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# Eelgrass Habitat Suitability Maps and Recommendations

**June 2014**

AB Borde  
RM Thom  
KE Buenau  
SA Zimmerman



Prepared for the U.S. Department of Energy  
under Contract DE-AC05-76RL01830

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Pacific Northwest National Laboratory  
Richland, Washington 99352



## Preface

This technical report is Deliverable 5.3 of Task 5 of the project, “20% More Eelgrass (*Zostera marina*) by 2020: Restoration Site Selection and Testing, and Resolving Regulatory and Social Barriers to Conservation and Recovery.” It represents work performed by the Pacific Northwest National Laboratory’s (PNNL’s) Marine Sciences Laboratory (MSL) for the Washington State Department of Natural Resources (DNR), with financial support by the Puget Sound Marine and Nearshore Protection and Restoration Grant Program.









## **Acknowledgments**

This project has been funded wholly or in part by the United States Environmental Protection Agency (EPA) under assistance agreement PC 00J29801 to Washington Department of Fish and Wildlife. The contents of this document do not necessarily reflect the views and policies of the Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

We thank our colleagues at PNNL: Chaeli Judd for initial data collection efforts, Heida Diefenderfer for assisting with the report, and Susan Ennor for editing and formatting assistance. We also thank Greg Williams (NOAA Fisheries), Keith Marco (Lower Columbia Estuary Partnership), and Suzanne Shull (Padilla Bay National Estuarine Research Reserve) for their thoughtful reviews.



## Acronyms and Abbreviations

DNR	Washington State Department of Natural Resources
EBM	Eelgrass Biomass Model Productivity Potential
ECI	Environmental Condition Index
ERP	Eelgrass Restoration Potential
GIS	Geographic Information System
ha	hectares
m	meter(s)
MLLW	Mean Lower Low Water
MSL	Mean Sea Level
NAVD88	North American Vertical Datum of 1988
NOAA	National Oceanic and Atmospheric Administration
PNNL	Pacific Northwest National Laboratory
PSNERP	Puget Sound Nearshore Ecosystem Restoration Project
SVMP	Submerged Vegetation Monitoring Program



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# 1.0 Introduction

Globally the seagrass *Zostera marina* L. (eelgrass) is an important nursery and foraging habitat for numerous species of fish and birds (Hemminga and Duarte 2000). There are an estimated 23,000 hectares of eelgrass now present in Puget Sound (Gaeckle et al. 2011). Although not easily quantified, substantial losses are believed to have occurred in Puget Sound due to physical changes in shorelines, periodic physical disturbances, and degradation in water quality (Thom and Hallum 1990, Thom 1995, Dowty et al. 2010, Thom et al. 2011). The Puget Sound Partnership, a public program to restore Puget Sound's ecosystem health (<http://www.psp.wa.gov/>), adopted a 2020 eelgrass recovery target to address these losses.

## 1.1 Objectives

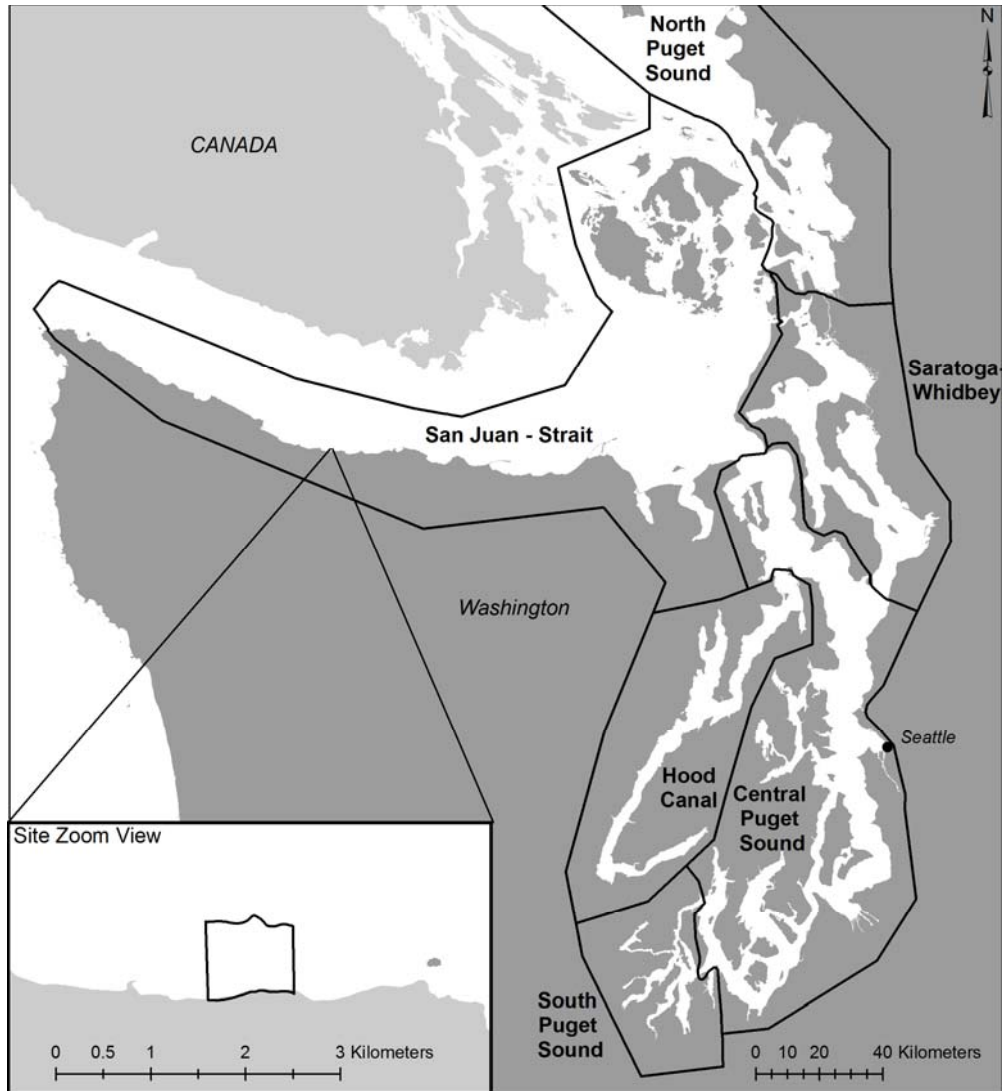
The overall objective of the project, “20% More Eelgrass (*Zostera marina*) by 2020: Restoration Site Selection and Testing, and Resolving Regulatory and Social Barriers to Conservation and Recovery” was to identify areas within Puget Sound where eelgrass restoration could be accomplished to meet the recovery goal of a 20% increase in eelgrass by 2020. The primary work objective of Task 5 was to produce eelgrass habitat suitability maps based on the results of modeling, coordination work, and experimental plantings, which indicate where eelgrass is likely to be restorable under current environmental conditions. To that end we have developed a geospatial database that contains multiple data sources used for this analysis.

## 1.2 Contents of this Report

This report includes the methods used to develop the Eelgrass Restoration Site Prioritization geodatabase, and specific information regarding the structure and attributes of the geodatabase, as supporting documentation for the ArcGIS product that accompanies it. In addition, we provide summary results on eelgrass habitat suitability and the restoration site prioritization.

# 2.0 Geospatial Database Structure

The fundamental spatial unit in this geodatabase is the “assessment unit” or “site” produced by the DNR's Submerged Vegetation Monitoring Program (SVMP). Under this program, the Puget Sound area is divided into six regions containing 2,781 assessment units (**Figure 1**). These units are further divided into fringe and flats sites, with each fringe site approximately 1,000 m in length and the flats of varying size. The geodatabase delivered with this memorandum consists of a shapefile containing attributes for all factors in the eelgrass habitat suitability index for restoration prioritization (Table 1 and Appendix A). In addition, six shapefiles produced by intersecting source data with DNR's assessment units are included (see Table 1 and Appendix A).



