PUGET SOUND NEARSHORE ECOSYSTEM RESTORATION

APPENDIX G

ECOSYSTEM OUTPUT MODEL

Integrated Feasibility Report and Environmental Impact Statement

US Army Corps of Engineers®
Seattle District

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PUGET SOUND NEARSHORE ECOSYSTEM OUTPUT MODEL DOCUMENTATION REPORT

PUGET SOUND NEARSHORE ECOSYSTEM RESTORATION PROJECT

Prepared in Support of Puget Sound Nearshore Ecosystem Restoration Project

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1 INTRODUCTION

This report documents the methodology for quantitatively estimating the ecological benefits that could be realized through implementation of the Puget Sound Nearshore Ecosystem Restoration Project (PSNERP). Quantification of ecological benefits is accomplished typically through the application of a model. This report describes the model for evaluating potential achievement of restoration objectives for the PSNERP (PSNERP Ecosystem Output model), and how the model was developed.

A benefits model should measure the level of performance, raise awareness and understanding, measure progress toward programmatic goals, and support decision making. Models can be quantitative (e.g., length), semi-quantitative (e.g., long, longer, longest), non-quantitative (e.g., color), or nominal (e.g., yes or no); however, U.S. Army Corps of Engineers (USACE) policy requires that restoration projects only use models that are "expressed quantitatively" (ER 1105-2-100 [USACE 2000]). Throughout this report, the term "ecosystem output" is synonymous with "ecological benefit" for the purpose of quantifying anticipated positive outcomes of proposed restoration actions.

Through a collaborative effort, an interdisciplinary sub-group of the PSNERP team including: USACE staff, Washington Department of Fish and Wildlife (WDFW; the non-Federal sponsor), contractor support staff, and Nearshore Science Team (NST) members, has created the PSNERP Ecosystem Output model described in this report.

2 MODEL REQUIREMENTS

The USACE defines the purpose of ecological restoration as "to restore significant ecosystem function, structure, and dynamic processes that have been degraded" (ER 1165-2-501 [USACE 1999a]). The goal is to restore ecological resources of "significance," with significance generally being defined subjectively as a measure of quality and/or institutional or public recognition. In USACE projects, ecosystem resources are generally expressed quantitatively either in physical units (acres, for example) or with indices that are surrogates for functions or processes. According to USACE policy guidance, "Ecosystem structure is the state and spatial distribution of material forms within the ecosystem at a specified time. It includes microscopic and macroscopic material components in diverse living and non-living assemblages. Ecosystem functions are the dynamic cycling of inputs and outputs characterized by rate and direction of change in material and energy flows through time and space. Ecosystem functions redistribute components of structure through abiotic (non-living) and biotic (living) processes" (EP 1165-2-502 [USACE 1999b]).

Within programs of the USACE, models can quantify ecological benefits at multiple scales, including the project, regional, and national scales of the following benefits considerations (ER 1105-2-100):

- *Comparison of project alternatives*– How do ecosystem restoration planners compare ecological benefits of alternative restoration measures and plans (e.g., fish bypasses, ladders, or lifts at a given location)?
- *Development of project performance assessment and success criteria* – Following implementation, is the project successfully accomplishing objectives?
- *Adaptive management of project outcomes* – Are the monitoring plan and metrics appropriate for identifying problems and adaptively managing deficiencies?
- *Regional programmatic assessment and portfolio management* – How do managers prioritize and manage multiple, smaller projects to achieve objectives in large-scale, system-wide efforts (e.g., the Comprehensive Everglades Restoration Plan)?
- *National programmatic assessment and portfolio management* – How do managers prioritize and budget projects and track results to achieve goals at a national scale?

"Ecosystem restoration outputs must be clearly identified and quantified in appropriate units" (ER 1105-2-100). Ecological benefits can be estimated using area restored as a surrogate index, as in a known quantity used as an indicator for an unknown value. This is problematic, however, because area is not a measure that accounts for the quality or the relative value of a specific restoration action at a given location. Models that measure one or more ecosystem outputs can estimate project benefits more accurately than models that estimate only the amount of area restored. USACE restoration planning documents often express direct outputs in terms of either simple abundance (e.g., how many fish are in a given river reach) or index-based values (e.g., habitat units). USACE policy does not emphasize a preferred model or model type to measure performance, but instead states, "All relevant ecosystem components need to be described and assessed" (EP 1165-2-502 [USACE 1999b]). Selection of outputs, units, and techniques for quantification is challenging because, for each problem, there are many types of metrics, or performance measurement equivalencies, that could be applied; however, mission objectives and USACE policy provide some guidance for the use of metrics and development of models.

Given that the purpose of the USACE Ecosystem Restoration mission is "to restore degraded ecosystem structure, function, and dynamic processes to a less degraded, more natural condition" (ER 1105-2-100 [USACE 2000]), indices and metrics that capture aspects of structure, function, and process are obvious candidates for use in an ecosystem output model.

USACE policy states that single-species approaches should be discouraged as they narrow the breadth of benefits potentially provided, and community-based approaches are preferred (ER 1105-2-100). Furthermore, USACE guidance has traditionally favored habitat-based approaches, stating "habitat-based evaluation methodologies, supplemented with production, user-day, population census, and/or other appropriate information, shall be used to the extent possible to describe and evaluate ecological resources and impacts associated with alternative plans" (ER 1105-2-100). Habitat focus, however, tends to limit the number of species analyzed and is not as holistic as incorporating more ecosystem components than habitat needs of one or a few species. Alternative approaches may include other physical measurement metrics (e.g., spatial characteristics, community structure, or water quality conditions) or ones that may be more function- or process-based (e.g., bank retreat, organic matter breakdown). Function- and process-based metrics of ecological condition are often highlighted as underused measurements of the state of an ecosystem (Young et al. 2008).

Effective metrics have the following characteristics, as documented by several authors including Roy (1985) and Yoe (2002):

- **Scientifically verifiable** – Two independent assessments would yield similar results.

- **Cost-effective** – The technology required to generate data for the metric is economically feasible and would not require an intensive deployment of labor.
- **Easy to communicate to a wide audience** – The public would understand the scale and context and be able to interpret the metric with little additional explanation.
- **Changeable by human intervention** – The metric would have a causal relationship between the state of the system and the variables that are under a decision maker's control. Metrics that are independent of human action do not inform a management, policy-making, or design process.
- **Credible** – Most stakeholders would perceive the metric as accurately measuring what it is intended to measure.
- **Scalable** – The metric would be directional, whether qualitative (best, good, worst) or quantitative, as appropriate.
- **Relevant** – The metric would reflect the priorities of the public and other stakeholders and enhance the ability of managers and regulators to execute faithfully their stewardship responsibilities.
- **Sensitive** – The metric would be sensitive enough to capture the minimum meaningful level of change or make the smallest distinctions that are still significant, and it would have uncertainty bounds that are easy to communicate.
- **Minimally redundant** – What the metric measures is not duplicating another metric in the set being used.
- **Transparent** – Use of the metric does not create or promote any "secret agenda."

The purpose of the PSNERP Ecosystem Output model is to provide quantification of the potential ecological improvement of proposed restoration actions so that the actions can be compared against each other, and to compare alternative suites of actions at the Sound-wide scale; the goal for the model is to have the characteristics listed above along with achieving the purpose. This contributes to the planning effort by quantifying the benefits of the actions, allowing comparison of action benefits to the "Future Without Project" condition, and serving as a screening tool for selecting actions from those that are proposed and evaluated.

3 PSNERP APPROACH TO MODEL BUILDING

The team, charged with inventing a way to estimate the ecological benefits of nearshore restoration actions, wanted to move beyond the simplistic single-species, index-based, or habitat-focused models. The goal was to express the expected improvement of restoring process, structure, and function in a more holistic approach based in sound science. The resulting PSNERP Ecosystem Output model is a synthesis of much of the work done throughout the general investigation.

3.1 Theoretical Basis for Conceptual Model

The PSNERP Ecosystem Output model accounts for both quantity and quality. Quantity is accounted for as number of acres restored. The quality portion of the model includes considerations of process, structure, and function. These are the three conceptual components of the model that together describe the relationship of ecosystem components to ecological goods and services (Figure 1). In this conceptual model, **processes** are the dynamic abiotic (i.e., physical and chemical) cycles and interactions that create and sustain other ecosystem components, specifically structure and function. Examples of processes include sediment delivery and transport, tidal hydrology, and detritus import and export. **Structures** are the stationary abiotic and biotic attributes of an ecosystem. Examples of structures are distributions of shoreform types, beach substrate, and aquatic vegetation composition. **Functions** include interactions between organisms and their physical environment, as well as other ecosystem goods and services including nutrient cycling, food web support, and water quality.

The theory behind the development of this model is that processes, structures, and functions all contribute to ecosystem goods and services. Ecosystem goods and services are the diverse benefits that humans enjoy, consume, or use from ecosystems (MEA 2005). A simple example of this relationship is common on Puget Sound beaches and embayments: sediments from bluff-backed beaches deposited at small creek mouths (natural process) form barrier spits that partially enclose estuaries and lagoons (natural structure) that in turn provide habitat for clams (ecological function). Clams are at the consumer base of the food web, and provide food to humans (ecological good), and filter nutrients from the water column (ecological service).

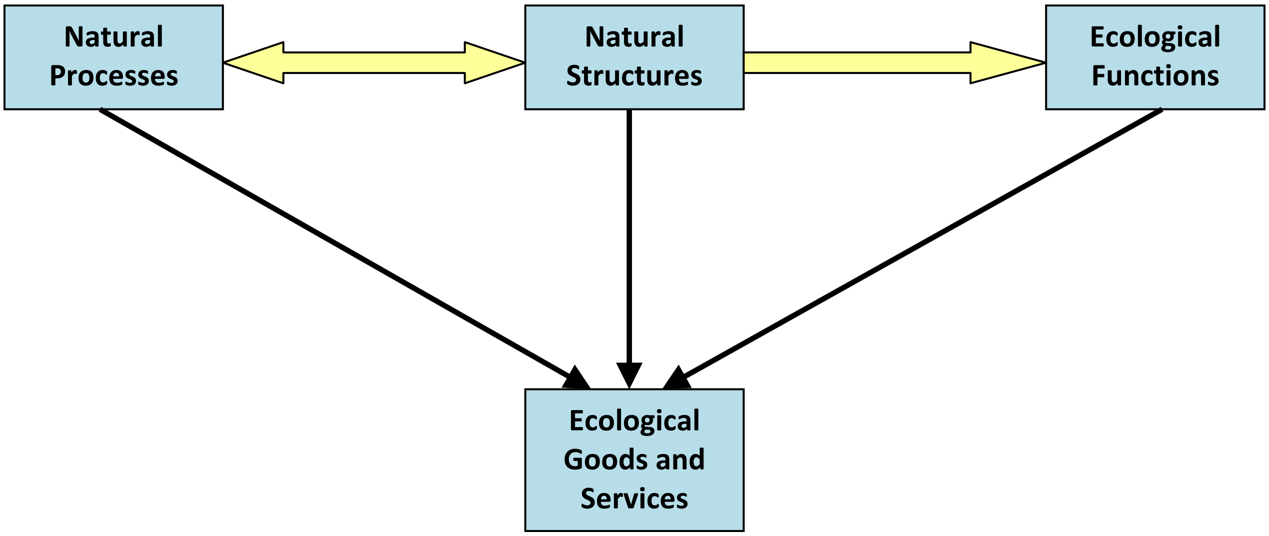

Figure 1. Conceptual Model of Linkages between Processes, Structures, and Functions and Ecological Goods and Services.

Modified from Gelfenbaum et al. (2006) and Simenstad et al. (2006)

3.2 Benefits Measurement Concept

Much of the PSNERP general investigation work has been an analysis aimed at characterizing problems of Puget Sound's nearshore ecosystems, identifying restoration objectives, and identifying management measures to achieve those objectives. To that end, two separate tools have been developed to characterize the degree to which anthropogenic changes to the nearshore have affected the capacity for ecological processes to support ecosystem functions, goods, and services (EFG&S). These two tools are quantification of process degradation, and quantification of impairment of EFG&S. The process evaluation framework is described in the strategic needs assessment report ([SNAR]; Schlenger et al. 2011), and the EFG&S impairment metric is described in the change analysis report (Simenstad et al. 2011). These two tools are used to characterize different components of the conceptual model represented in Figure 1. The PSNERP Ecosystem Output model incorporates these process degradation and EFG&S impairment analysis tools in assessment of ecological benefits for USACE planning purposes.

The process evaluation framework characterizes the capacity of shoreline process units (SPUs) and delta process units (DPUs) to support nearshore processes; process evaluation and degradation are described in the SNAR (Schlenger et al. 2011).

