromodification - flow regulation
m.	Hydromodification - structural barriers to water, sediment, debris flow
n.	Hydromodification - water diversion
o.	Hydromodification - water extraction
p.	Increased competition - due to increased native species
q.	Increased competition - due to increased non-native species
r.	Increased predation - due to overwater structures and shading
s.	Increased predation - due to increased native or introduced species
t.	Introduced genetic material
u.	Overwater structures
v.	Pollution - air pollution
w.	Pollution - atmospheric deposition
x.	Pollution - pesticide application
y.	Pollution - munitions testing
z.	Pollution - release of legacy toxics
aa.	Pollution - toxics, nutrients, sediment, pathogens in water
bb.	Pollution - underwater bombs & testing
cc.	Shoreline hardening
dd.	Soil compaction
ee.	Species disturbance
ff.	Toxic spills
gg.	Toxics in environment

Refinement to this list of stressors, including the addition of stressors associated with climate change, ocean acidification, and sea level rise, are an expected product of initial expert workshops associated with each of the three ecosystem domains.

Assessment scales, units of assessment

The concept of “assessment scales” is somewhat complicated by the fact that scale applies to several aspects of the analysis. In the intended context, “assessment scale” refers to the scale at which an expert provides judgment regarding the vulnerability criteria associated with a stressor/endpoint pair. From this point of view, assessment scale could be thought of as a “unit of assessment”, since the database of intrinsic vulnerability scores (μ_{ijk}) will be defined at those scales. As discussed in the “ecosystem vulnerability model” section, we emphasize that the scales of assessment are distinct from the “scale of impact” vulnerability criterion.

The primary assessment scales, the scales at which expert judgment regarding the vulnerability criteria associated with stressor/endpoint pairs, are considered separately for each of the three ecosystem domains (Table 6).

Table 6. Assessment scales for elicitation of vulnerability criteria, by ecosystem domain

Ecosystem domain of assessment endpoint	*Assessment scale for elicitation of vulnerability criteria*
Marine and nearshore	Basin/sub-basins as defined by the Puget Sound Nearshore Ecosystem Restoration project.
Terrestrial	Water Resource Inventory Areas (WRIAs), grouped as determined to be appropriate
Freshwater aquatic	Water Resource Inventory Areas (WRIAs), grouped as determined to be appropriate

Implementing the pressures assessment through workshops, surveys, and expert panels

The assessment approach distinguishes between two types of workshop: 1) model refinement workshops and 2) model elicitation workshops. Each type of workshop would be required for the three ecosystem domains, each involving teams chosen by expertise. For a given ecosystem domain, the *model refinement workshops* would involve an expert group reviewing and potential refining the proposed vulnerability model criteria definitions, the choice of assessment stressors and endpoints, the choice of spatial scales for assessment, and assumptions about the context underlying the stressor/endpoint pairs. For a given ecosystem domain, the *model elicitation workshops* would involve expert groups providing their inputs to the vulnerability model for specific pressure/endpoint pairs, including a facilitated assessment of their uncertainty on those inputs. Individual assessments would be shared between the experts during workshops with an opportunity for the experts to discuss and modify their answers. The use of information technology to allow individual participants to input their answers online during the workshop with a group facilitator synthesizing and displaying the group results as part of a Delphi process is suggested. Individual experts would be expected to respond only to stressor/endpoint pairs for which they have sufficient expertise and experience. For this reason, when choosing experts, confirming that all stressor/endpoint pairs are covered would be essential. The use of survey documentation and online tools could be used to facilitate assessments and increase participation of a broader audience of experts, but the use of workshops to drive and manage the assessment process is essential.

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