**Figure 1.** Puget Sound with the SVMP regions and example of a SVMP fringe site assessment unit.



**Table 1.** The contents of the Eelgrass Restoration Site Prioritization Geodatabase. All data files are products of the intersection of the source feature classes with the SVMP site assessment units (DNR 2014). See Appendix A for details of each feature class.

Name	Type	Source	Description
Sites_eg_restoration_potential	Polygon feature class	This project	All attributes that were used to determine eelgrass restoration site potential (ERP).
Sites_eg_biomass_model_output <sup>(a)</sup>	Polygon feature class	This project	Potential biomass value (EBM) applied to depth polygons ( $a_p$ ). Biomass values range: 0 – 2.3 mol C/m <sup>2</sup> . 2 mol C/m <sup>2</sup> = model start value. Values >2 indicate growth in 1-year model run.
Sites_current_eg_presence <sup>(b)</sup>	Polygon feature class	PNNL 2014 (25 sites) DNR 2014 (390 sites)	Binary presence or absence. Presence if observations from either source occurred in the assessment unit.
Sites_shorezone_ln	Line feature class	ShoreZone Inventory, DNR 2001	Binary presence or absence. Presence if any of the line occurred in the assessment unit <u>and</u> site was not sampled by either of the above sources (DNR 2014 and PNNL 2014). Substrate: Proportion of each assessment unit (length) with suitable substrate (P).
Sites_shorezone_eg_presence_poly	Polygon feature class	ShoreZone Inventory, DNR 2001	Binary presence or absence of eelgrass. Presence if the polygon occurred in the assessment unit and the site was not sampled by either of the above sources.
Sites_historical_eg_presence	Polygon feature class	Thom and Hallum 1990 digitized by Jeremy Davies, NOAA	Binary presence or absence. Presence if historical eelgrass polygon was present in the assessment unit.
Sites_overwater_structures	Polygon feature class	PSNERP <sup>(c)</sup> 2012	Proportion of assessment unit (area) with overwater structure.
Sites_shoreline_armoring	Line feature class	PSNERP 2012	Proportion of assessment unit (length) armored.

(a) See Task 2 technical report for eelgrass biomass model source data (Buenau et al., 2013).

(b) See Task 4 technical report for PNNL field reconnaissance survey detail (Vavrinec et al., 2014).

(c) PSNERP = Puget Sound Nearshore Ecosystem Restoration Project.

## 3.0 Database Development and Results

### 3.1 Potential Eelgrass Biomass Model Results

The methods by which the potential eelgrass biomass production was modeled are detailed in a previous technical report delivered to DNR (Task 2, Buenau et al. 2014). The model included eelgrass growth rates and best-available data on the environmental conditions for growth requirements—light, salinity, temperature, and depth. The model results were reported in 1-m water-surface elevation bins at nearshore “nodes” or points, relative to the North American Vertical Datum of 1988 (NAVD88). The node data were spatially joined to a mosaicked bathymetry data set, thereby applying the model values for each depth bin to the appropriate bathymetry polygons in the nearshore, also in NAVD88. Data sources for the mosaicked bathymetry data set are identified in Table 2.

**Table 2.** Data sources for the mosaicked bathymetry data set.

Source	Datum	Horizontal Resolution	Spatial Extent
Finlayson 2000	NGVD29	30 m	San Juan Islands and Strait of Juan de Fuca
Finlayson 2005	NAVD88	9.1 m	North Puget Sound, Central Puget Sound, Hood Canal

To exclude areas that were above the upper depth limit of eelgrass we developed a spatial data set of the upper depth limits based on data from the SVMP between 2000 and 2013 (Washington DNR SVMP, data request, 16 June 2014; Table 3). These upper elevations were relative to mean lower low water (MLLW), so we used the National Oceanic and Atmospheric Administration’s (NOAA’s) VDatum tool, version 3.3 (Parker et al. 2003; NOAA 2010) to convert them to NAVD88. The bathymetry polygons occurring above the upper depth limit elevations were excluded and the remaining bathymetry polygons with the associated eelgrass biomass values were intersected with the SVMP sites. Maps of the eelgrass model results are provided in a Supplement to this report titled Eelgrass Potential Restoration Site Maps.

NOTE: The two bathymetry data sets described above have an area of missing data in north Puget Sound and the eastern San Juan Islands. As a result, 204 site assessment units do not have model results associated with them. Most of the sites are narrow fringes, and collectively they have an estimated area of eelgrass of approximately 2,000 ha.<sup>1</sup> A portion of Padilla Bay and Fidalgo Bay, which have larger areas of flats, were also excluded from the bathymetry data set; in these areas, an estimated 5,600 ha and 500 ha of eelgrass area are not included in data set, respectively. Based on the SVMP data, the areas where bathymetry data are missing are primarily areas where eelgrass currently exists and therefore do not affect the analysis for determining restoration potential.

<sup>1</sup> Based on the DNR SVMP monitoring data in the area of missing data. The mean eelgrass area at sampled sites was approximately 7 ha per site. This value was multiplied times the number of sites that were missing data.

**Table 3.** Upper depth limits for eelgrass in Puget Sound estimated from the 2000–2013 SVMP data.

Region	Fringe Sites Average Upper Elevation (m, MLLW)	Standard Error	Flats Sites Average Upper Elevation (m, MLLW)	Standard Error
Central Puget Sound (cps)	-0.08	0.03	0.06	0.09
Hood Canal (hdc)	-0.16	0.05	0.27	0.34
North Puget Sound (nps)	-0.37	0.05	0.42	0.18
Strait of Juan de Fuca and San Juan Islands (sjs)	-0.97	0.08	-0.39	0.08
Saratoga-Whidbey (swh)	0.01	0.04	0.26	0.06
South Puget Sound (sps)	-1.0 <sup>(a)</sup>	NA <sup>(b)</sup>	-1.0 <sup>(a)</sup>	NA

(a) This elevation was based on observations made in the south Puget Sound area by DNR and PNNL since no data existed from the SVMP for this area.  
(b) NA = not available.

### 3.2 Substrate

The ShoreZone Inventory was conducted by the DNR between 1994 and 2000 along the entire Washington saltwater shoreline and documents the biota and physical structure along 0.8 km linear units (DNR 2001). Data from the ShoreZone Inventory were collected along the shoreline but also perpendicular to the shoreline in order from supratidal to intertidal to subtidal (three zones). Because eelgrass only occurs in the intertidal and subtidal zones we excluded the zones that were not appropriate for eelgrass and targeted only those where eelgrass could grow. To that end, we excluded the supratidal and included the intertidal and subtidal areas. For the intertidal zone we included only the lowest zone if the zone was subdivided. We defined appropriate substrate for eelgrass as sand or fines. Although small gravel can support eelgrass, the ShoreZone gravel category included very coarse material and was therefore not included. Eelgrass can tolerate a wide range of substrate conditions (Thom et al. 2001), but to maximize the likelihood of restoration success we selected only those substrates where eelgrass survival would be optimized. Following these procedures, we culled the data until each ShoreZone unit had a binary classification of appropriate substrate or not. We intersected this with the assessment unit polygons, and calculated the proportion of good substrate length for each assessment unit as the final attribute for that assessment unit. Therefore, the resolution of the data is only as fine as the ShoreZone unit scale (~800 m). The proportion of appropriate substrate for the assessment unit is based on division of the substrate line over length of the site assessment unit.