The assessment of EFG&S impairment is presented in the change analysis report (Simenstad et al. 2011), which documents Puget Sound shoreline changes between the late 1800s and the present. The EFG&S analysis applies the following four categories of goods and services, which are classified in the Millennium Ecosystem Assessment report (MEA 2005) and the World Resources Institute report (WRI 2005):

1. **Regulating services** such as the regulation of climate, floods, disease, wastes, and air and water quality
2. **Supporting services** such as soil formation, photosynthesis, and nutrient cycling
3. **Provisioning services** such as food, water, timber, fuel, and fiber
4. **Cultural services** such as educational, recreational, aesthetic, and spiritual benefits

The EFG&S impairment as calculated in the change analysis report (Simenstad et al. 2011) characterizes changes to the ecological functions and the human-focused goods and services. During the PSNERP Feasibility Scoping Meeting on May 6, 2010, USACE Headquarters provided guidance that the human-focused inputs of provisioning and cultural services do not meet the purpose of the USACE ecosystem restoration mission. Corps policy (ER 1165-2-501) on the ecosystem restoration mission area states, "Projects implemented under this guidance should address the restoration of ecosystems, i.e., ecological resources, and not restoration of cultural and historic resources, aesthetic resources, or cleanup of hazardous and toxic wastes." Therefore, the EFG&S impairment analysis tool provided in the change analysis report was modified for use in this ecosystem output model by isolating the broader ecological category inputs (regulating and supporting) from the human-focused inputs (provisioning and cultural) so that calculations could be designed to include only the ecological category inputs.

In addition to process and function, the ecosystem output model includes a characterization of structure. The structural benefit indices focus on landscape-scale distributions of shoreforms[1]. The five aspects of landscape structure are (1) shoreform scarcity, (2) shoreform heterogeneity, (3) shoreline sinuosity, (4) longshore connectivity, and (5) cross-shore connectivity. Indices used to quantify these five aspects, detailed in section 4.3.2, were developed through workshops and close coordination with members of the NST.

3.3 Aligning Model Components with Planning Objectives

Four PSNERP planning objectives were identified, with no intended prioritization, in a problem statement that was informed by two documents mentioned earlier: 1) a strategic needs assessment report (SNAR; Schlenger et al. 2011), which identifies areas of degraded processes and functions in the Puget Sound nearshore zone based on interpretations of historic change in the shoreline, and 2) the change analysis report (Simenstad et al. 2011), in which historic shoreline conditions from the late 1800s are compared to shoreline conditions circa 2006. These objectives, along with their sub-objectives, are listed below. Planning objectives 1 through 3 describe restoration, and planning objective 4 describes monitoring and adaptive management.

1. <u>Restore the size and quality of large river deltas</u>

    a. Restore tidal flow and inundation area in river deltas
    b. Restore quality and quantity of tidal wetlands in river deltas with emphasis on oligohaline and tidal freshwater wetlands
    c. Improve connectivity between the nearshore and adjacent uplands/ watershed
    d. Increase the shoreline length of large river deltas

2. <u>Restore the number and quality of coastal embayments</u>

    a. Restore embayment shoreline length that has been reduced through fill placement
    b. Restore embayments that have transitioned to an artificial shoreform or have been lost through conversion to uplands
    c. Restore existing embayments that have been degraded
    d. Restore quality and quantity tidal wetlands in coastal embayments

3. <u>Restore the size and quality of beaches</u>

    a. Restore sediment input processes by reducing degradation of bluff-backed beaches in divergence zones and transport zones of sediment drift cells
    b. Improve sediment transport and accretion processes by removing subtidal and intertidal stressors contributing to shoreline degradation

4. Increase understanding of natural processes in order to improve effectiveness of program action

    a. Gather and analyze data to inform adaptive management and ensure project success
    b. Gather and analyze data to inform future restoration efforts by the Corps and others

The metrics and indices that are the components of the quality portion of the ecosystem output model (process, structure, and function) are based on these objectives. (See section 4 for discussion of the quality and quantity portions of the model.)

3.4 Overview of PSNERP Spatial Scales

Four spatial scales are used in this PSNERP study:

- **Puget Sound –** includes the Puget Sound, the Strait of Juan de Fuca, and southern portions of the Strait of Georgia that occur within the borders of the United States
- **Sub-basins –** PSNERP-defined divisions of Puget Sound based on geographic features including oceanographic sills and bathymetry, the common issues and interests of the entities in these areas, and the water that flows into and within the Sound
- **Process Units** – from the change analysis report (Simenstad et al. 2011)
    - Delta process units (DPUs) – characterized by the large river deltas, and their associated drainages, that encompass varying salinity and flooding regimes
    - Shoreline process units (SPUs) – individual littoral drift cells that drive sediment delivery and transport along the shore to accretionary features or discharge offshore
- **Action –** refers to a specific restoration management measure or a combination thereof, within a site, with a single non-Federal sponsor (i.e., a separable element).

Different indices are calculated at different scales (e.g., process unit or sub-basin scale) depending on which scale is most appropriate.

3.5 Data Source and Software Applications Used for Measurements and Calculations

The ecosystem output calculations are generated from the project's geodatabase, which contains information on the physical conditions along the shoreline and throughout the upland drainage areas. The geodatabase includes all parameters necessary to calculate each component of the ecosystem output model such as area, length, number, and deviation from a straight line (for sinuosity). These are calculated using the following types of data from the geodatabase:

- Geographic spatial units (GSUs) that define drainage areas contributing to specified portions of the shoreline
- Shoreline alignment
- Shoreline stressor distributions and dimensions (e.g., shoreline armoring and nearshore fill)
- Upland stressor distributions and dimensions (e.g., impervious surfaces and land development)
- Tidal wetland distributions and dimensions by wetland class
- Shoreform types, locations, and dimensions
- Shoreline process unit (SPU) and delta process unit (DPU) delineations

Information is either provided or calculated for historic, current, and post-restoration, as appropriate for each parameter. To limit complexity of the ecosystem output model and to maximize its usability and transparency, the only software needed is ArcGIS® for measuring features present on the landscape and Excel for calculating formulas. Since calculations rely on "off-the-shelf" software, no special programming is required to perform the benefits calculations.

4 PSNERP ECOSYSTEM OUTPUT MODEL COMPONENTS

The primary equation of the PSNERP Ecosystem Output model, presented in section 4.1, was progressively developed and tested in several iterations. It is based on the following general equation:

Ecosystem Output (EO) = Quantity x Quality

Where:

Quantity – Area (described in Section 4.2)

Quality – Components: process, structure, and function (described in Section 4.3)

When the ecosystem output model is used to evaluate individual actions, ecological benefits are calculated at the process unit scale; process units are operationally defined by littoral drift cells (SPUs) or large deltas (DPUs). This ecosystem output model works at multiple scales; evaluations may be conducted that compare and rank individual sites, full alternatives within the seven sub-basins defined for PSNERP, or at the Sound-wide scale. The inputs to the model are either data or data derivatives from a geospatial information system (GIS) geodatabase.

4.1 Development of the Ecosystem Output Equation

Following is the final form of the primary equation in the PSNERP Ecosystem Output model. Each of the equation elements is based on one of the four types of model parameters: Area (A), process (P), structure (S), or function (F). The equation is used to measure potential ecological benefits of proposed restoration actions.

$EO = A^{*} [(P^2 + S + F)/\text{maximum possible score}]$

Where:

EO – ecosystem output

A – area of restored process, in acres or other areal units (Quantity score)

P – process degradation index score, 0 – 10

S – summation of landscape indices, 0 – 10

F – EFG&S Tier 2 impairment score, 0 – 10

Maximum possible score: 120

Quality score: $(P^2 + S + F)/\text{maximum possible score}$

The following sections describe the equation components in more detail and discuss how they were refined for this purpose through several iterations of development and testing.

Each component has a score on a 0 – 10 scale. Each component is composed of one or more indices, which are described in more detail in section 3.5. For a detailed description of the set of calculations the equation is based on, see Appendix A. Each of the three variables — process, structure , and function—represents a piece of the information about the quality of the area, and the score for any one of these components does not modify the score for any other individual component; therefore, they are additive so that together they modify the area component.

Initially, an equation with different weighting was proposed (discussed in section 5.1). After testing the initial equation on a suite of proposed restoration actions, including the 36 that have undergone 10% design, the team discovered that the area component explained more than 90% of the variance of the ecosystem output values; i.e., the measurements of quality (process, structure, function) were not contributing enough to the calculated ecosystem outputs to be meaningful components. Another component that was initially considered, ancillary benefits (E), was contributing very little and therefore it was excluded from calculation of ecological benefits. This undue dominance of area on the ecosystem outputs and under-representation of the quality components led to the refined equation presented above that is ultimately used in the model. The new equation represents the following rationale regarding the importance of components:

- The ecosystem output model results should be sensitive to both quantity and quality components in the equation.
- The process component of quality is weighted most heavily because the PSNERP intent is to ensure sustainability by restoring the nearshore processes, so the weighting of the process component needs to be strong enough to influence the ranking of the proposed actions.
- The structure and function components of quality shall contribute equally to the ecosystem output, but less than the process component does.
- The final quality score is represented by a proportion that will be multiplied by area. A quality score of 1.0 indicates the maximum quality that could be achieved by the action.

Alternate methods of weighting the process component were considered. One way would have been to multiply the other components by small fractions (e.g., 0.1 or 0.02); however, results showed that, with this method, the process component did not affect the quality score enough to make any statement about improving the quality of a large area. Therefore, using only the area of restoration would have dominated the entire EO score and the quality portion would have had no effect. Ultimately, the team chose the commonly applied weighting method of squaring the most important component—in this case, process—so that it has a greater influence on the final score; in this case, the EO.

Based on a Spearman's Rank Correlation Test, the quality portion of the equation affects the total score such that outcome (EO score) and rank are not based solely on the area of the proposed action; actions that would restore more process score higher.

For each index described in the following sections, scores have been calculated for two scenarios of "Future With Project" conditions (partial restoration and full restoration) and for the corresponding scenarios of "Future Without Project" conditions (without partial and without full restoration), for conceptual designs of 36 proposed actions. For the "Future Without Project" conditions, the team has elected to use the inventory of current conditions. This is a conservative estimate, which assumes zero degradation, although the more likely case would be further degradation of the nearshore ecosystem due to the predicted population increase in the Puget Sound area over the next 50 years. Additional stressors from this population increase, however, could be mitigated through environmental regulations and permitting requirements. Since it is not possible to predict exact population increases, their effects on the nearshore, or changes in environmental regulations, the assumption is made that the existing stressors will remain unchanged for the period of analysis.

Finally, per USACE planning guidance, average annual net benefit will be used for cost effectiveness/incremental cost analyses (CE/ICA) and is calculated as follows:

Net EO = (EO "With Project" conditions – EO "Future Without Project" conditions) * Average Annual Benefit Factor

4.2 Area Component

Traditionally, USACE has used the quantity and quality of habitat jointly, in the form of habitat units, to measure structural improvements provided by ecosystem restoration projects. The quantity portion is often measured as area (acres of habitat, landform, etc.) or number of species; in some systems, it is measured as length (miles of stream bank). The PSNERP Ecosystem Output model uses acres, delineated by polygons, to represent the quantity portion of the equation. The area associated with each management measure must have a clear definition for use as guidance in estimating the area component of the ecosystem output model, and must be applied consistently to all actions evaluated.

Three different scales of area were considered for quantification of PSNERP management measures to determine which would be the most suitable area metric to use in the model. For each scale, the capabilities and limitations were considered.

- **Action footprint** –A measurement of the physical footprint of the management measures (for example, the area where vegetation is planted or the footprint of a removed berm). When multiple management measures are included in an action, the footprint equals the total of the management-measure footprints with no double counting of overlap areas addressed by two or more management measures.
  - Capability – Can be accurately quantified with a high degree of certainty
  - Limitation – May grossly underestimate the areal extent of ecological benefits from each management measure because process restoration covers a broader area

- **Area of restored process –** This is a measurement of the area directly affected by the restoration of process. For areas where armor is removed to restore sediment input, the area is measured along the length of the shoreline where armor is removed for length and from the top of the bluff to the mean lower low water (MLLW) level for width, but the measurement does not extend down-drift. For areas where tidal inundation is restored, the measurement extends up-gradient to include the total tidally inundated area regardless of salinity level.
  - Capability – Can be accurately quantified with high level of certainty for some management measures (for example, those that restore tidal inundation), and more fully captures the area that would experience ecological benefits from restoration of a process
  - Limitation – Difficult to quantify with certainty for some management measures (for example, those management measures that restore sediment transport and delivery); does not identify whether an action is too small to have a significant benefit to the ecosystem

- **Potential area of influence** – This is a measurement of the area that could benefit from the process restoration provided by the action. In some cases, this may be the same as the area of restored process. In other cases, it could extend beyond the area of restored process to the greater ecosystem area that a stressor affects; indirect effects can extend well beyond the immediate area of stressor removal. While potential area of influence is an estimated area that is more consistent with the guidance calling for a systems approach (ER 1165-2-501), it was not feasible to devise consistent rules for defining this area. For instance, an increase in primary productivity has an effect across a much larger spatial area than just the area where new aquatic vegetation is placed; however, the affected area would be difficult to quantify systematically.
  - Capability – Fully captures the area of ecological benefits of a given management measure
  - Limitation – Not feasible to estimate with any degree of certainty and consistency

To develop definitions of all three scales of area for each of the 21 management measures, as defined in Clancy et al. (2009), a workshop was conducted. Through the workshop discussion and follow-up, it was determined that, of the three scales considered, using area of restored process is the optimal approach to estimating ecological benefits beyond the specific action footprint with the least amount of uncertainty. The action footprint was considered to provide too significant an underestimate. Estimating the potential area of influence scale was considered too uncertain and speculative.

