SITE SELECTION FOR EELGRASS: A MODEL FOR PUGET SOUND REPLANTING PROJECTS

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ABSTRACT

A Site Selection Model for Eelgrass (*Zostera marina*)
Replanting Projects in the Puget Sound

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Eelgrass (*Zostera marina*) is an important nearshore habitat in ecosystems around the world. In recent years extensive meadows have been threatened or destroyed by anthropogenic pressures consistent with development and increasing human population, resulting in experimental replanting projects that have met with mixed success. Replanters have reached consensus that site selection is a crucial first step in such projects. Site selection for eelgrass is often based on a prioritization matrix that takes into account parameters such as wave energy and substrate. Models of this kind have been used with success on the east coast of the US, but not to date with replanting efforts in Washington State Puget Sound. The Washington State Department of Natural Resources (WA-DNR) is currently inventorying eelgrass stocks and has created extensive Geographic Information Systems (GIS) files detailing Puget Sound aquatic conditions including substrate, shoreline modification, exposure, overwater structures, and vegetation. The research described in this thesis used the WA-DNR GIS files to produce maps of Puget Sound highlighting areas that appear to be good candidates for eelgrass replanting projects. These sites were chosen by substrate, exposure class, degree and type of shoreline modification, and proximity to existing eelgrass beds. It was found that of the total shoreline under consideration, 19.02% was already populated with continuous eelgrass beds, and 5.55% was suitable for replanting. These maps are preliminary and the recommended sites require field testing before any replanting projects are commenced.

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ACRONYMS AND ABBREVIATIONS USED

GIS	Geographic Information Systems
GPS	Global Positioning System
MLLW	Mean Lower Low Water
NAIP	US Department of Agricultural National Agriculture Imagery Program
PSAMP	Puget Sound Assessment and Monitoring Program
SAV	Submerged Aquatic Vegetation
SVMP	Submerged Vegetation Monitoring Project
WA-DNR	Washington State Department of Natural Resources
WDFW	Washington Department of Fish and Wildlife

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I. INTRODUCTION

Zostera marina, familiarly known as eelgrass, is the most common and widespread species of approximately 60 seagrasses found in near-shore coastal environments around the world. Seagrasses form meadows via horizontal rhizomes and grow leafy shoots vertically into the water column. All seagrasses with the exception of surfgrass (*Phyllospadix torreyi*, which adheres to rocks) grow in soft substrates, which they stabilize with their rhizomes. These meadows play a significant role as habitat and food for many species, including commercially important fish and crustacean species. Eelgrass meadows are in worldwide decline due to anthropogenic stress factors.

As eelgrass is sensitive to many stressors associated with the development that has taken place since European settlement, the Washington State Department of Natural Resources (WA-DNR) has made it a priority to steward the health of Puget Sound by using eelgrass as one of the top five indicator species. Although there is little data concerning historical eelgrass extent, researchers suspect that eelgrass habitat has been degraded by development, agricultural run-offs, increased boat traffic, changing oceanic and climate conditions, and introduction of invasive species (Thom et al. 2008). Debilitated eelgrass meadows affect the survival of many species that depend on eelgrass for food, shelter, or habitat and represents a significant threat to the health of Puget Sound.

Attempts to restore eelgrass meadows have met with mixed success as its habitat is complex and affected by many different factors. Given that the reason for the cause of the original loss is known and has been corrected, the scientific community has generally concluded that restoring eelgrass meadows is possible but that restoration efforts are hampered by large knowledge gaps. One of the main factors that will determine the success of any restoration attempt is an understanding of what natural conditions influence eelgrass success and how these condition can be used to predict suitable habitat for restoration. As Fonseca et al. (1998) suggest in *Guidelines for the Conservation and Restoration of Seagrasses*, replanting is not technically complex but “planting will not succeed unless managers appreciate and emphasize the extreme importance of site selection.”

This work uses geographic data from WA-DNR and Geographic Information Systems (GIS) to prioritize potential replanting locations in the Puget Sound with the goal of increasing the chance for replanting success. Section II, Background, discusses current and historic eelgrass extent, factors limiting eelgrass growth and survival, and previous replanting efforts and site selection models. Section III, Methods, describes a model developed using WA-DNR GIS data to select optimal sites for restoration based on a number of specific metrics (variables that characterize a place). The maps generated by this model are presented in Section IV, Results, and the limitations of the model are discussed in Section V, Conclusions.

II. BACKGROUND

SIGNIFICANCE OF EELGRASS

Eelgrasses and seagrasses provide extensive nearshore habitat around the world. In Washington State eelgrass provides nursery and spawning habitat for Pacific herring and salmon, feeding and foraging habitat for waterbirds, and also acts to improve water quality and prevent erosion by stabilizing sediment. Eelgrass meadows are also a sink for nutrients and shelter for many valuable species such as Dungeness crab (Dowty et al. 2010).