### 3.3 Current Eelgrass Presence and Absence

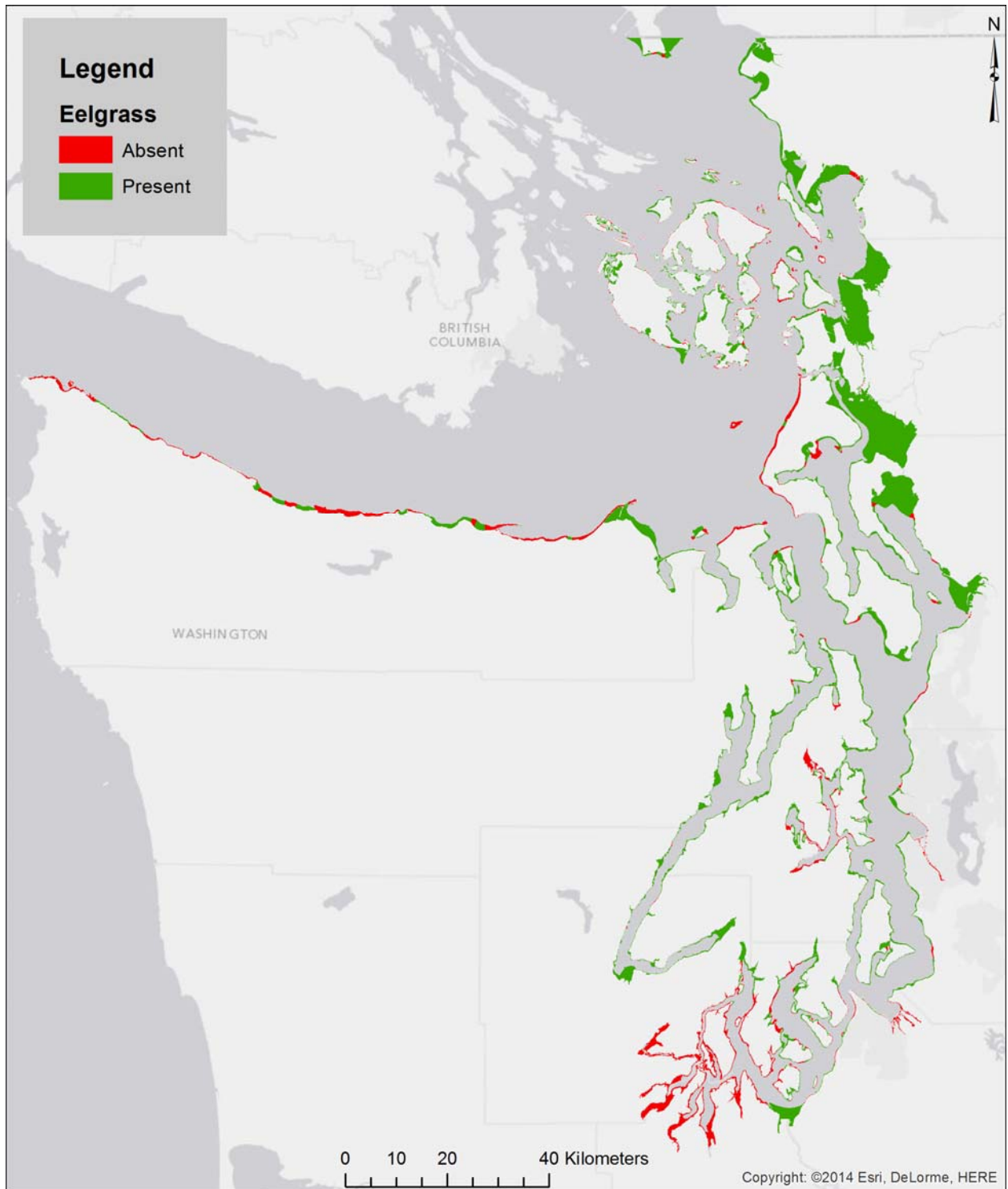
Four sources of data were integrated to estimate the current location of eelgrass in Puget Sound, including 1) the ShoreZone Inventory data, which represent all locations (as patchy, continuous or absent), which we combined as eelgrass presence/absence; 2) the DNR SVMP data for 390 sites, which we also summarized as eelgrass presence/absence; 3) PNNL 2013 reconnaissance survey data from Task 4 of this project for 25 sites, which were collected as eelgrass presence/absence; and 4) PNNL stakeholder survey results from Task 3 of this project for 182 sites, which identified areas of eelgrass loss (absence). Combinatory rules were developed in consideration of the fact that in order from greatest to least areal coverage, these data sets are ranked as ShoreZone, SVMP, and PNNL reconnaissance data; while in order from most recent to oldest, they are ranked as PNNL, SVMP, and ShoreZone (Table 1). On that basis, the rules for final attribute data for each assessment unit were that 1) the SVMP data took precedence over ShoreZone data, and 2) the PNNL reconnaissance survey data—which were exclusively focused on sites not sampled by SVMP—took precedence over the ShoreZone data. The current location of eelgrass based on these three data sources is shown in Figure 2. The final attribute was binary presence or absence (presence if eelgrass was observed in the assessment unit).

The PNNL stakeholder survey conducted as part of Task 3 of this project identified 30 areas that formerly supported eelgrass but where respondents noted that eelgrass had declined or was absent in recent years (Figure 3). These 30 areas correspond to 182 site assessment units. Of the 182 sites, 124 had eelgrass previously reported as being present by the DNR SVMP or the DNR ShoreZone Inventory (none of the sites were included in the PNNL reconnaissance survey) and 58 had eelgrass identified as being absent by at least one of the three data sources. The Task 3 results were used as the final step in identifying areas where eelgrass was absent and that were potential areas for restoration. In total, from all four data sources, 1,117 site assessment units were identified as having eelgrass absent (out of 2,781 total). These sites were further evaluated against the eelgrass model and substrate results to identify the best potential areas for restoration.