To define the area of restored process for each management measure at the proposed action locations, the target processes for each management measure were identified at the action scale. The proposed management measures that restore process, and the area of restored process for each, are in Table 1. The proposed management measures that do not directly address process and their target areas of restoration are in Table 2.

Table 1. Management Measures that Restore Process and Area of Restored Process

Management Measure	Primary Process Restored	Area of Restored Process
Armor Removal or Modification	Sediment input	Applicable to divergence zones and transport zones of drift cells: a polygon defined by the length of the shoreline where armor is removed or modified multiplied by the distance between the top of the bluff and mean lower low water (MLLW) Applicable to convergence zones and shorelines of no appreciable drift: footprint of the armor removed or modified
Berm or Dike Removal or Modification	Tidal hydrology via inundation	Area where tidal inundation is restored
Channel Rehabilitation or Creation	Tidal channel formation and maintenance, and distributary channel migration	Area where tidal inundation is restored
Groin Removal or Modification	Sediment transport and wave energy	Length squared plus the footprint
Hydraulic Modification	Tidal hydrology via energy and freshwater input	Tidally inundated area
Overwater Structure Removal or Modification	Solar radiation	Footprint of the overwater structure removed or modified, plus any additional area shaded by the structure
Revegetation	Vegetation processes	Area planted plus area shaded by the vegetation
Topography Restoration	Beach shoreline: topographic processes	Area of fill removed
	Embayment and wetland: tidal hydrology via inundation	Area where tidal inundation is restored

Table 2. Management Measures that Do Not Directly Address Process

Management Measure	Category [a]	Primary Process Restored	Area of Restored Process
Beach Nourishment	Enhancement	NA	Footprint of the substrate placement
Contaminant Removal	Prerequisite	NA	Footprint of removal
Debris Removal	Prerequisite	NA	Footprint of removal
Habitat Protection and Policy Regulation	Protective	NA	For habitat protection, footprint of the area being protected
Invasive Species Control	Enhancement	NA	Area of removal
Large Wood Placement	Enhancement	NA	Footprint of the large wood
Physical Exclusion (fences, barriers, etc. to exclude human or animal use)	Prerequisite	NA	Footprint of the exclusion area
Pollution Control	Prerequisite	NA	Difficult to accurately quantify an area that would benefit from pollution control, action specific
Property Acquisition and Conservation	Prerequisite and Protective	NA	Area of acquisition or conservation
Public Education and Involvement	Protective	NA	NA
Species Habitat Enhancement	Enhancement	Species lifecycle	Species specific
Reintroduction of Native Animals	Enhancement	Species lifecycle	Species specific
Substrate Modification	Enhancement	NA	Footprint of the substrate placement

Notes:
NA Not applicable
a Defined in Clancy et al. 2009

4.3 Quality-Component Indices

Indices to quantify the ecological benefits of the process, structure, and function components were developed with input from the NST. In July 2010, the concepts of these indices were presented to the NST. In August 2010, members of the NST, the project management team, and the USACE planning team, as well as USACE employees from the Engineer Research and Development Center (ERDC) and other districts with expertise in developing ecosystem output models for use in plan formulation of USACE projects, participated in a two-day workshop to develop indices for the quality-component. During the workshop, formulas for calculating each of these indices were proposed. Since then the ecosystem output team has worked on refining these formulas, through weekly meetings and occasional workshops and discussions with NST members. The following sections describe the indices and their development.

4.3.1 Process

As already described, processes are the ecosystem cycles and interactions that create and sustain other ecosystem components; specifically, structure and function. The nearshore processes that influence the marine and estuarine shorelines of Puget Sound occur and vary over diverse spatial and temporal scales (Simenstad et al. 2011). The process index (P) addresses all of the PSNERP objectives (see section 3.3) by measuring the removal of stressors that impede the processes that shape and sustain river deltas, embayments and beaches, . The PSNERP assessment of nearshore ecosystem conditions focuses on the broad physiographic processes that can be considered landscape-forming processes. The NST identified the following 11 broad ecosystem processes as being most important for the creation, maintenance, and function of Puget Sound's shoreline (Simenstad et al. 2011). To characterize the effects of shoreline and watershed alterations (or stressors) on nearshore ecosystem processes, the NST used a simplified version of an evaluation framework developed in the SNAR (Schlenger et al. 2011). These effects are termed "process degradation." Process degradation is evaluated with a separate metric for each of the processes at the scale of process units (10 processes in SPUs and 10 processes in DPUs). Process degradation is estimated by measuring the percent of a process unit with one or more stressors present in areas where a process would occur. Following are the 11 processes:

- <u>Sediment input</u> - calculated as the length of the shoreline with one or more stressors divided by total shoreline length
- <u>Sediment transport</u> - calculated as the length of the shoreline with one or more stressors divided by total shoreline length
- <u>Erosion and accretion of sediments</u> - calculated as the length of the shoreline with one or more stressors divided by total shoreline length
- <u>Tidal flow</u> - calculated as the area of inundation divided by area of inundation if all stressors were removed
- <u>Distributary channel migration</u> - calculated as the length of the shoreline with one or more stressors divided by total shoreline length (applies to DPUs only)

- **Tidal channel formation and maintenance** - calculated as the tidal wetland area divided by the historic tidal wetland area
- **Freshwater input** - For DPUs: calculated as the area downstream of the lowermost dam divided by the total area. For SPUs: calculated as the area in adjacent upland with ten percent or more impervious surface divided by the total area in adjacent upland
- **Detritus import and export** - calculated as the length of the shoreline with one or more stressors divided by total shoreline length
- **Exchange of aquatic organisms** - calculated as the length of the shoreline with one or more stressors divided by total shoreline length
- **Physical disturbance** - calculated as the length of the shoreline with one or more stressors divided by total shoreline length (applies to SPUs only)
- **Solar incidence** - calculated as the aquatic area with overwater structures divided by the total aquatic area.

Only ten of these eleven processes apply to any given process unit. The distributary channel migration process does not apply to SPUs, and the physical disturbance process does not apply to DPUs. Stressors that affect these processes include the following:

- Wetland loss
- Armoring
- Jetties and groins
- Tidal barriers such as dikes and levees
- Overwater structures
- Fill
- Marinas
- Roads
- Railroads

Different stressors are considered for each of the processes. For example, armoring, roads, fill, and railroads in SPUs apply to the sediment-input degradation process. So, if there are one or more of these stressors along 50% of the shoreline (by length) where sediment input occurs, then the process degradation score for sediment input within that process unit is 0.5. The overall process degradation score is the sum of the individual degradation scores for all the process within an action area.

The calculation methodology for process degradation is as follows:

- Calculate degradation of each process at the action scale
- Sum the scores for the various processes
- **Apply the formula:**
  P = Process Degradation,

$$P = 10 - \sum_{i=1}^{10} D$$

Where:

D = the degradation of each process

While: $10 - D \begin{Bmatrix} 10 \\ 0 \end{Bmatrix}$: 0 = fully degraded, and 10 = not degraded (no stressors present)

- **Data needs**: Current degradation scores from the SNAR framework (Schlenger et al. 2011), and post-project degradation scores, which are calculated by estimating the percent of process that will still be degraded after the construction process removes some amount of stressors.
- **Identified issues/concerns:**
  - Are certain process degradation scores co-dependent?
  - The assumption is that all processes are of equal value within a process unit, because determining primary or dominant processes would largely be subjective.

The raw process degradation scores (D) are on a scale of 0 to 1000 (the sum of each of the ten process-degradation percentages at a given action). Values are divided by 100 to get them on a 0 to 10 scale, and then subtracted from 10 to reflect higher scores for less process degradation. "Future Without Project" condition is represented by existing degradation scores; "With Project" condition is represented by post-action degradation scores, after stressor(s) have been removed from the shoreline through application of management measures. See the accompanying Excel spreadsheet that demonstrates how P is calculated.

4.3.2 Structure

The general PSNERP definition of structure is the complex pattern of shoreforms that make up the Puget Sound shoreline. Nearshore processes have affected the shape and the formation of these shoreforms that are largely the result of significant geologic events that occurred long ago. For the purpose of the ecosystem output model, structural benefits are quantified with indices that measure how actions contribute to restoration of the historic landscape patterns of shoreforms. These indices, taken from the study of landscape ecology, include scarcity, heterogeneity, sinuosity, longshore connectivity, and cross-shore connectivity, which are described in more detail in the following sections. The structure indices do not attempt to predict a quantity of post-project benefits, but rather provide a pre-project score to support decisions on whether to take action at a particular geographic location. The objective for the structure component is to increase the score for actions that address certain characteristics of nearshore structures. The following equation represents the structure component:

S = Structure,

$$S = 2\,(Sc + H + Lc + Cc + Sn)$$

Where:

Sc = scarcity

H = heterogeneity

Lc = longshore connectivity

Cc = cross-shore connectivity

Sn = sinuosity

Structure is on a scale of 0 to 10. For this to occur, because each individual index is on a scale of 0 to 1 and there are five indices, the sum of values for the five indices is multiplied by 2. For a “Future Without Project” score for each action, the indices in this component of the model do not attempt to predict what the condition would be, but rather they remain at zero to provide no credit for no action. For calculation of four of the five indices that comprise the structure score, these do not predict the beneficial outcome of taking an action, but rather provide a credit for taking action for the "With Project" condition, and zero credit for no action, or the "Without Project" condition. The exception is heterogeneity, discussed in more detail below. The team sees this as a way to encourage the right project at the right location, which is one of the Project's restoration strategies.

4.3.2.1 Scarcity

The objective of the scarcity index is to assign higher scores to actions that restore wetland types and shoreforms that were historically rare *and* that are now at a fraction of their historic occurrence. These scarce shoreforms are often of high ecological value. This index addresses PSNERP planning objectives 1 and 2 as it will favor actions that will restore scarce wetland types in river deltas and embayments. If an action takes place in a scarce shoreform or wetland zone (regardless of whether it is creating a lost shoreform or improving one that still exists), it will affect the value for this index. Scarcity index values are calculated and assigned to each shoreform at the sub-basin scale since this index is not very sensitive at the process unit scale; therefore, the scarcity index of a given shoreform/wetland type differs among sub-basins. Table 3 shows example calculations for scarcity of shoreforms in one of the seven sub-basins. If there is no change in count of shoreform type between historic and current conditions, or if shoreform count increased from historic to current conditions, then the [|(C-H)/H|] value is zero or rounded to zero. This increases an action's score for working in a scarce shoreform without decreasing its score for working in a shoreform that is not scarce. The calculation methodology is as follows:

- **Apply the formula:**

  Sc = Scarcity Index

$$\text{Scarcity Index} = [|(C-H)/H|] * [1-(H/T)]$$

Where:

C = current occurrence of a shoreform by count within a basin, or current wetland zone by area within a basin

H = historic occurrence a of shoreform by count within a basin, or historic wetland zone by area within a basin

T = total count of all historic shoreforms within a basin, or total historic wetland area within a basin

While: $Sc \begin{Bmatrix} 1 \\ 0 \end{Bmatrix}$: 0 = low scarcity shoreform, and 1 = highly scarce shoreform

- **Data needs:** Historic and current occurrence of shoreforms by count within a basin and historic and current wetland zone areas within a basin.

The scarcity index is on a scale of 0 to 1. The value of this index is 0 for "Future Without Project" condition as no credit is given if there is no restoration action. For many actions there is more than one shoreform type; in these cases, the highest scarcity index is assigned. Table 3 gives examples of how scarcity is calculated.