Although nature should not be viewed solely in terms of its uses for humankind, eelgrass meadows hold a significant economic value. Eelgrass meadows are an aquatic net primary producer, providing food for the marine environment and the secondary production of fish species, and thus ultimately sustain humans. An Australian study found that, in terms of catch reduction, the loss of just 16% of seagrass in one fishing block (an area corresponding loosely to 1° latitude and longitude) resulted in an economic loss of A$235,000 per year, and that the relationship would conceivably arrive at a 'catastrophic' point if habitat loss continued (McArthur and Boland, 2006). In short, even relatively small losses of eelgrass and seagrass habitat can have significant impacts on the species composition of the nearshore habitat, and negatively affect the fishing industry.

Washington State recognizes the significance of eelgrass meadow health and affords meadows special protection through the Department of Fish and Wildlife (WDFW). In 2010 the Puget Sound Partnership created the Dashboard of Ecosystem Indicators intended to estimate the health of the Puget Sound by monitoring twenty species, of which eelgrass was one of the top five (Puget Sound Partnership 2010). The Washington State Department of Natural Resources subsequently recommended that the Puget Sound Partnership adopt a target of a 20% increase in eelgrass meadow areas by 2020. Replanting is one of the strategies recommended to achieve this goal.

CAUSES OF EELGRASS DECLINE

With the increase in human population on the shorelines of the Puget Sound it is inevitable that nearshore resources become stressed. Due to relatively high light requirements eelgrasses thrive in shallow nearshore waters which makes them especially vulnerable to damage by human activities (Fonseca et al. 1998). Logging and agriculture has led to increased runoff, siltation, increased turbitidy, and loss of water quality that all restrict eelgrass growth. Other activities such as the dredging and filling required to maintain shipping lanes and the construction of coastal armoring and overwater structures such as docks and bridges also impact on eelgrass habitat.

Aside from anthropogenic influences eelgrass also suffers from a periodic wasting disease, first documented in the 1930s when it virtually eliminated the species in the North Atlantic. This disease is caused by a pathogenic strain of *Labyrinthula* and has been isolated in the Puget Sound, although it has yet to cause a mass dieoff in that area (Short et al. 1987). The slowness of the recovery of North Atlantic eelgrass indicates that natural recruitment of eelgrass does not keep pace with population mortality that can occur very rapidly (Fonseca et al. 1998).

EELGRASS REPLANTING TECHNIQUES

The basic rationale behind replanting is to adjust the ratio of recruitment to mortality and thus effect net eelgrass population growth. Replanting eelgrass, however, is not a simple matter. Eelgrass is aquatic and replanting is typically an expensive and labor-intensive process involving boats and SCUBA divers. Shoots are fragile and very susceptible to physical damage and must be kept wet during the entire period between collecting and replanting, which should ideally take place on the same day (Fonseca et al. 1998).

Existing methods for eelgrass replanting typically involve fastening collected shoots to the substrate with either bamboo staples or temporary metal frameworks. When this is performed by SCUBA the cost of replanting increases significantly. Restoration dollars, with eelgrass as with many species, are scarce, and it is important to maximize their value by doing everything possible to ensure replanting success. Good site selection is thus a crucial first step.

HISTORICAL EELGRASS PRESENCE IN PUGET SOUND

Eelgrass restoration in the Puget Sound differs from restoration efforts in some other parts of the world (notably the Eastern US coast) due to a comparative paucity of data concerning historical eelgrass meadow extent. As Dowty et al. (2010) point out, historical abundance is an appropriate reference point for setting management targets for future abundance, as well as suggesting whether management practices should focus on restoration of lost meadows or protection of remaining vegetation. Since eelgrass is affected by a wide range of stressors it seems reasonable that increased human activity in the Puget Sound has resulted in eelgrass loss from the factors considered above; however, limitations in the historic record make the extent of this hypothetical loss difficult to estimate.

The earliest records of eelgrass in the Sound are from 19th century hydrographic charts and are limited by the scale of the charts and the fact that eelgrass, not being a navigational aid or of economic importance, was not of great concern at the time (Thom & Hallum 1990). In 1962-3 Ron Phillips used divers and boats to conduct a survey of eelgrass density at 107 sites throughout the Puget Sound. In 1974 he estimated that 9% of the lower Puget Sound photic zone below mean lower low water (MLLW) was covered with eelgrass (Phillips 1984).