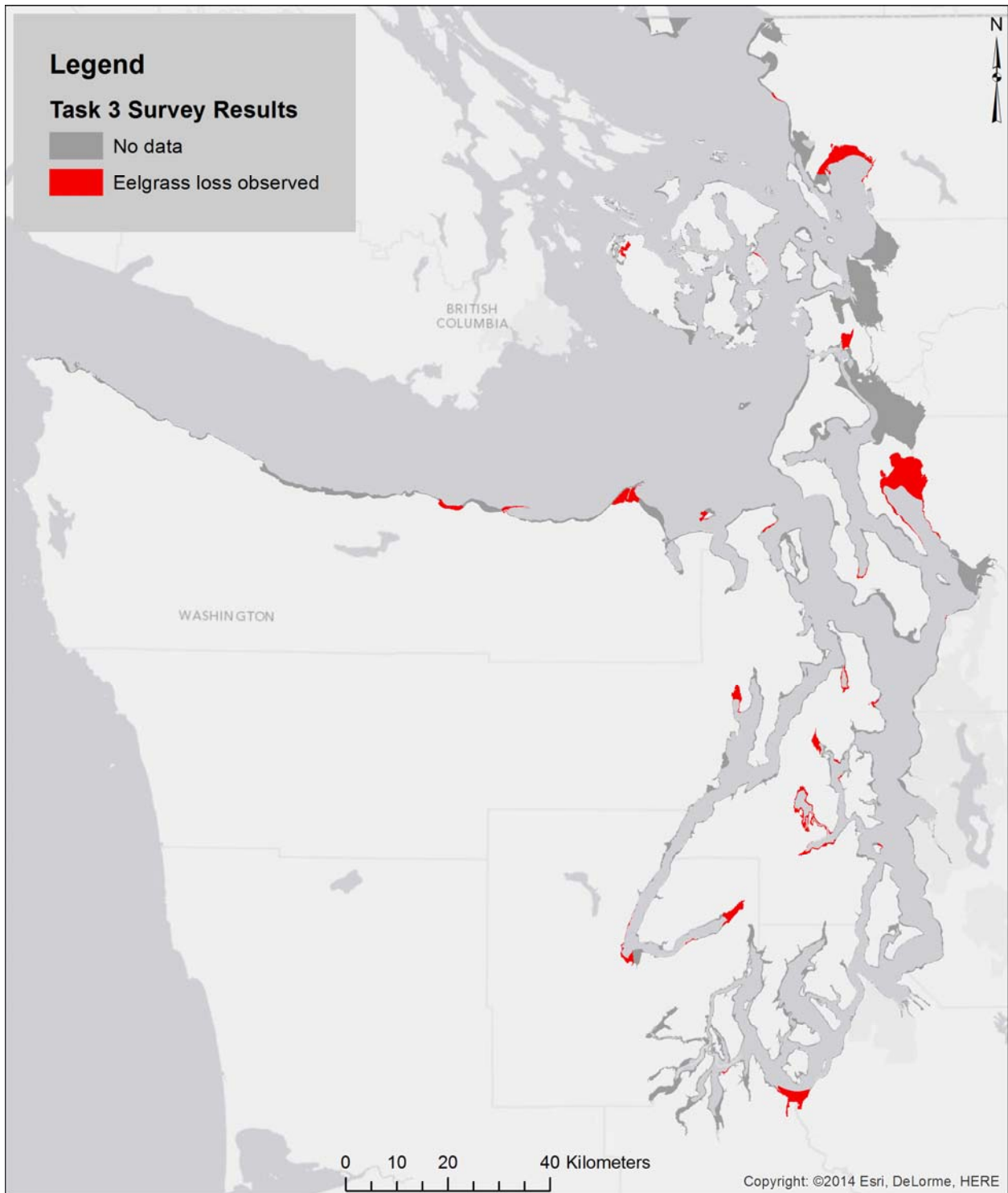
### 3.4 Historical Eelgrass Presence

Historical eelgrass presence was based on the U.S. Coast Survey (later called the U.S. Coast & Geodetic Survey, beginning in 1878) topographic sheets or “T-sheets” (available at: <http://riverhistory.ess.washington.edu/tsheets.php>). The Puget Sound nearshore was mapped in the late 1800’s. Thom and Hallum (1990) evaluated eelgrass noted on T-Sheets, but the entire Puget Sound shoreline was not included in this analysis. These results were digitized more recently by Jeremy Davies of NOAA (2009; from Thom and Hallum 1990). The final attribute in our data set was binary presence or absence (presence if any area of the historical eelgrass polygon occurred in the assessment unit).

A total of 1,061 sites had eelgrass present historically. Currently, 1,664 sites have been identified as having eelgrass present; however, these results should not be directly compared due to differences in the spatial resolution of current assessments versus the lower resolution of eelgrass data mapped historically and the fact that not all areas were surveyed historically. Based on this somewhat limited data we evaluated the sites that have changed from the historical condition. One hundred seventy-four sites with eelgrass present historically are reported as having no eelgrass present currently. Of these, 7 had no bathymetry data, but the remaining 167 sites comprise 4,974 ha of area where eelgrass loss has been observed.



**Figure 2.** Current distribution of eelgrass based on the SVMP data (DNR 2014), PNNL reconnaissance data, and ShoreZone Inventory (DNR 2001).



**Figure 3.** Survey results from Task 3 indicating areas of recent eelgrass loss.

### 3.5 Overwater Structures

Overwater structures can affect the distribution of eelgrass by fragmenting suitable nearshore habitats. The structures limit light, modify the substrate, and can change the bathymetry of the area surrounding them. We collected data on the extent of overwater structures to determine if there was a relationship to eelgrass restoration potential (ERP). The source data were obtained from the Puget Sound Nearshore Ecosystem Restoration Project (PSNERP) and intersected with the assessment unit boundaries. The final attribute calculated was the proportion of the assessment unit area covered by overwater structures.

### 3.6 Shoreline Armoring

The effects of shoreline armoring on eelgrass are not well documented, but substrate effects due to increased erosion and reduced sediment supply from feeder bluffs due to armoring likely have an effect on eelgrass distribution. To evaluate the restoration potential relative to shoreline armoring, we collected data on the extent of shoreline armoring. The source data were obtained from the PSNERP as a line file that delineated where armoring occurred and intersected with the assessment unit boundaries. We calculated the length per assessment unit and the proportion of armored shoreline to total shoreline by assessment unit. As a quality control, we compared the total length (sum of lines within assessment unit polygons) to the total length (original data), and found that it was ~5% less. We determined that this occurred because of concave shoreline segments that are outside of the assessment units but armored. We experimentally changed the XY tolerance for the intersection but found there was a limit to expanding it before data quality was compromised. The final XY tolerance was 3 m and the final difference between the sum of the current lines and the original total line length was 5%.

### 3.7 Eelgrass Restoration Potential

To provide an integrative metric that describes the restoration potential of an assessment unit for eelgrass, based on the environmental conditions, we calculated an area-weighted value of

$$ERP = EBM * P * A \quad (1)$$

where

- ERP = eelgrass restoration potential,
- EBM = biomass productivity potential,
- P = proportion of the assessment unit with appropriate substrate, and
- A = area of the appropriate bathymetry polygons within the assessment unit.

The EBM was calculated for each assessment unit by taking into account that within each assessment unit multiple depth polygons occur at which the eelgrass biomass was predicted. The depth polygons vary in size; therefore, EBM was calculated as a weighted value that corrects for polygon area (Eq. 2).

$$EBM = \frac{\sum_1^n (value * a_p)}{\sum_1^n a_p} \quad (2)$$

where  $n$  is the number of polygons with a predicted biomass (*value*) and  $a_p$  is the area of the depth polygon.

The environmental condition index (ECI) is an intermediate metric that accounts for the proportion of suitable substrate at a site, but not the total area:

$$ECI = EBM * P \quad (3)$$

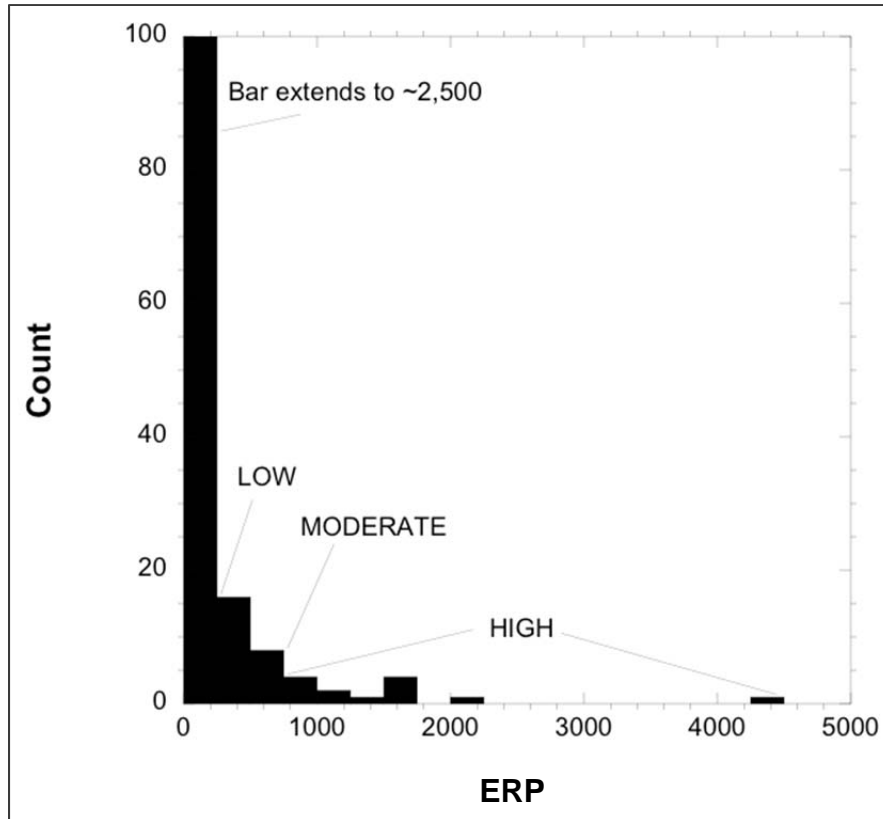
We evaluated the potential for eelgrass restoration, using the attributes just described, for 2,630 assessment units. (Of the 2,781 assessment units, we removed 151 sites that had no bathymetry data.) We calculated EBM, ECI, and ERP scores for each site. These scores allow us to account for physical conditions not including substrate (EBM), including substrate (ECI), and weighted by area (ERP).