Table 3. Example Calculations for the Scarcity Index

SUBBASIN	Shoreform Class	Shoreform _Type	CountOfHistID	CountOfCurrID	(c-h)/h	|(c-h)/h|	h/t	1-(h/t)	Soreform Scarcity Index |(c-h)/h| * [1-(h/t)]
SC	Beaches	BLB	170	163	-0.04	0.04	0.34	0.66	0.03
SC	Beaches	BAB	160	136	-0.15	0.15	0.32	0.68	0.10
SC	Embayments	BE	39	27	-0.31	0.31	0.08	0.92	0.28
SC	Embayments	BL	31	10	-0.68	0.68	0.06	0.94	0.64
SC	Embayments	CLM	41	5	-0.88	0.88	0.08	0.92	0.81
SC	Embayments	OCI	31	24	-0.23	0.23	0.06	0.94	0.21
SC	Rocky Shores	RP	22	21	-0.05	0.05	0.04	0.96	0.04
SC	Rocky Shores	PB	10	10	0	0	0.02	0.98	0.00
	TOTAL without Artifical or Delta		**504**	**396**					
SUBBASIN	**Wetland_Zone**		**Hist_Area**	**Curr_Area**	**(c-h)/h**	**|(c-h)/h|**	**h/t**	**1-(h/t)**	**Wetland Scarcity Index|(c-h)/h| * [1-(h/t)]**
SC	EM	EM	18781324.96	3113631.44	-0.83	0.83	0.22	0.78	0.65
SC	EU	EU	60375948.17	45046381.37	-0.25	0.25	0.72	0.28	0.07
SC	OT	OT	380021.03	60867.17	-0.84	0.84	0.00	1.00	0.84
SC	TF	TF	4614405.34	3402.12	-1.00	1.00	0.05	0.95	0.94
SC	Unclassified								
		TOTAL	**84,151,700**	**48,224,282**					

4.3.2.2 Heterogeneity

The objective of the heterogeneity index is to assign higher scores to actions that contribute to restoring the historic diversity of shoreforms. This index measures the composition and abundance (diversity) of shoreform types within a geographic area. It does not capture arrangement of shoreforms. This index addresses PSNERP planning objectives 1,2, and 3; a variety of shoreforms and wetland types along the shoreline is useful because the diversity and richness of natural shoreforms in Puget Sound will provide many habitat types and niches for nearshore species to occupy. Heterogeneity is calculated by shoreform length at the sub-basin scale since this index is not very sensitive within a process unit. Increases in heterogeneity due to artificial shoreforms are not valued for this index; therefore, artificial shoreforms are left out during calculations. Historic heterogeneity is the target because it is not PSNERP's intent to "create" heterogeneity along the shoreline in areas where there was none historically. Heterogeneity levels that are greater than historic reach an apex score as being equal to historic (no additional value is given to actions that increase heterogeneity levels above that of historic conditions).

The calculation methodology is as follows:

- Determine the natural shoreform lengths of each shoreform type in a sub-basin.
- Use the Shannon Weiner Diversity Index to determine heterogeneity.
- **Apply the formula**:
  H = Heterogeneity,

$$H = -\sum_{i=1}^{Sh} (p_i \ln p_i)$$

Where:

Sh = the number of shoreforms in a sub-basin

p_i = the proportion of each shoreform (by length) in a sub-basin (shoreform length divided by total shoreline length)

<u>For current conditions</u>: current shoreform lengths will be divided by current total shoreline length

<u>For post-action conditions:</u> post-action shoreforms lengths will be divided by 1) the post-action total shoreline length if it is greater than the current total shoreline length; or 2) the current total shoreline length if the post-action total shoreline length is less than the current total shoreline length

While: $H\begin{Bmatrix}1\\0\end{Bmatrix}$: 0 = no heterogeneity (dominated by one shoreform), and 1 = high heterogeneity (many types of shoreforms).

- **Data needs**: Shoreform counts by length in sub-basins and Puget Sound.
- **Identified Issues**: The heterogeneity index value may not change (or may change only slightly) when evaluating post-project conditions of one action because this index is calculated at the sub-basin scale. Use of this index may be more appropriate when evaluating a suite of actions within a geographic unit rather than an individual action.

The ln used in the formula will often result in a negative number, thus the absolute value will be used. Raw heterogeneity values are on a scale of 0 to infinity. Because there is no upper limit of potential heterogeneity, the highest ranking score in the dataset will be used. For the 36 actions proposed the highest score is 2. The values are normalized to a scale of 0 to 1 by multiplying by 0.5. The current heterogeneity index value is used for “Future Without Project” conditions, and the post-action heterogeneity value is used for “With Project” conditions, thereby providing an assessment of how a project increases heterogeneity. Table 4 gives example calculations for heterogeneity.

Table 4. Example Calculations for Heterogeneity

Shoreform Type	Current length	Subtract Action Area existing length	Add restoration length	Post action length	Full Proportion	Ln (Curr proportion)	Prop * Ln(proportion)	Sum (Prop* Ln (proportion)	Absolute value of sum	Final Hetreogeneity: multiply by 0.5 to get on scale of 0-->1
Bluff-Backed Beach	217435.045			217435.045	0.511	-0.671	-0.343	-1.629	1.629	0.815
Barrier Beach	59364.846			59364.846	0.140	-1.969	-0.275			
Delta	35555.420			35555.420	0.084	-2.482	-0.207			
Barrier Estuary	44146.117	1994.724		42151.393	0.099	-2.312	-0.229			
Barrier Lagoon	14827.917			14827.917	0.035	-3.356	-0.117			
Closed Lagoon/Marsh	10333.607			10333.607	0.024	-3.717	-0.090			
Open Coastal Inlet	15834.647	1395.038	3375.436	17815.045	0.042	-3.173	-0.133			
Plunging Rocky Shoreline	6660.090			6660.090	0.016	-4.157	-0.065			
Rocky Platform	18178.052			18178.052	0.043	-3.153	-0.135			
Pocket Beach	2986.759			2986.759	0.007	-4.959	-0.035			
SUM	**425322.498**	**3389.761**	**3375.436**	**425308.173**						

4.3.2.3 Sinuosity

The objective of the sinuosity index is to assign higher scores to actions that are located in process units that were historically sinuous. This index measures how much the shoreline length of a particular process unit deviates from a straight line. Sinuosity quantifies how an action will add to the length and complexity of the Puget Sound shoreline (addressing planning objectives 1,2, and 3), providing a variety of habitat types for nearshore species. The Puget Sound shoreline length has declined approximately 15 percent from historic conditions (Simenstad et al. 2011). Thus, actions in historically more sinuous process units are preferable to those in historically simpler process units. A sinuosity index value is calculated for each process unit in Puget Sound; then values for all process units within the same sub-basin are compared. The calculation methodology is as follows:

- Calculate the sinuosity index value of a process unit using GIS tools
- Assign the sinuosity index value to the actions based on the process unit in which they are located.
- **Apply the formula**

  Sn = Sinuosity

$$Sn = \frac{[(HisL_{PU} / HisSL_{PU}) - (Min\ (HisL/HisSL)_{SB})]}{[Max\ (HisL_{pu}/HisSL_{pu})_{SB} - Min\ (HisL_{pu}/HisSL_{pu})_{SB}]}$$

Where:

$HisL_{PU}$= Historic length of the process unit a candidate action is in
$HisSL_{PU}$ = Historic straight-line length of the process unit a candidate action is in
$Min\ (HisL_{pu}/HisSL_{pu})_{SB}$ = The process unit with the minimum ratio of historic length to straight-line length among PUs in the sub-basin the candidate action is in
$Max\ (HisL_{pu}/HisSL_{pu})_{SB}$ = The process unit with the maximum ratio of historic length to straight-line length among PUs in the sub-basin the candidate action is in

While: $Sn \begin{Bmatrix} 1 \\ 0 \end{Bmatrix}$: 0 = lowest sinuosity PU in a sub-basin

and 1 = highest sinuosity PU in a sub-basin

- **Data needs:** Historic sinuosity of:
  - the process unit a candidate action is in;
  - process unit with the maximum historic sinuosity within the sub-basin the candidate action is in; and
  - process unit with the minimum historic sinuosity within the sub-basin the candidate action is in.

- **Identified Issues**:
  - This index does not include closed marsh lagoons, which are not part of the shoreline, but may be part of a restoration action.

Sinuosity is on a scale of 0 to 1. The value of this index is 0 for "Future Without Project" condition, as no credit is given if there is no restoration action. Table 5 gives example sinuosity calculations.

Table 5. Example Sinuosity Calculation

Candidate Action	SPU	Current Straight Line Length of PU (m)	Historic Shoreline Length (m)	ACTION PU HisLpu/HisSLpu	Sub-basin	PU with Minimum HisLps/	Current Straight Line Length of PU that	Historic Shoreline Length of PU that has the	MINIMUM PU HisLpu/HisSLpu in SUB-BASIN	PU with Maximum HisLps/HisSLpu in Sub-basin	Current Straight Line Length of PU that has the	Historic Shoreline Length of PU that has the	MAXIMUM PU HisLpu/HisSLpu in SUB-BASIN	Numerator	Denominator	Final Sinuosity
Beaconsfield Feeder Bluff Restoration	4015	10,527	12,803	1.22	SC	4034	6,335	6,772	1.07	4031	221	6,133	27.77	0.147	26.700	0.006
Big Beef Causeway Replacement and Estuary Restoration	2088	7,848	14,244	1.81	HC	2038	3,693	3,999	1.08	2010	676	6,641	9.82	0.732	8.740	0.084
Big Quilcene River Delta	2056	3,950	7,091	1.8	HC	2038	3,693	3,999	1.08	2010	676	6,641	9.82	0.712	8.740	0.082
Chambers Bay Estuarine and Riparin Enhancement	3002	6,730	10,459	1.55	SP	3190	1,110	1,271	1.14	3003	202	6,312	31.21	0.409	30.063	0.014
Chuckanut Estuary Restoration	7161	10,142	26,659	2.63	SJ	7157	5,672	6,516	1.15	7053	1,465	41,047	28.02	1.480	26.871	0.055
Deepwater Slough Phase 2	SKG	25,416	224,130	8.82	WH	8055	35,800	42,844	1.2	6037	295	4,472	15.17	7.622	13.974	0.545
Deer Harbor Estuary Restoration	7055	6,668	43,873	6.58	SJ	7157	5,672	6,516	1.15	7053	1,465	41,047	28.02	5.431	26.871	0.202
Deschutes River Estuary Restoration	DES	1,562	18,614	11.92	SP	3190	1,110	1,271	1.14	3003	202	6,312	31.21	10.774	30.063	0.358

4.3.2.4 Longshore Connectivity

The objective of the longshore connectivity index is to assign higher scores to actions adjacent to low degradation process units *and* actions that have degradation values more similar to those of their neighbors, so that longer stretches of low-degradation shoreline result from the action. This index compares the degradation scores of adjacent process units to the degradation score of the process unit in which the action would occur. Actions where adjacent process unit have lower degradation and have degradation scores that are more similar to those of adjacent process units receive a higher value for this index. The Puget Sound shoreline has become fragmented due to anthropogenic stressors, and large areas of intact natural habitat tend to be more ecologically valuable than the sum of individual fragmented segments. The index addresses all four PSNERP objectives; favoring the restoration of shoreforms in continuous stretches (1-3) so they will be more effective at restoring Nearshore processes (4). The calculation methodology is as follows:

- Obtain degradation scores for adjacent process units.
- **Apply the formula:**
  C_{LS} = Longshore Connectivity,

$$C_{LS} = \frac{2(1-D)}{\text{Max}\,\{(1-D_L), (1-D_R)\} + P_{pot}}$$

Where:

D = current degradation score of the process unit the action is located in.

Max $\{(1-D_L), (1-D_R)\}$ = the higher of the degradation scores for the two adjacent (left and right) process units

P_{pot} = the maximum potential degradation score

While: $CLS\begin{Bmatrix}1\\0\end{Bmatrix}$: 0 = degradation score for the action's process unit is highly dissimilar from the score for adjacent process units, and adjacent process units' values are much lower than the degradation score of the action's process unit; 1 = degradation score of the action's process unit is the same as for adjacent process units, and adjacent process units' degradation score (D) is low.

- **Data needs:** Degradation scores for: 1) the process unit in which the action is located, and 2) the process units adjacent to the the action's process unit (process units to the left and right)

Raw degradation scores (D) are on a scale 0-1000. They are scaled from 0-1 by dividing by 1000, and then subtracted from 1 (1-D) to reflect a higher value for less process degradation. The value of this index is 0 for "Future Without Project" conditions because no credit is given if there is no restoration action. Values greater than 1 indicate the process unit the action is in is has a much better score than its neighboring process unit, which is not ideal. To address this issue, any amount greater than 1 will be subtracted from 1 (e.g. a score of 1.2 becomes 0.8). Table 6 gives example longshore connectivity calculations.