## 4.0 Restoration Site Prioritization Methods and Results

The general approach for highlighting sites for eelgrass restoration focused on considering attributes that provided information about the probability of successful restoration. The critical elements of this assessment included 1) if eelgrass presently occurred at the site or not, 2) if eelgrass had been documented in historical records as having occurred at the site, 3) if the model predictions indicated that the site was highly suitable, 4) if ancillary stressors (i.e., we had comprehensive data sets on overwater structures and armoring) were an issue, and 5) if local planners and other environmental professionals knew of specific opportunities for restoration within the regions with which they were very familiar. Because the goal for the Puget Sound Partnership is to restore on the order of 4,000 ha by 2020, we felt that larger areas for restoration should be given priority. Because of inherent uncertainties associated with suitability predictions, we classified our suitability rankings into three categories of restoration potential: low (EBM or ECI <1.9), moderate (1.9 <EBM or ECI <2.1), and high (EBM or ECI >2.1), based on natural breaks in the data and other considerations. An ECI score of 0 is possible if no suitable substrate exists in the assessment unit. Classification into three bins acknowledges that there is uncertainty (i.e., natural, sampling, and model variances) yet provides guidance for prioritizing restoration efforts.

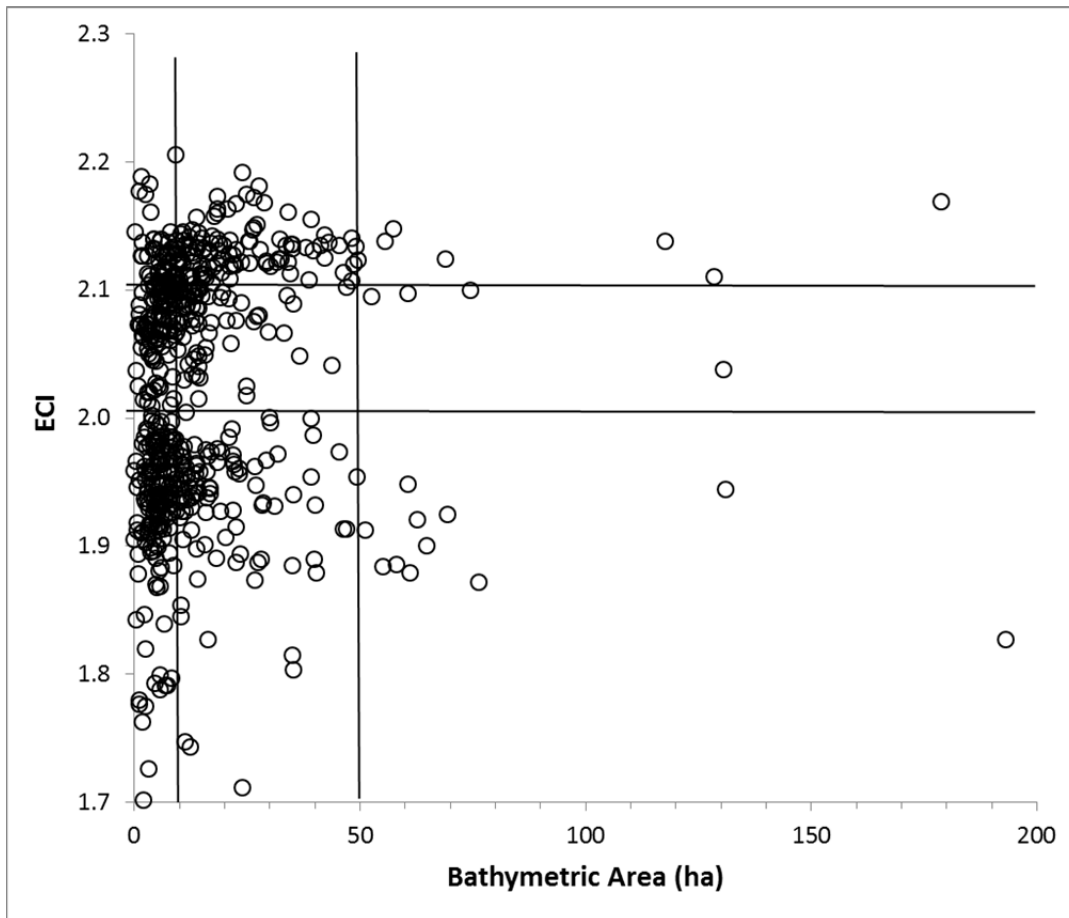
We focused our analysis on the ERP, which is a metric developed from the eelgrass biomass model results, the ECI, and the bathymetry area. This provides an index that incorporates the quality and size of the site. A histogram plot of all of the data from the 2,630 sites is shown in Figure 4. The figure shows that the vast majority (~85%) of the sites have a low (<200) ERP score. This means about 2,487 of the sites are small and have a relative low EBM score. The remaining 43 sites have a moderate to high score.





**Figure 4.** Count of scored sites, indicating low, moderate, and high ERP scores for the potential to support eelgrass restoration.

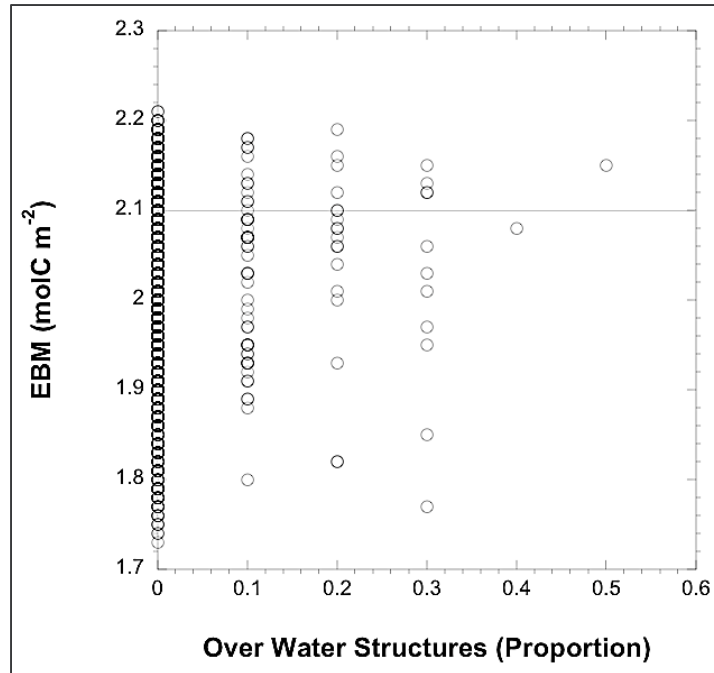
Next we evaluated the ECI scores against bathymetry area in order to locate sites that were large and showed high ECI scores. To do this we only used the 1,117 sites where eelgrass was not currently present based on the three data sources described above (DNR 2001, 2014; PNNL 2014 - this study; of these 1,045 sites have bathymetry data). We divided the sites into small (<10 ha), medium (10–50 ha), and large (>50 ha) (as shown in Figure 5; only a few sites were greater than 150 ha). To restore 4,000 ha would require eighty 50-ha sites and forty 100-ha sites. A total of 11 sites with areas >50 ha in area had ECI scores of 2.0 or greater. There are hundreds sites with ECI scores of 2.0 or more that are 10–50 ha in area. Based on our analysis, it appears that there are enough moderate to large sites with relatively high ECI scores to meet this goal.



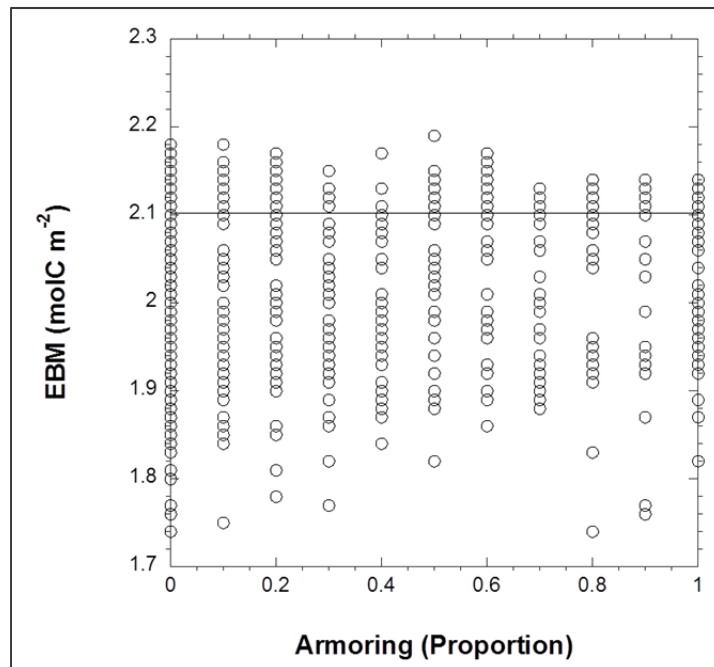
**Figure 5.** Plot of ECI versus bathymetry area for 1,117 sites containing no present eelgrass. The 11 sites greater than 50 ha and with ECI scores of  $>2.0$  represent larger sites with a relatively high potential for restoration. One site 314 ha in area with an ECI scores  $\geq 2.0$  is not shown. Six sites  $>200$  ha that are not shown had ECI scores  $<2.0$ .

Overwater structures have well-documented direct negative effect on eelgrass (Fresh et al. 1995; Thom et al. 2001). To evaluate the potential for eelgrass restoration relative to overwater structures, we plotted the proportion of the site with overwater structures against the EBM for the sites where eelgrass is currently documented as being absent. Figure 6 shows 17 sites that are suitable for eelgrass (i.e., EBM  $\geq 2.1$ ), however, there is currently no eelgrass present and overwater structures account for 10–50% of the available area. This suggests that abatement of shading associated with these structures may facilitate eelgrass restoration efforts. Field studies are required to further evaluate these sites.

Research on the effects of shoreline armoring on eelgrass is recent and ongoing (e.g., Heerhartz 2013). The data set we obtained for this project, although interesting, is subject to significant shortcomings in terms of linking armoring directly with eelgrass. The relationship between EBM and the proportion of shoreline armored at sites where no eelgrass presently exists indicates that many of these sites, even with more than 50% of the shoreline with armoring, may be suitable for eelgrass (Figure 7). Intertidal populations may be more affected by armoring, but we did not separate the data in this analysis. Based on the data set, there is a very weak correlation between proportions of armored shoreline and overwater structures ( $r^2 = 0.053$ ). As with overwater structures and other potential stressors, site-specific studies are required to further evaluate the potential for these sites to support eelgrass.

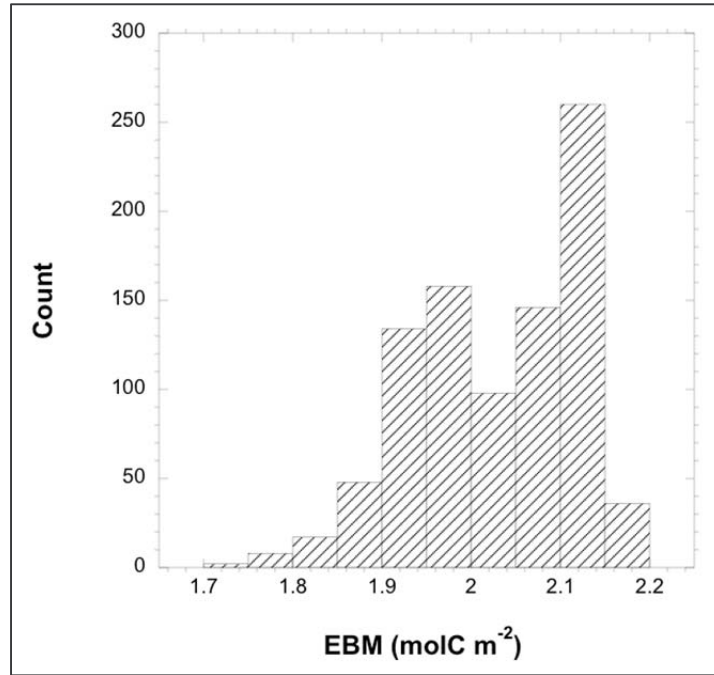


**Figure 6.** Plot of EBM for areas with no present eelgrass versus proportion of the site with overwater structures. Sites with EBM scores  $>2.0$  represent potentially good sites for restoration, especially if the overwater structures are removed or improved to reduce shading. Sites with the best growth conditions are indicated with scores  $>2.1$ .



**Figure 7.** Plot of EBM for areas with no present eelgrass versus proportion of the site with shoreline armoring. Sites with EBM scores  $>2.0$  represent potentially good sites for restoration, especially if the armoring is removed or the armoring is presently not disturbing potential eelgrass areas. Sites with the best growth conditions are indicated with scores  $>2.1$ .

A histogram of EBM for sites with no present eelgrass indicates that on the order 500 sites show moderate to high potential (i.e., EBM scores  $\geq 2.0$ ) to support eelgrass (Figure 8).



**Figure 8.** Histogram of EBM values for sites without present eelgrass.

#### 4.1 Summary Spatial Statistics

The area suitable for eelgrass varies by region (Table 4). A total of 22,924 ha showed moderate to high ECI scores. The Saratoga-Whidbey region contained the greatest proportion of this area (27.1%) followed by North Sound (25.0%), Central Sound (21.3%), South Sound (10.7%), and Hood Canal (8.5%), and the San Juans and Strait (7.4%).

**Table 4.** Summary statistics by Puget Sound region for the total bathymetric area covered within each category range of the ECI score (not suitable = 0, low = <1.9; moderate = 1.9-2.1; high = >2.1).

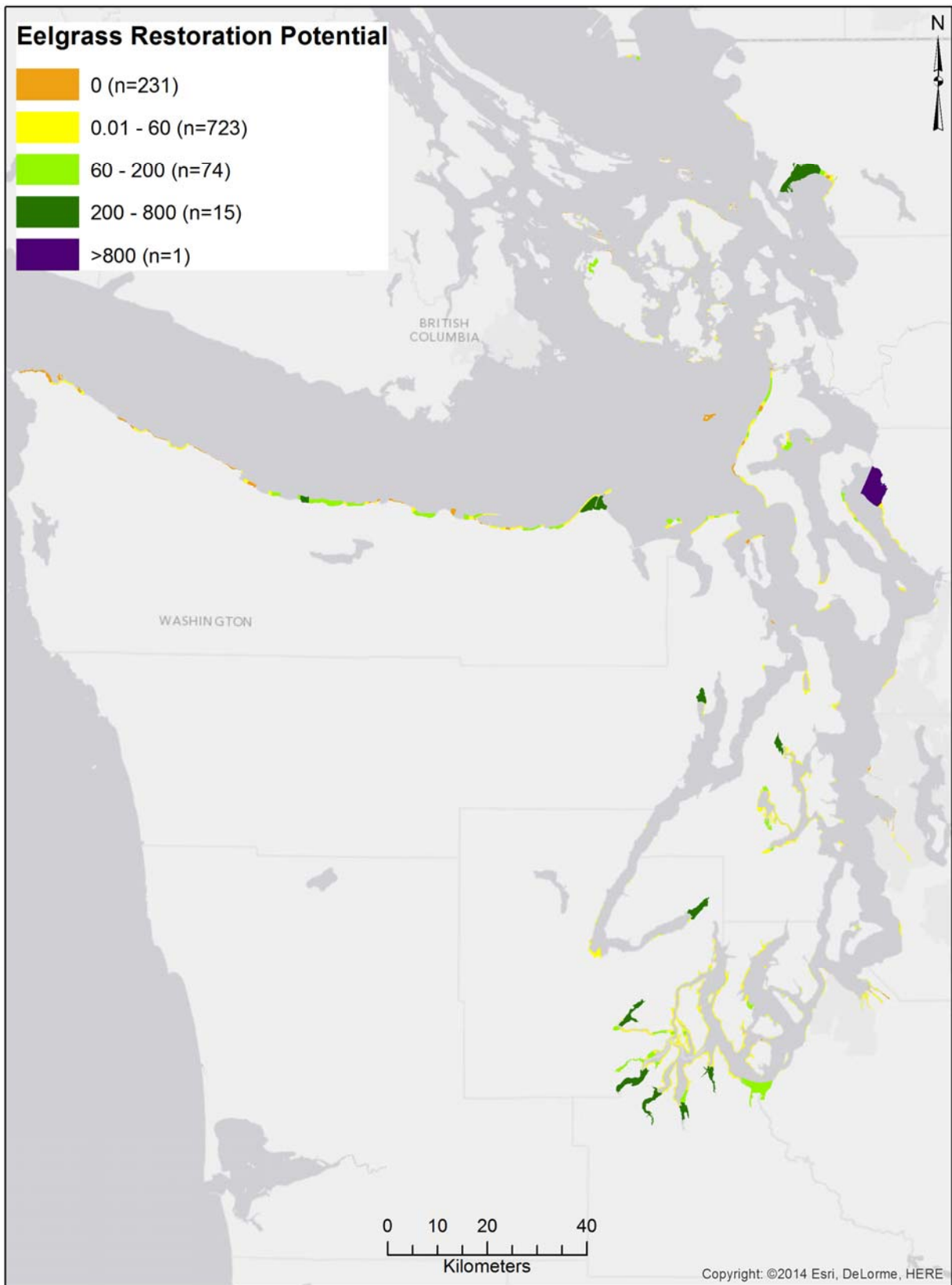
Region	Environmental Condition Index			
	0	<1.9	1.9 – 2.1	>2.1
Central (cps)	210	1,936	4,888	3,519
Hood Canal (hdc)	150	782	1,939	0
North (nps)	145	1,977	5,728	1,832
San Juan Islands and Strait (sjs)	1,443	3,940	1,701	4,511
South (sps)	0	567	2,458	0
Saratoga-Whidbey (swh)	6	9,381	6,210	0