Table 6. Example Longshore Connectivity Calculation

Candidate Action	Process Units	Degradation (D) on scale 0 to 1	1-D	FORMULA NUMERATOR 2(1-D)	Max adjacent PU	Max(1-D)adj	Maximum Potential Score for Process (i.e., no degradation)	FORMULA DENOMINATOR	FORMULA CALCULATION (Cls raw score)	FINAL Cls SCORE
Beaconsfield Feeder Bluff Restoration	SPU 4015	0.71	0.290	0.580	4014	0.461	1	1.461	0.397	0.397
Big Beef Causeway Replacement and Estuary Restoration	SPU 2088	0.515	0.485	0.970	2080	0.810	1	1.810	0.536	0.536
Big Quilcene River Delta	SPU 2056	0.085	0.915	1.830	2055	0.965	1	1.965	0.931	0.931
Chambers Bay Estuarine and Riparian Enhancement	SPU 3002	0.757	0.243	0.486	3001	0.273	1	1.273	0.382	0.382
Chuckanut Estuary Restoration	SPU 7161	0.531	0.469	0.938	SAM	0.456	1	1.456	0.644	0.644
Deepwater Slough Phase 2	Delta SKG	0.547	0.453	0.906	6036	1.000	1	2.000	0.453	0.453
Deer Harbor Estuary Restoration	SPU 7055	0.261	0.739	1.478	7056	0.984	1	1.984	0.745	0.745
Deschutes River Estuary Restoration	Delta DES	0.866	0.134	0.268	3042	0.436	1	1.436	0.187	0.187

4.3.2.5 Cross-shore Connectivity

The objective of the cross-shore connectivity index is to assign higher scores to actions adjacent to undeveloped uplands that increase the likelihood of restoration success. This index evaluates an action's proximity to non-degraded areas upland of an action. Therefore, actions located adjacent to relatively pristine uplands receive a higher value for this index. This excludes open water due to the assumption that stressors are not entering the nearshore zone from the waterward side of the action, and that all open water functions the same across all proposed actions and therefore should have no bearing on the connectivity score. The size of the 1000-foot buffer provides more information about the adjacent land than merely using the immediate border area. In this case, "connectivity" is not used to measure access for species; it is intended to show the characteristics of the adjacent uplands that may influence the nearshore. Areas connected to undeveloped lands are more ecologically valuable for restoration than those adjacent to degraded sites; hence this index addresses all 4 PSNERP planning objectives, by ensuring greater success of restoring shoreform types and the Nearshore processes that create and sustain them. The following land use types in the geodatabase are considered undeveloped:

- Emergent Herbaceous Wetlands
- Woody Wetlands
- Herbaceous
- Evergreen Forest
- Deciduous Forest
- Mixed Forest
- Scrub/Shrub
- Open Water
- Perennial Snow/Ice
- Cultivated Crops
- Hay/Pasture
- Barren Land

The calculation methodology is as follows:

- Using GIS tools, estimate land use classified as undeveloped within a 1000-foot border along an action boundary.

- **Apply the formula:**
  C_{cs} = Cross-shore Connectivity,

$$C_{cs} = \frac{\text{undeveloped land area that borders the landward portion of an action}}{\text{total land area that borders the landward portion of an action}}$$

While: $Ccs \begin{Bmatrix} 1 \\ 0 \end{Bmatrix}$: 0 = no lands bordering the action are undeveloped;
and 1 = all lands bordering the action are undeveloped

- **Data needs:** Land use data from the geodatabase.

This index is on a scale of 0 to 1, as it is a percentage thus requires no modification. The value of this index is 0 for "Future Without Project" conditions because no credit is given if there is no restoration action. Table 7 gives example calculations for cross-shore connectivity.

Table 7. Example Cross-shore Connectivity Calculations

Candicate Action	Developed Area in 1000' buffer	Undeveloped Area in 1000' buffer	Total Area	CROSS-SHORE CONNECTIVITY (% Undeveloped land within 1000' buffer of ActionArea)	Final Ccs Scaled 0-1
Deschutes River Estuary	2268436	475767	2744203	17.3370	0.1734
Duckabush Causeway Replacement and Estuary Restoration	488881	1233110	1721991	71.6100	0.7161
Hamma Hamma Causeway Replacement and Estuary Restoration	159801	1125418	1285219	87.5660	0.8757
Nooksack River Estuary	1789948	8585525	10375473	82.7480	0.8275
Big Quilcene River Delta	259506	3476763	3736268	93.0540	0.9305
Milltown Island	223484	1993462	2216946	89.9190	0.8992
McGlinn Island Causeway	60215	606018	666232	90.9620	0.9096

4.3.3 Function

Ecological function is the interaction between organisms and their physical environment, including activities such as nutrient cycling, food web support, and water filtering, which result in the production of ecosystem goods and services. The function component of the ecosystem output equation is represented by F, and is quantified by estimating the impairment of EFG&S along the shoreline using the EFG&S Tier 2 impairment score from the change analysis report (see Simenstad et al. 2011). This index evaluates the expected change (improvement) in the delivery of EFG&S as shoreline stressors are removed. The EFG&S Tier 2 index increases the ecosystem output value for actions with stressor-removal or wetlands-restoration that result in the greatest improvement in Tier 2 EFG&S impairment scores. The EFG&S index has been modified from the version used in the Change Analysis report to omit human-derived goods and services from the calculation, per USACE Headquarters' request and USACE policy for the national ecosystem restoration mission. The modification entails removing scores for the provisioning and cultural categories from the EFG&S impairment calculation (see Table 8). Values for this index are calculated at the action scale. This action addresses PSNERP planning objectives 1-3; river deltas, embayments, and beaches all provide ecosystem goods, functions, and services. The calculation methodology is as follows:

- Use raw EFG&S ranked scores for regulating and supporting categories (second to last row of Table 8).
- Normalize the raw EFG&S scores to scale of 0 to 1 by dividing each rank by 13 (last row of table 8).
- To get impairment scores, multiply the normalized EFG&S scores by the proportion of shoreline with stressors length (compared to total shoreline length) or the proportion of area with stressors (compared to total aquatic area), OR by wetland area loss or gain compared to historic conditions. Current total shoreline length is used for "With" and "Without Project" conditions so that if the post-project shoreline length is reduced, impairment scores do not increase. Length and area are calculated as follows:

  <u>For stressors:</u>

  - "Without Project" conditions = (Current stressor length / current total shoreline length) OR (Current stressor area / current total aquatic area)
  - "With Project" conditions = (Post project stressor length / current total shoreline length) OR (Post project stressor area / post-project total aquatic area)

  <u>For wetland zones:</u>

  - "Without Project" conditions = (Current wetland area - historic wetland area) divided by historic wetland area

- "With Project" conditions = (Post project wetland area - historic wetland area) divided by historic wetland area

- **Apply the formula:**
  F = Tier 2 EFG&S Impairment

$$F = \sum_{i=1}^{13} I$$

Where:

I= Tier 2 EFG&S Impairment scores (modified) for regulating and supporting categories

While: $F\begin{Bmatrix}10\\0\end{Bmatrix}$: 0 = complete impairment and wetland loss, and 10 = no impairment and/or 100 percent wetland gain in all four wetland classes

- **Data needs:** Tier 2 EFG&S ranks for regulating and supporting, total stressor lengths or areas, total shoreline length or aquatic area, or wetland area in the action area pre-action and post-action.

<u>Scaling:</u>

The Tier 2 EFG&S impairment raw scores for an action will usually be negative. The minimum possible raw score for EFG&S impairment is - 7.462, described as follows:

- 100% stressor length and wetland loss * the normalized maximum rank sum for the 9 stressors and 4 wetland categories.

The maximum possible raw score for EFG&S impairment is 3.233, described as follows:

- No stressors present (all 0%) + [100% increase in all 4 wetland types * sum of the normalized rank value of the 4 wetland types (3.233)].

Note that percent stressor length or area and percent wetland loss are reflected as negative numbers, and percent wetland gains are reflected as positive numbers. The absolute value of -7.462 (the lowest potential score), referred to as the positive scaling constant, will be added to all EFG&S raw values to make the scores positive. So an action with an impairment score of -7.462 will be reflected as a 0. To get scores on a 0-10 scale values are multiplied by:

- 0.935, calculated as 10/[3.233 + 7.462 (scaling constant)]

The denominator reflects the maximum EFG&S impairment value possible after the positive scaling constant is applied. See Table 9 for example EFG&S impairment calculations.

Nearshore Science Team rank of stressors and loss of wetlands across rows for a particular EFG&S (1-13)

Table 8. EFG&S Scores with Provisioning and Cultural Categories Removed

		Loss of:				Addition of:								
		Wetlands (marine => tidal freshwater)											Railroads	
	EFG&S	Euryhaline unvegetated (mud/sandflat)	Estuarine mixing	Oligohaline transition	Tidal fresh water	Armoring	Breakwaters & Jetties	Tidal Barriers (levees, dikes)	Overwater Structures	Fill	Marinas	Roads	Active	Abandoned
Regulating	Air quality regulation	4	10	12	13	1	2	6	3	8	7	11	9	5
	Global Climate	6	11	12	13	1	2	10	3	9	8	7	5	4
	Regional and local Climate	7	11	12	13	3	2	5	1	10	8	9	6	4
	Water (quantity)	5	10	11	13	2	3	12	1	8	4	9	7	6
	Water purification and waste treatment- quality	9	11	12	13	2	3	10	1	8	7	6	5	4
	Disease	2	6	11	13	3	4	7	1	8	10	12	9	5
	Pests	3	11	12	13	4	2	10	1	7	8	9	6	5
	Pollination	1	11	12	13	3	4	8	2	10	6	9	7	5
	Natural Hazards	2	11	12	13	8	6	9	1	10	3	7	5	4
Supporting	Nutrient Cycling	12	11	12	13	4	6	9	2	8	7	5	3	1
	Soil Formation	10	13	11	12	9	5	8	1	7	2	6	4	3
	Food Web	9	11	12	13	7	2	5	4	10	8	6	3	1
	Photosynthesis	6	11	13	12	2	4	9	10	7	8	5	3	1
	Sediment Supply	3	5	6	4	13	10	7	2	9	1	11	12	8
RANK SUM		79	143	160	171	62	55	115	33	119	87	112	84	56
RANK		5	11	12	13	4	2	9	1	10	7	8	6	3
Normalized values		0.462	0.836	0.936	1	0.363	0.322	0.673	0.193	0.696	0.509	0.655	0.491	0.327

Scores highlighted in orange are the highest ranking (13) and scores highlighted in blue are the lowest ranking (1).

Table 9. Example calculations for EFG&S Index

Action Name	% Wetland Gain/Loss Euryhaline unvegetated[1]	% Wetland Gain/Loss Estuarine mixing	% Wetland Gain/Loss Oligohaline transition	% Wetland Gain/Loss Tidal freshwater	Armoring Length by Total Shoreline Length	BW/J Length by Total Shoreline Length	Tidal Barrier Length by Total Shoreline Length	OWS Area by Total Aquatic Area	Nearshore Fill Area by Total Aquatic Area	Marina Area by Total Aquatic Area	Road Length by Total Shoreline Length	Railroads-Active Length by Total Shoreline Length	Railroads-Abandoned Length by Total Shoreline Length	SUM across rows (across Action Area)	add 7.462 to get positive numbers	Final F score: scale from 0 to 10 by multiplying by 10/max potential, which = 0.0935
	0.462	0.836	0.936	1.000	0.363	0.322	0.673	0.193	0.696	0.509	0.655	0.491	0.327			
Deschutes River	-0.459	0	0	0	-0.303	0	-0.385	-0.002	-0.020	-0.012	-0.464	0	0	-1.643	5.819	5.440
Duckabush	-0.105	0.251	-0.069	-1	-0.013	0	-0.139	0	-0.007	0	-0.133	0	0	-1.216	6.246	5.840
Hamma Hamma	-0.015	0.230	-0.665	-1	-0.002	0	-0.051	0	0	0	-0.099	0	0	-1.601	5.861	5.479
Nooksack	-0.279	-0.101	-0.903	-0.956	-0.071	-0.027	-0.248	0	0	0	-0.165	0	0	-2.751	4.711	4.405
Big Quilcene-Combine	-0.449	0.836	-0.804	1	0	0	-0.178	0	0	0	-0.002	0	0	0.403	7.865	7.354
Milltown Island	-0.068	-0.394	-0.917	1	0	0	-0.269	0	0	0	0	0	0	-0.648	6.814	6.370
McGlinn Island	-0.348	0.752	-0.379	0	-0.059	-0.079	-0.330	0	-0.009	0	-0.007	0	0	-0.460	7.002	6.546
Deepwater Slough Pha	0	0	-0.923	-0.802	0	0	-0.832	0	0	0	-0.008	0	0	-2.565	4.897	4.578
North Fork Skagit	0	-0.795	-0.936	-0.370	0	0	-0.458	0	0	0	-0.002	0	0	-2.560	4.902	4.583

[1]- Euryhaline wetlands can only be delineated for Delta Process Units because the deeper edge of mud- and sandflats were inconsistent for Shoreline Process Units. Although the geodatabase gives a calculated value for Sediment Process Units, the team was not confident in the estimation from historical data and decided to not include euryhaline unvegetated percent change in any analysis. Therefore a score of zero is given for percent euryhaline unvegetated gain/loss for actions within Sediment Process Units.

Notes:
Step 1: Percent wetland loss/gain OR stressor length/area of shoreline length/total aquatic area
Step 2: Multiply Step 1 by normalized rank sum (row 3) to get impairment value
Step 3: Sum all impairment values for each action
Step 4: Increase by positive scaling constant value, 7.462, to get positive scores
Step 5: Multiply by 0.0935 to get on a scale of 0-10.

4.4 Summary of Equation Components

Table 10 summarizes the ranges and scales of analysis for each of the equation components. Table 11 summarizes which components address each management measure.

Table 10. Summary of Scoring Range and Scales of Analysis for Each Equation Component

Component		Indices	Scoring Range	Scale of Analysis			
				Action Area	Site (process unit)	Sub-basin	Sound-wide
Quantity		Area of Restored Process	0 to maximum size in acres	Area of restored process for an action	Sum of actions in site	Sum of actions in sub-basin	Sum of actions Sound-wide
Quality	Process	Process Degradation	0 to 10	Action scale	Site scale	Overall calculation for all sites with actions	Overall calculation for all sites with actions
Quality	Structure	Scarcity	0 to 1	n/a	Sub-basin scale	Sub-basin scale	Sound-wide scale
		Heterogeneity	0 to 1	n/a	Sub-basin scale	Sub-basin scale	Sound-wide scale
		Sinuosity	0 to 1	n/a	Site scale	Overall calculation for all sites with actions	Overall calculation for all sites with actions
		Longshore Connectivity	0 to 1	n/a	Site scale	Overall calculation for all actions in sub-basin	Overall calculation for all actions Sound-wide
		Cross-shore Connectivity	0 to 1	Action scale	Overall calculation for all actions in site	Overall calculation for all actions in sub-basin	Overall calculation for all actions Sound-wide
	Function	EFG&S Tier 2 Impairment [a]	0 to 10	Action scale	Site scale	Overall calculation for all sites with actions	Overall calculation for all sites with actions

Note:

a A modified EFG&S Impairment calculation is used that removes human-derived goods and services.

Table 11. Summary of which Management Measures are Addressed by Each Model Quality-Component

	PROCESS	STRUCTURE					FUNCTION	Summary: Is MM addressed by at least one index?
Management Measure	Degradation	Scarcity	Hetero-geneity	Sinuosity	Longshore Connectivity	Cross-shore Connectivity	EFG&S Tier 2	
1. Armor Removal or Modification	+	+[a]	+[b]	+	+		+	Yes
2. Beach Nourishment								No
3. Berm or Dike Removal or Modification	+	+[a]	+[b]	+	+		+	Yes
4. Channel Rehabilitation or Creation	+	+[a]	+[b]	+			+	Yes
5. Contaminant Removal								No
6. Debris Removal								No
7. Groin Removal or Modification					+			Yes
8. Habitat Protection and Policy Regulation	+[c]	+[c]					+[c]	Yes
9. Hydraulic Modification		+			+		+	Yes
10. Invasive Species control								No
11. Large Wood Placement								No
12. Overwater Structure Removal or Modification	+	+			+		+	Yes
13. Physical Exclusion								No
14. Pollution Control								No
15. Property Acquisition and Conservation	+[c]	+[c]					+[c]	Yes
16. Public Education and Involvement								No

Management Measure	PROCESS	STRUCTURE					FUNCTION	Summary: Is MM addressed by at least one index?
	Degradation	Scarcity	Hetero-geneity	Sinuosity	Longshore Connectivity	Cross-shore Connectivity	EFG&S Tier 2	
17. Revegetation								No
18. Species Habitat Enhancement								No
19. Reintroduction of Native Animals								No
20. Substrate Modification								No
21. Topography Restoration	+	+[a]	+	+	+		+	Yes

Notes:

a Model includes benefits of the management measure in situations where the management measure contributes to re-creating, restoring, or enhancing a scarce shoreform, or changes the length of shoreforms.

b Model includes benefits of the management measure in situations where the measure adds a shoreform.

c The benefits of habitat protection and property acquisition management measures on degradation, EFG&S Tier 2 impairment (modified), and scarcity index can be quantified. The benefits of these management measures are evaluated assuming that no additional stressors are constructed over the life of the project.

4.5 Benefits over Time

USACE policy requires that the benefits of a project be estimated over its period of analysis (typically 50 years), and on an annual average basis. Therefore, a project's expected benefits at intermittent points over 50 years are averaged to establish an annual average benefit factor. Process-based management measures may take several years before their ecological benefits to accrue. As discussed in section 5.1.1.1, enhancement measures could serve to "jump start" secondary ecological benefits (i.e., the habitat elements that will gradually be restored after processes begin operating again) during the early years of a project's life, while the process-based measures are still evolving and adjusting.

The maximum benefit (or 100 percent of the potential benefit calculated for a given action) is the raw ecosystem output (net) calculated for a particular action. For example, if an action's "With Project" ecosystem output is estimated to be 340 and its "Future Without Project" ecosystem output is estimated at 250, then the raw net ecosystem output is 90, which represents the maximum benefit (or 100 percent of the potential benefit). However, because this benefit of 90 is assumed not to be realized immediately, benefit trajectories were developed to estimate what portion of the calculated benefits will have accrued at any given point during the period of analysis.

Benefit-accrual curves (Figure 2 through Figure 6) to represent the accrual of ecological benefits over a 50-year period were developed with guidance from NST members. These curves are hypothetical trajectories of when benefits will accrue. Equations were developed from these curves (presented in the upper right corner of each figure). The curve-derived equations were used to generate data points, which can be used to calculate the annual average percentage of benefits, expressed as a percentage of the total calculated benefits (see Table 12). These benefit trajectories differ depending on what the primary restorative management measure is at a particular action, and whether additional restorative management measures and/or enhancement management measures are included as part of an action (see Table 13). The final ecosystem output score is the net benefit multiplied by the average annual benefit factor.

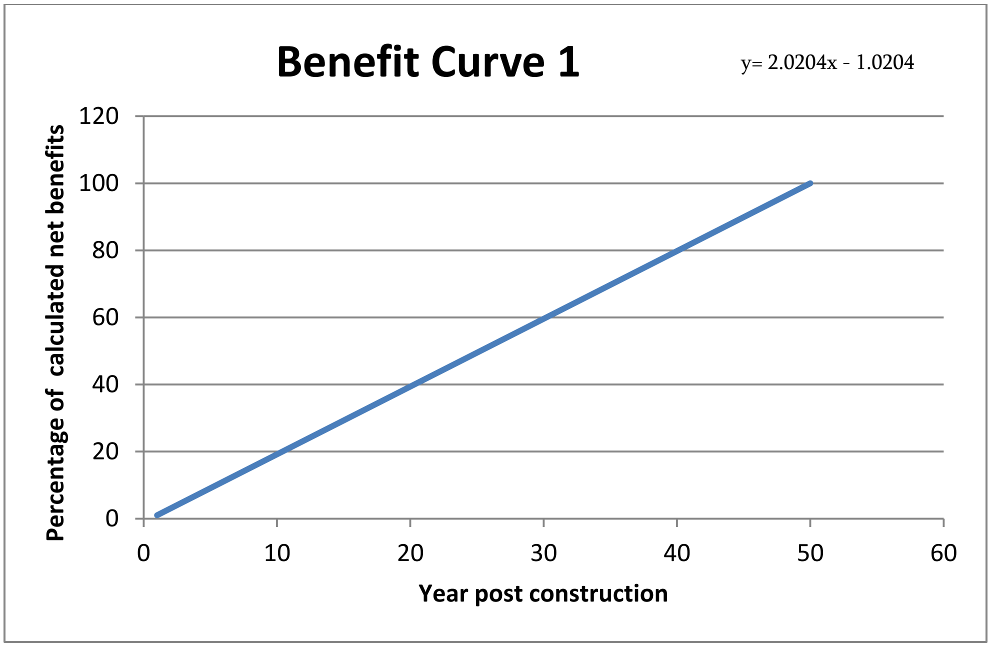

Figure 2.

Linear Benefit Curve: Benefits Accrue Steadily over 50-year Period

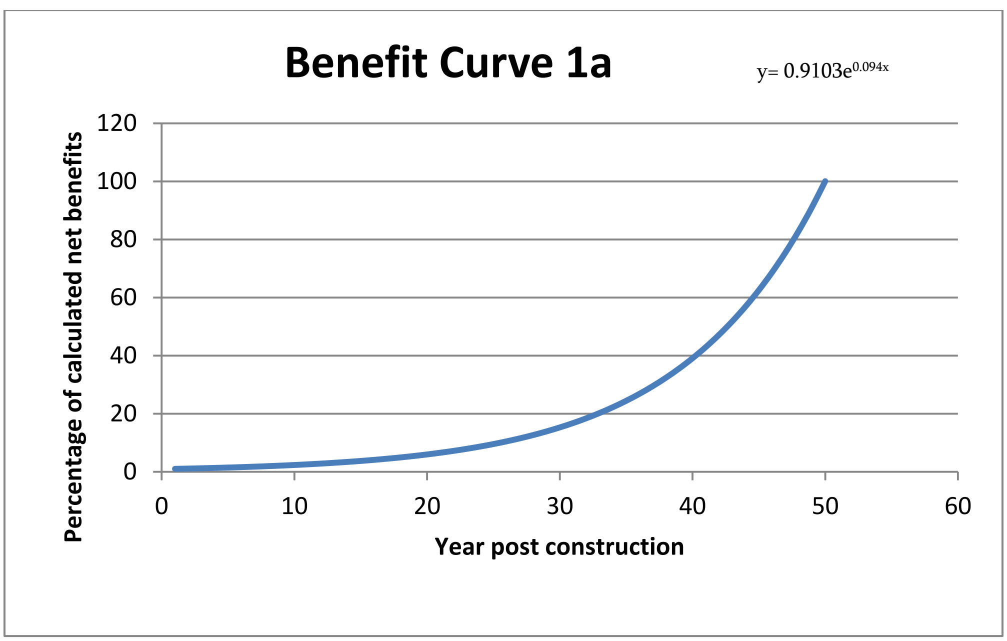

Figure 3.

Exponential Benefit Curve: Initially Benefits Accrue Slowly, Rate Increases toward End of 50-year Period

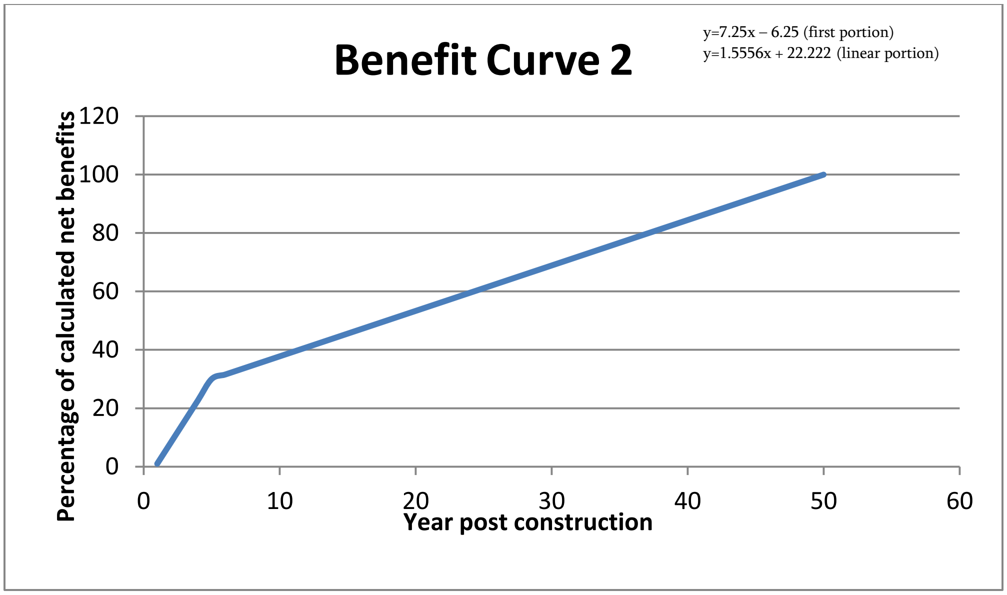

Figure 4.