In Table 5 we summarize statistics for all 2,630 sites in Puget Sound. We divided the summary into four bins of unsuitable, low, moderate, and high ECI scores and then calculated the area associated with each of those bins within each of 11 attributes. Within each ECI bin we provide an estimate of how much area currently has eelgrass, historically had eelgrass, how much may be restored based on survey results from local planners and scientists, and the total area that currently does not have eelgrass based on all available data sources (DNR 2001, DNR 2014; PNNL 2014) including the survey results. These data suggest that large areas could be restored relatively easily if appropriate actions are taken. For example, 3,000 ha (i.e., 75% of the 4,000 ha goal) presently without eelgrass has a high ECI value of >2.1. Historical eelgrass was present over 5,593 ha within this bin. The stakeholder survey indicated that 1,275 ha appeared to be suitable for eelgrass within the high ECI bin if some actions are taken to reduce stressors. Overall, an estimated 4,031 ha have potential for eelgrass restoration based on the high ECI and the estimated area where eelgrass is currently absent.

**Table 5.** Summary statistics for the total bathymetric area covered within each category range of ECI score (not suitable = 0, low = <1.9; moderate = 1.9-2.1; high = >2.1). The historical eelgrass area in this table was calculated at the site scale (i.e., if any eelgrass was observed in the site historically then the entire potential eelgrass area was included in the calculation) and is likely an overestimation, however, not all areas were covered by historical surveys. The survey potential is based on evaluations from the stakeholder survey for specific areas. Not all areas in Puget Sound were represented in the survey results. Total absent eelgrass is the total bathymetric area where eelgrass absence was noted using all data sources including the stakeholder survey.

	Environmental Condition Index			
	0	<1.9	1.9-2.1	>2.1
0.1 – 9.9 ha	600	1,957	3,843	1,224
10.0 – 50.0 ha	1,178	4,186	8,048	4,591
>50 ha	176	12,440	11,034	4,046
Total Hectares	1,954	18,583	22,925	9,861
Present Eelgrass (ha)	672	16,024	18,523	6,862
Absent Eelgrass (ha)	1,282	2,560	4,401	3,000
Historical Eelgrass (ha)	352	13,125	15,464	5,593
Overwater Structures (average percent of area)	1.6	1.1	0.3	0.3
Armored Shoreline (average percent of shoreline)	14	23	31	32
Survey Potential (ha)	48	3,199	3,280	1,275
Total Absent Eelgrass (ha)	1,287	5,250	7,380	4,031

A map of ERP (Figure 9) illustrates the location of potential restoration sites where eelgrass was not currently present, including the areas identified in the stakeholder survey; those with highest potential are shown in purple followed by green. The bathymetric area associated with the sites with an EPR >200 6,390 ha, with all sites greater than 100 ha each. This is could be an overestimate because the areas identified in the stakeholder survey were sometimes general areas that may not be completely devoid of eelgrass. Of the 74 sites with an ERP between 60 and 200, 36 sites (all between 27 and 75 ha) have an ECI greater than 2.1 and comprise an additional 1,478 ha of potential restoration area.



**Figure 9.** Eelgrass restoration potential (ERP = Environmental Condition x Area). Areas shown are those that currently have no eelgrass present.

## 4.2 Discussion and Recommendations

Based on the modeling and substrate data, we estimate that an area of about 4,031 ha at appropriate depths is highly suitable for eelgrass but does not currently contain eelgrass according to available records. An additional 7,380 ha are estimated to be moderately suitable. When taking the area of sites into account, it appears that there are enough moderate to large sites with relatively high EBM scores to meet the 4,000-hectare goal. That said, sites smaller than 10 ha should not be excluded from consideration for restoration, because most successful eelgrass restoration projects in the region and on the west coast are generally small in area (Thom 1990; Fonseca et al. 1998). Further, strategically located but small eelgrass meadows can serve significant ecological functions for that area.

We used the most up-to-date numerical models and data for circulation, water quality, and eelgrass biomass, but significant uncertainty remains in our estimates. Most importantly, data on water clarity were sparse in nearshore areas of Puget Sound, and modeling all components of total suspended solids, including sediment, is difficult to impractical at large scales. Because light is a key driver of eelgrass productivity and survival, understanding water clarity at relevant locations and scales is critical for understanding the distribution of eelgrass and determining site suitability. We were limited to data collected once a month away from shore; while this captures some of the spatial and temporal variability, it likely underestimates turbidity in nearshore areas with poor water circulation and/or large amounts of sediment, as well as areas subject to macroalgal blooms. Specific data on light availability are important for locating restoration sites, especially at finer scales.

### 4.2.1 Recommendations

The basic strategies used for restoration include protection, conservation, enhancement, and restoration. First, protect or conserve existing meadows because they are a source of renewal for new and existing meadows. Second, enhance the rate of expansion of meadows by planting, as needed, and reducing stressors. Third, restore former eelgrass sites again by planting and reducing stressors. Finally, protect the sources of renewal and expansion meadows. That means protect the integrity of the marine landscape so that the suitability of the site is maintained. For example, implement actions that maintain the process of natural renourishment of soft sediment required by eelgrass.

The geodatabase and related suitability maps provide the source of information on possible sites for restoration. Even if sites contain some eelgrass, the distribution and cover of eelgrass could be expanded through enhancement of the site to reduce stressors coupled with strategically placed eelgrass plantings. Because eelgrass does not recruit by seeds to a great extent in Puget Sound (Phillips et al. 1983), planting of eelgrass must be undertaken to enhance the rate of colonization. Actions to make sites suitable can range from removal of a derelict dock to restoring riparian zones in watersheds to reduce nutrient loading and subsequent eutrophication in the area where eelgrass normally grows. Thus, site-specific investigations must be done to ensure that actions taken to enhance eelgrass recovery will be effective.