Step Function Curve: Initial Spike in Benefits, but then Accrual at a Steady Rate over 50-year Period

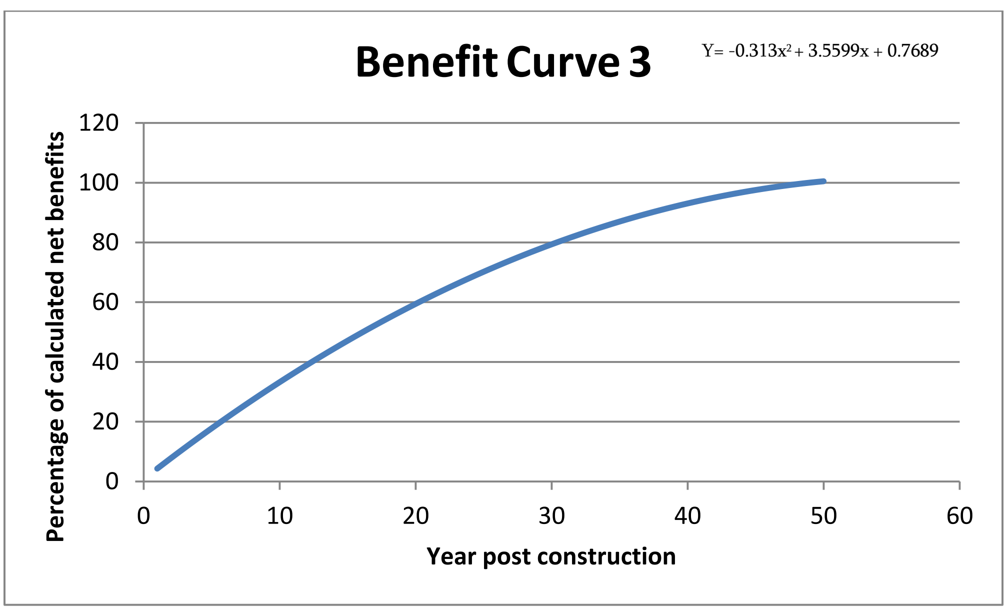

Figure 5.

Polynomial Curve: Benefits Accrue Steadily, but at a Faster Rate than Linear Curve over 50-year Period

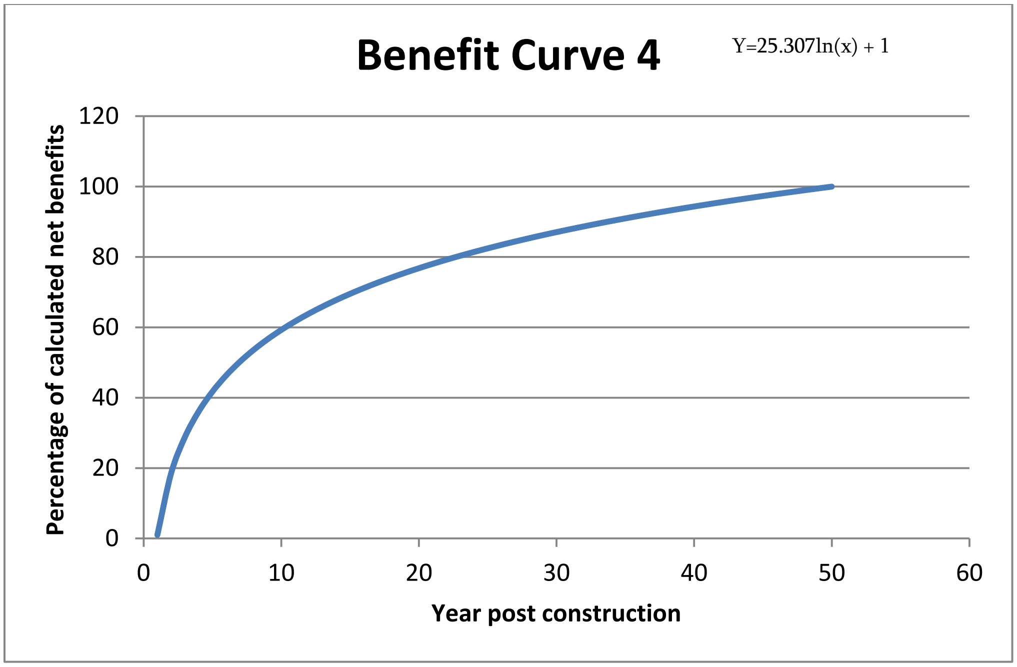

Figure 6.

Log Curve: Benefits Accrue Quickly Initially, then Level Off over 50-year Period

Table 12. Average Annual Benefits Factor for Each Benefits-Accrual Curve Type

Average Annual Benefit to Be Applied to Net Benefits	
Curve 1 – Linear	50%
Curve 1a – Exponential	22%
Curve 2 – Step Function	60%
Curve 3 – Polynomial	65%
Curve 4 – Log	76%

Table 13. Assignments of Benefit-Accrual Curves to Restorative Management Measures

Management Measure	Combination	Curve	Rationale for curve assignment
Armor Removal	Alone	1	Benefits acquired from armor removal will accrue progressively over time, with likely small fluctuations, as sediment from the feeder bluffs nourish the beach to their natural profile
	Plus enhancement measures (any number)	2	Enhancement measures such as beach nourishment and revegetation will increase the accrual rate of armor removal benefits over time
	Plus restorative measures (any number)	3	Restorative management measures such as berm/dike removal and groin removal will initially increase the rate of armor removal benefits over time (more so than enhancement measures)
Berm or Dike Removal or Modification	Full removal alone	3	Benefits acquired from a full berm/dike removal will accrue steadily but at a faster rate than linear since tidal inundation returns instantly and the establishment of low and high salt marsh is steadier.
	Full plus restorative measures (any number)	4	Restorative management measures such as armor removal and groin removal will increase the accrual rate of full berm/dike removal benefits over time (more so than enhancement measures)
	Partial alone	2	Benefits acquired from a partial berm/dike removal will accrue quickly in the first few years as natural tidal inundation is partially restored, but will transition to linear since tidal inundation is still constrained and still has altered tidal velocities.
	Partial plus restorative measures (any number)	3	Restorative management measures such as armor removal and groin removal will increase the accrual rate of partial berm/dike removal benefits over time (initially more so than enhancement measures)
Distributary Channel Creation or Rehabilitation	Alone	3	Benefits of distributary channel creation or rehabilitation will accrue quickly initially, due to immediate water flow; however, benefit accrual will transition to a linear pattern as tidal influence and sediment transport lead to channel migration and evolution.
	Plus enhancement measures (any number)	3	Enhancement management measures such as substrate modification and/or large woody debris placement will increase the accrual of benefits rate for distributary channel creation or rehabilitation as they mimic the results of natural processes.
	Plus restorative measures (any number)	4	Restorative management measures such as berm/dike removal and or armor removal will increase the accrual of benefits rate more quickly as natural processes return. The rate will decrease as channel migration and evolution slow.
Groin Removal	Alone	1	Benefits acquired from groin removal will accrue steadily over time as sediment from littoral drift nourishes the beach downdrift of the groin to its natural profile
	Plus enhancement measures (any number)	2	Enhancement measure such as beach nourishment and revegetation will increase the rate of groin removal benefits over time
	Plus restorative measures (any number)	3	Restorative management measures such as a berm/dike removal and armor removal will increase the accrual rate of groin removal benefits over time

Management Measure	Combination	Curve	Rationale for curve assignment
Hydraulic Modification	Alone	2	Benefits acquired from hydraulic modification will accrue quickly in the first few years as tidal inundation and/or freshwater input is less constricted, but will transition to a steadier accrual as the establishment of marsh communities occurs.
	Plus enhancement measures (any number)	3	Enhancement measures such as placement of large woody debris and revegetation will increase the accrual rate of hydraulic modification benefits over time
	Plus restorative measures (any number)	4	Restorative management measures such as berm/dike removal and armor removal will increase the accrual rate of groin removal benefits over time (more so than enhancement measures)
Overwater Structure	Removal	4	Benefits of removing an overwater structure will accrue quickly as submerged vegetation reestablishes and fish migration along the shoreline improves. The benefit accrual rate will decrease as communities become established
	Modification	1	Benefits of modification of an overwater structure will accrue steadily as submerged vegetation and benthic communities partially reestablish, although shoreline migration may still be inhibited.
	Modification plus enhancement	2	Enhancement measures such as revegetation will increase the accrual rate of overwater structure modification initially, but after a few years, it will change to a linear accrual as benthic communities readjust toward equilibrium.
Topography Restoration	Alone	1	Benefits of topography restoration will initially accrue slowly as sediment shifts around and tidal inundation forms more localized topography. The accrual rate will increase more rapidly once vegetation and benthic communities are established.
	Plus enhancement measures (any number)	3	Enhancement management measures such as revegetation and substrate modification will increase the benefits accrual rate for topography restoration to a linear pattern.
	Plus restorative measures (any number)	2	Restorative management measures such as berm/dike removal and armor removal will increase the benefits accrual rate more instantly in the first few years and then transition to a linear pattern.

The average annual benefits factor from Table 12 is assigned to each of the 36 proposed actions under PSNERP evaluation based on the curve that applies (detailed in Table 13). These percentages are applied to the net ecological benefits value, adjusting it to give an estimated ecosystem output value over a 50-year period. Actual timing of accrual of benefits could vary by different geographical areas, shoreform types, or process restored; however, these five benefits-accrual curves are applied generally to management measures regardless of geography, shoreform, or process. This adjusted value will be used in the benefits portion of the CE/ICA. The equation below details the process for applying these percentages:

Final EO = (EO "With Project" conditions – EO "Without Project" conditions)
* (Average annual benefit percentage)

The resulting time-weighted net benefits value for each proposed action is a score for that action that has no units associated with it. Changing the type or number of management measures applied at any given restoration action will change the resulting ecosystem output benefit score.

5 MODEL DEVELOPMENT WORK

The process of model design began with specifying the problem the model is needed to solve, and listing the objectives for the model. The purpose of the ecosystem output model is to support the CE/ICA that will comply with Corps planning policy, and to provide a decision-making tool for comparing potential restoration actions against each other.

5.1 Ecosystem Output Model Development Process

The Corps assembled an interdisciplinary team from within the broad group of PSNERP program participants; this team established the method for estimating ecosystem outputs likely to result from applying management measures at proposed restoration actions.

5.1.1 Development of Equation Components

The team selected and developed the individual metrics and indices that are the components of the quality portion of the ecosystem output model. These components represent process, structure, and function. As discussed in this report, an ecosystem output equation was developed for use in the model.

5.1.1.1 Consideration of Ancillary Benefits as an Equation Component

The team considered including Ancillary Benefits to account for the 13 management measures that would not directly restore process (Table 2). The term "ancillary" refers to management measures that do not directly restore nearshore processes, but rather enhance or "jump start" them by providing temporary on-site structure (a.k.a. habitat) while processes and functions recover enough to build natural structure on their own. Because these measures do not directly restore process, the ecosystem output component indices described above do not capture the ecological value of ancillary benefits. Therefore, the team chose initially developed an additional component that would quantify the benefits of these management measures, to evaluate how a particular management measure provides ancillary benefits to process and function. Through discussion at a workshop, the team decided that three variables would be included to characterize ancillary benefits. The three variables are 1) the proportion of processes benefiting from the enhancement management measure; 2) the proportion of EFG&S attributes affected; and 3) the area of the enhancement management measure. Eventually, the team decided to leave this component out of the equation because it did not influence the overall scores.

5.1.1.2 The Ecosystem Output Equation as First Proposed

The initial version of the equation used a different weighting of the components (as well as including the later-omitted ancillary benefits component), but was later revised so that the quality portion had more influence. The first equation proposed was the following:

$$EO = A * \left[P + S\ (.25 \text{ and } .10) + F\ (.25 \text{ and } .10) + E\ (.05 \text{ and } .02)\right]$$

Where: EO = ecosystem output

A = area of restored process

P = process degradation score, scale of 0 to 10

S = summation of landscape indices, scale of 0 to 10

F = EFG&S Tier 2 impairment, scale of 0 to 10

E = Ancillary benefits

In this equation, when ran on a suite of action, the area component accounted for 90 to 95% of the total score; in the final equation, area accounts for 75%.

5.1.1.3 The Quality Component of the Ecosystem Output Equation

The order of functions of the ecosystem output equation shows that process, structure, and function—which together make up the equation's quality component—are additive, that they combine to indicate the character of the physical location; therefore, the quantity component is multiplied by the quality component.

5.1.2 Testing of the Initial Ecosystem Output Equation

The team assessed the ecosystem output equation based on its ability to represent the measurement of ecological benefits for actions and alternatives. To test the equation, the model was applied to a selection of potential restoration actions, including actions from the PSNERP database that had previously been screened out or other comparable USACE projects. The results were analyzed to determine whether any of the parameters had a disproportionate effect on the EO scores.