All regions of Puget Sound appear to be moderately to highly suitable for eelgrass and thus represent areas potentially supporting eelgrass expansion (Figure 9). Larger sites occur in South Sound, Hood

Canal, Port Susan, Bellingham Bay, and Dungeness Bay. Based on this analysis, and with the goal of restoring 4,000 ha by 2020, our primary recommendations for priority actions are as follows:

1. Evaluate larger areas identified in Figure 9 that have relatively high ECI and EBM scores. It is critical to understand the reasons why eelgrass either does not exist in an area or is very sparse. Understanding the reason for the loss, and if that cause has been abated, are critical to developing plans to restore the site. The indices we use only provide an indication of issues. Site studies are required to fully evaluate the conditions at a site.
2. Large areas are developing where upstream processes have been restored and delta formation is resulting in suitable eelgrass habitat, such as those of the Nisqually, Skokomish and Elwha Rivers. At least on the Skokomish River delta, eelgrass appears to be colonizing recently accreted sediment. These large deltas represent a major potential opportunity to enhance the rate of expansion of eelgrass as driven by natural processes of delta formation.
3. Modeling and test planting indicate that South Puget Sound could contain more eelgrass than presently exists there. We are not sure why eelgrass has not colonized areas that appear suitable according to the modeling and test plantings. Mumford (2007) suggests that the extreme tidal amplitudes and the timing of low tides during the summer may contribute to the limited distribution in this region. We tried to account for this possibility by using a conservative estimate for the upper depth limit in our suitability model. Water clarity may also be relatively low much of the year due to phytoplankton blooms and/or suspended sediment loads. Further analysis of the sources of turbidity, and potential methods for improving water clarity should be conducted prior to implementation of larger planting efforts.
4. Using the geodatabase as a source of information, select all areas and sites showing high suitability, but with no documented eelgrass, and evaluate more closely. The resolution of the model results and the bathymetry data allow for closer examination of the results than are presented here. If an area is determined to be suitable, then recolonization may have been recruitment limited. In such cases, planting efforts may be needed to enhance the rate of recovery.
5. Work with local shoreline planners and other scientists who are knowledgeable about local issues and conditions for eelgrass. Strategies proven to be successful (e.g., anchor out zones) can be simple and relatively easy to implement. Examples of obvious actions with high chances of succeeding include removal of overwater structures that shade otherwise suitable areas and restriction of activities that can disturb eelgrass such as recreational shellfish harvest, boat groundings, and boat anchors and chains.
6. Monitor results from projects to build the knowledge base for future projects.

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**Appendix A**  
**Geodatabase Structure**



# Appendix A

## Geodatabase Structure

**Table A.1.** Attributes of feature classes in the Eelgrass Restoration Site Prioritization Geodatabase.

Field Name	Type	Description
<b>Sites_eg_restoration_potential</b>		
SITE_CODE	Text	DNR SVMP monitoring site code
SITE_NAME	Text	DNR SVMP monitoring site name
St_area_ha	Float	Area of site assessment units in hectares
Bathy_area	Float	Total area of the bathymetry polygons, between the upper depth limit and -9.5 m, in hectares for each site assessment unit. This area is less than the site assessment unit area because the upper depths are excluded. This is $a_p$ in Equation 2.
shrl_len_m	Float	Shoreline length in meters. From ShoreZone Inventory.
DNR_eg_pa	Short	Presence or Absence of eelgrass based on the DNR SVMP data. 0=not sampled, 1=absent, 2=present
PNNL_eg_pa	Short	Presence or Absence of eelgrass based on PNNL 2012 survey data. 0=not sampled, 1=absent, 2=present
sz_eg_pa	Short	Presence or Absence of eelgrass based on the DNR SVMP data. 1=absent, 2=present
All_eg_PA	Short	Presence or Absence of eelgrass based on the DNR SVMP data and PNNL survey. If not surveyed by either than ShoreZone data used to determine presence or absence. 1=absent, 2=present
SUM_sub_m	Float	Total shoreline length in the assessment unit with appropriate substrate for eelgrass as determined from the ShoreZone data.
PROP_sub	Float	Proportion of the total shoreline length in the site assessment unit with appropriate substrate for eelgrass. This is “P” in Equation 1.
EBM_AREA	Float	Sum of potential eelgrass biomass value (EBM) from model times the area of each bathymetry polygon ( $a_p$ ). This is a value weighted potential eelgrass area estimate.
EBM	Float	Weighted average of potential eelgrass biomass value from model. This is “EBM” in Equation 1 and 2.
Envr_Cond	Float	The environmental condition index (ECI) = potential eelgrass biomass value (EBM) times the proportion of the shoreline with appropriate substrate (P).
EBM_SUB_A	Float	The potential eelgrass biomass value (EBM) times the proportion of the shoreline with appropriate substrate (P) times the area of the site assessment unit (A). This value

Field Name	Type	Description
		was not used in the habitat suitability analysis.
EBM_SUB_B	Float	The potential eelgrass biomass value (EBM) times the proportion of the shoreline with appropriate substrate (P) times the suitable bathymetric area within the site assessment unit ( $a_p$ ). This is ERP in Equation 1.
ARMOR_m	Float	Total shoreline length in the assessment unit with shoreline armoring.
PropArmor	Float	Proportion of the total shoreline length in the site assessment unit with shoreline armoring.
Prop_OWS	Float	Proportion of the site assessment unit with overwater structures.
EG_hist	Short	Estimated historical eelgrass presence. 0=absence, 1=presence.
<b>Sites_eg_biomass_model_output</b>		
SITE_CODE	Text	code associated with the site polygon as determined by DNR
SITE_NAME	Text	long name of site polygon as determined by DNR
UDL_mNAVD8	Float	upper depth limit elevation of eelgrass in meters relative to NAVD88
Bathy_m	Float	bathymetry elevation in meters relative to NAVD88
DepthBin	Short	eelgrass model depth bin relative to EBM
EBM	Double	eelgrass biomass model output value ( $\text{mol C/m}^2$ )
Shape_Length	Double	GIS autogenerated polygon length value in meters
Shape_Area	Double	GIS autogenerated polygon area in square meters
<b>Sites_historical_eelgrass_presence</b>		
Site Code	Text	code associated with the site polygon as determined by DNR
SITE_NAME	Text	long name of site polygon as determined by DNR
OBJECTID	Long	Index value from Historic_PS_Eelgrass_Dist_From_Thom_v2 shapefile
Shape_Length	Double	GIS autogenerated polygon length value in meters
Shape_Area	Double	GIS autogenerated polygon area in square meters
<b>Sites_overwater_structures</b>		
Site Code	Text	code associated with the site polygon as determined by DNR
SITE_NAME	Text	long name of site polygon as determined by DNR
OBJECTID	Long	OBJECTID
SUBBASIN	Text	SUBBASIN
Structure_	Text	short description of type of structure
Shape_Length	Double	GIS autogenerated polygon length value in meters
Shape_Area	Double	GIS autogenerated polygon area in square meters

<b>Field Name</b>	<b>Type</b>	<b>Description</b>
<b>Sites_shoreline_armoring</b>		
Site Code	Text	code associated with the site polygon as determined by DNR
SITE_NAME	Text	long name of site polygon as determined by DNR
OBJECTID_1	Long	Index value from PSARMORt (original data set), equivalent value is OBJECTID
SUBBASIN	Text	short regional descriptor
Armor_YN	Text	Y = armoring present
Shape_Length	Double	GIS autogenerated polygon length value in meters
<b>Sites_shorezone_eg_presence_poly</b>		
Site Code	Text	code associated with the site polygon as determined by DNR
SITE_NAME	Text	long name of site polygon as determined by DNR
UNIT_ID	Long	Index value from eelgrass ShoreZone inventory theme
EELGRASS	Text	Quaternary indicator of eelgrass status, ABSENT, PATCHY, CONTINUOUS, NO DATA
eelsub_area_ha	Double	area of eelgrass/substrate area in hectares
eel_pa	Short	Binary indication of eelgrass presence/absence where 1 = presence
Shape_Length	Double	GIS autogenerated polygon length value in meters
Shape_Area	Double	GIS autogenerated polygon area in square meters
<b>Sites_shorezone_ln</b>		
Site Code	Text	code associated with the site polygon as determined by DNR
SITE_NAME	Text	long name of site polygon as determined by DNR
UNIT_ID	Long	Index value from eelgrass ShoreZone inventory theme
EELGRASS	Text	Quaternary indicator of eelgrass status, ABSENT, PATCHY, CONTINUOUS, NO DATA
ZoneComp	Text	shorezone tidal zone value from ShoreZone inventory
Material	Text	substrate material components from sz inventory
Good_sed	Short	Binary indicator of good substrate where 1 = good substrate
eelsub_len_m	Double	length of eelgrass zone within the assessment unit
eel_pa	Short	Binary indication of eelgrass presence/absence where 1 = presence
Shape_Length	Double	GIS autogenerated polygon length value in meters









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