This testing provided some insight on the sensitivity of the components' weighting. As a result, the "Ancillary Measures" index was removed from the equation when it was determined to have no meaningful effect on the scores.

The equation was tested further by calculating benefits for the suite of 36 actions that went forward to 10% design. A preliminary analysis of the calculated benefits indicated that the Area component was driving the outcome with excessive influence. Therefore, the final equation as presented in section 4.1 has been proposed to resolve this issue.

The final equation, as proposed in section 4.1 was tested to identify unwanted biases.

The team has used the final ecosystem output model to calculate ecological benefits of the final list of proposed actions that align with PSNERP strategies.

5.2 Ecosystem Output Model Documentation

This report documents the development process of the ecosystem output model for inclusion in the draft feasibility report, and provides the basis for peer review and model-approval analysis.

5.3 NST Review

The NST's involvement in the development of the ecosystem output model has been essential for a scientifically defensible product that is compatible with USACE policy. The following aspects of the ecosystem output model development process have had assistance, oversight, and review by the NST:

- Table 1, which specifies the area of restored process associated with each management measure
- Development and calculations of the individual components and their indices
- The order of functions for the complex of variable factors that comprise the ecosystem output equation
- How to estimate accrual of ecological benefits over time (discussed in Section 4.5)

5.4 Recognizing Uncertainty in Model Development

There are uncertainties that are inherent in the development of an ecosystem output model.

5.4.1 Sensitivity Analysis

The most common analytical technique used to explore the significance of uncertainty is a sensitivity analysis, which can be either qualitative or quantitative. Some project outcomes and decisions are sensitive to minor changes in assumptions and input values. Thorough, rational decision-making requires an explicit examination of such sensitivities.

Because the quantity component, expressed as area, seems to have a significant effect on the total output score, the team conducted a Spearman's Rank Correlation Test to determine whether the quality component of the equation affects the total output score. The test results show that the rank order of total scores is significantly different from the rank order of area among the 72 projects evaluated; therefore, the quality component does indeed have a significant contribution to the ranking of project by total score.

5.4.2 Area

The area of restored process, as defined in Table 1, can provide a useful way to incorporate an uncertainty element in the approximation of ecological benefits. The area of restored process could incorporate and present the uncertainty by creating polygons on a cost-effectiveness/incremental cost analysis frontier graph rather than points. Doing this provides some latitude to make decisions based on best professional judgment rather than adhering strictly to a single score (a point on the graph) that may seem more precise but which already incorporates some uncertainty. Assumptions could be made to characterize how far beyond the action area the benefit from the action reaches. The larger the distance, the more uncertainty there is.

5.5 Finalizing the Ecosystem Output Model

The team has finalized an ecosystem output equation. Results calculated with this equation reasonably estimate ecological benefits that make progress toward the planning objectives through a variety of restoration actions. The final benefits score has been calculated for proposed actions that will undergo CE/ICA. The team met in August 2011 for a final check on how the components are weighted and for discussion of any remaining issues.

5.6 USACE Model Certification/Approval Process

Any models used for planning and decision making in USACE projects must be either certified for repeated use or approved for one-time (i.e., single project) use by USACE

Headquarters (HQ). For certification, the Ecosystem Planning Center of Expertise (ECO-PCX) assembles a team to review the model, and the team may recommend that USACE HQ certify the model. Team members include experts from the Institute for Water resources (IWR), Hydraulic Engineering Center (HEC), Engineer Research and Development Center (ERDC), and other USACE field experts as appropriate (USACE 2007). Once ECO-PCX and USACE HQ certify a model, then any USACE project can use that model for planning and development. Model certification can take a significant amount of time and money to accomplish. For approval of this model for use in a single project, the model will be reviewed by an independent party and recommended for approval to USACE HQ. Approval for PSNERP-only use is the preferred route for this ecosystem output model.

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APPENDIX A
ECOSYSTEM OUTPUT EQUATION ALGORITHM

The following is the primary equation of the ecosystem output model including the formulas for its component metrics and indices:

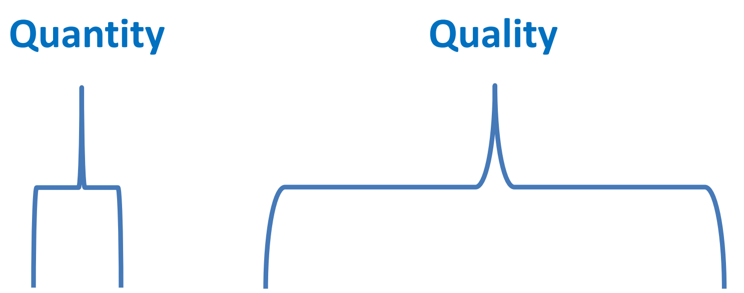
Equation:

Ecosystem Output = Quantity * Quality

Where:

Quantity = Area, in acres

Quality = Combined process, structure, and function components



$$EO = A * [(P^2 + S + F)/\text{maximum possible score}]$$

Where:

EO = ecosystem output

A = area of restored process

P = process degradation score, scale of 0-10

S = summation of landscape indices, scale of 0-10

F = EFG&S Tier 2 impairment (modified), scale of 0-10

Max possible score: 120

Components:

Process

P = Process

Where

Process = Process Degradation

Structure

S = Structure

Where:

$$S = 2\,(Sc + H + Lc + Cc + Sn)$$

Such that:

Sc = scarcity

H = heterogeneity

Lc = longshore connectivity

Cc = cross-shore connectivity

Sn = sinuosity

Function

F = Function

Where:

Function= Tier 2 EFG&S Impairment (modified)

Indices:

Process Index

P = Process Degradation,

$$\text{Processs degradation} = \sum_{i=1}^{10}(1 - D)$$

Where:

D = the degradation of each process

While: $1 - D \begin{Bmatrix} 10 \\ 0 \end{Bmatrix}$: 0 = fully degraded, and 10 = not degraded

Structure Indices

Sc = Scarcity Index

Scarcity Index = [|(C-H)/H|] * [1-(H/T)]

Where:

C = current occurrence of a shoreform by count within a basin, current wetland zone by area within a basin

H = historic occurrence a of shoreform by count within a basin, historic wetland zone by area within a basin

T = total count of all historic shoreforms within a basin, total wetland historic wetland area within a basin

While: $\text{Sc}\begin{Bmatrix} 1 \\ 0 \end{Bmatrix}$: 0 = low scarcity shoreform, and 1 = highly scarce shoreform

H = Heterogeneity

$\text{Heterogeneity} = -\sum_{i=1}^{Sh}(pi \ln pi)$

Where:

Sh = the number of shoreforms in a sub-basin

p_i = the proportion of each shoreform (by length) in a sub-basin (shoreform length/ total shoreline length).

While: $H\begin{Bmatrix}1\\0\end{Bmatrix}$: 0 =no heterogeneity, and 1 = high heterogeneity

Sn= Sinuosity

$$\text{Sinuosity} = \frac{[(HisL_{PU} / HisSL_{PU}) - (\text{Min}\ (HisL/HisSL)_{SB})]}{[\text{Max}\ (HisL_{pu}/HisSL_{pu})_{SB} - \text{Min}\ (HisL_{pu}/HisSL_{pu})_{SB}]}$$

Where:

$HisL_{PU}$= Historic length of the process unit a candidate action is in

$HisSL_{PU}$ = Historic straight-line length of the process unit a candidate action is in

Min $(HisL_{pu}/HisSL_{pu})_{SB}$ = The process unit with the minimum ratio of historic length to shortest length among PUs in the sub-basin the candidate action is in

Max $(HisL_{pu}/HisSL_{pu})_{SB}$ = The process unit with the maximum ratio of historic length to shortest length among PUs in the sub-basin the candidate action is in

While: $Sn\begin{Bmatrix}1\\0\end{Bmatrix}$: 0 = lowest sinuosity PU in a sub-basin and 1 = highest sinuosity PU in a sub-basin

C_{LS} = Longshore Connectivity

$$\text{Longshore connectivity} = \frac{2(1-D)}{\text{Max}\ \{(1-D_L), (1-D_R)\} + P_{pot}}$$

Where:

(1-D) = degradation score of the process unit the action is located in

Max $\{(1-D_L), (1-D_R)\}$ = the higher of the adjacent (left and right) process units' degradation scores

P_{pot} = the maximum potential degradation score

While: $\text{CLS}\begin{Bmatrix}1\\0\end{Bmatrix}$: 0 = degradation score of action highly dissimilar from adjacent process units, and adjacent process units values are much lower than the degradation score of the process unit the action is in;

1 = degradation scores same as adjacent process units and adjacent process units degradation score is high.

C_{cs} = Cross-shore Connectivity

Cross-shore connectivity = the percent of undeveloped land that borders the landward portion of an action boundary

While: $\text{Ccs}\begin{Bmatrix}1\\0\end{Bmatrix}$: 0 = no undeveloped lands bordering the action; and 1 = all undeveloped lands border the action

Function Index

F = Function

$$\text{Function} = \sum_{j=1}^{13}(1 - \text{I})$$

Where:

I= Tier 2 EFG&S Impairment (modified) scores for supporting and regulating categories

While: $1 - \text{I}\begin{Bmatrix}10\\0\end{Bmatrix}$: 0 = impaired , and 10 = not impaired

APPENDIX B
EXAMPLE CALCULATION BASED ON 10% CONCEPTUAL DESIGN

The equation, as presented in Appendix A, was tested on 36 actions that were advanced to 10% design. One project, Big Beef Creek Estuary Restoration, is presented here to show how the Puget Sound Nearshore Ecosystem Output Model can be applied to a proposed restoration action to calculate the average annual benefits.

- Action type: barrier estuary restoration

- Primary management measure: berm/dike removal

- Benefit accrual curve: #4 (65%)

- Area of restored process: 29.59 acres

Figure B-1. Big Beef Creek proposed estuary restoration area

Table 14 Calculations of model components for Big Beef Creek estuary restoration

.

	With Project	Without Project
Area	29.59	29.59
Process	7.66	3.63
Structure	5.05	1.62
Scarcity	0.22	0
Sinuosity	0.08	0
Heterogeneity	0.81	0.81
Longshore Connectivity	0.54	0
Cross-shore Connectivity	0.87	0
Function	7.16	6.67

With Project Conditions Benefit Calculation $A*(P^2+S+F)/120$

$29.59 * (7.66^2 + 5.05 + 7.16)/120 = 17.48$

Without Project Conditions Benefit Calculation

$29.59 * (3.63^2 + 1.62 + 6.67)/120 = 5.29$

Net Benefit (With – Without)

17.48 – 5.29 = 12.19

Time-weighting applied to calculate Average Annual Benefit

12.19 * 0.65 = **7.92**

APPENDIX C
EO CALCULATIONS FOR 36 ACTIONS EVALUATED FOR CE/ICA

Table 15. EO Scores for Sites Evaluated for CE/ICA

Site	Alternative	Average Annual Net Benefits[2]
Beaconsfield Feeder Bluff	Full	2.18
Beaconsfield Feeder Bluff	Partial	1.32
Big Beef Creek Estuary	Full	7.89
Big Quilcene River Delta	Partial	0.56
Chambers Bay Estuary	Full	8.47
Chambers Bay Estuary	Partial	3.44
Deepwater Slough	Partial	90.21
Deer Harbor Estuary	Full	4.76
Deschutes River Estuary	Full	107.30
Deschutes River Estuary	Partial	90.39
Duckabush Estuary	Full	12.74
Duckabush Estuary	Partial	12.20
Dugualla Bay	Partial	162.58
Everett Marshland	Full	349.31
Everett Marshland	Partial	167.82
Hamma Hamma Estuary	Partial	10.59
Harper Estuary	Full	1.67
Harper Estuary	Partial	1.05
Lilliwaup Estuary	Partial	1.08
Livingston Bay	Full	41.59
Livingston Bay	Partial	40.47
Milltown Island	Partial	63.97
Nooksack River Estuary	Partial	166.32
North Fork Skagit Levee River Delta	Full	53.69
Point Whitney Lagoon	Full	1.95
Sequalitchew Creek Estuary	Full	0.91
Smith Island	Partial	191.51
Snow Creek and Salmon Creek Estuary	Partial	6.83
Spencer Island	Partial	136.01
Tahuya Estuary	Full	7.58
Telegraph Slough	Full	253.94
Telegraph Slough	Partial	16.30
Twin Rivers	Partial	0.15
Washington Harbor	Partial	0.58
WDNR Budd Inlet Beach	Full	1.14

[2] Intermediate scores, as shown for the example in appendix B, for all 36 of these sites are contained within an excel workbook. They are available upon request.