ESTIMATIONS OF CURRENT EELGRASS EXTENT

In 1998, Bailey et al. used a probability model, based on 325 randomly selected sites along 3715 km (2303 mi) of Puget Sound shoreline, to estimate that 23.4% of the total shoreline was then vegetated with eelgrass (Bailey et al. 1998). This report covers an area similar to this thesis but also includes the South Puget Sound, where eelgrass is known not to occur for reasons of tidal range (Section: "Light and exposure"). Because of this tidal range, the South Puget Sound was eliminated as a location suitable for eelgrass restoration in this thesis.

The WA-DNR Submerged Vegetation Monitoring Project (SVMP), discussed in greater detail below, was established in 2000 and has since conducted a yearly survey of eelgrass extent. The 2009 report (which contains the 2008 data) estimate a Sound-wide eelgrass area of 22,800 ± 4,500 ha (± 95% CI) for the zones covered in the report (Gaekle et al. 2009).

PREVIOUS SITE SELECTION MODELS

Thom et al. (2008) summarized and evaluated all previous restoration efforts in the Pacific Northwest and included a synthesis of what researchers have learned about the process to improve project success. They found it difficult to summarize the relative performance of the more than 30 projects due to the wide variety in replanting techniques, project size, performance criteria, duration of monitoring, and project goals. Most projects were conducted as mitigation to compensate for shoreline development, and in all cases areas replanted shrunk in subsequent years, resulting in a net loss of habitat (Fonseca et al. 1998). Thom et al. concluded eelgrass restoration science is hampered by large knowledge gaps and that good site selection was of extreme importance.

The Judd et al. (2009) research into eelgrass restoration on the Lower Columbia River estuary used baseline *in-situ* field tests combined with satellite observations to determine ambient habitat conditions. Their measurements covered salinity, temperature, current velocity, light availability, wave energy, and desiccation to predict the suitability of an area for eelgrass replanting. Based on this model five areas were planted with eelgrass. One year later two of the five sites had good survival rates, two had poor survival, and one had total eelgrass loss. They concluded that this 40% survival rate represented reasonable success by restoration standards, although the labor required to obtain the site selection measurements was significant.

On the east coast of the United States Short et al. (2002) developed a site selection model and later generated a CD-ROM that takes field data entered by the researcher and produces a Geographic Information Systems (GIS) map of recommended suitable areas. The parameters considered were historical eelgrass distribution (from maps), current eelgrass distribution, proximity to natural eelgrass beds, sediment, wave exposure, water depth, and water quality. When using this model, replanting efforts showed a 62% success rate which was approximately double that reported by previous restoration efforts in the area. As with Judd et al., the model requires field tests be made as a necessary starting point. This model is not applicable to the west coast due to the comparative paucity of data concerning historical eelgrass extent. Although the model produced by Short et al. inspired the current work, this thesis differs in that it begins with existing GIS data sets which are to be supplemented later with field tests once inappropriate sites have been eliminated as a first step.

LIMITING FACTORS FOR EELGRASS GROWTH

To evaluate the success of any eelgrass restoration project, we first must understand the health and succession of eelgrass in an undisturbed state. At one location we might see a lush eelgrass meadow, but note that a nearby location with apparently the same depth range, water temperature, salinity, substrate, and turbidity, is barren. Before deciding that the second location is ideal for a replanting project, we must pose the question as to why eelgrass did not naturally recruit to this site.

Current and seed dispersal. Studying seed bank patterns in Chesapeake Bay, Harwell and Orth (2002) found that the number of viable seeds showed high variability both between and among zones sampled, with seeds found in sites not displaying any *Z. marina* shoots as well as in mixed species and *Z. marina* monospecific sites. The number of reproductive shoots was also highly variable, probably due to different local environmental conditions (Harwell 2002).

In their 2009 study of eelgrass restoration in the lower Columbia River estuary, Judd et al. found that eelgrass distribution may be limited by poor seed distribution, particularly in areas with a pronounced current (such as a river estuary). In other words, for eelgrass to colonize an area, water currents must be capable of dispersing the seeds to that area. Variability in local water currents may be one reason why a site that otherwise seems suited for eelgrass presence is unvegetated.

Wave energy. Eelgrass exists within a specific range of wave energy and tidal current speed (Murphy and Fonseca, 1995). Eelgrass seems to prefer a certain amount of water mixing to obtain oxygen and nutrients and thus avoids completely protected coves and bays. On the other hand, water energy is correlated with sediment stability (Fonseca et al. 1998) and at a certain threshold eelgrass will not be able to survive due to erosion and shoot burial.

Light and exposure. Eelgrass habitat is constrained to a depth gradient that represents at its upper boundary the likelihood of exposure to desiccation at low tide, and at its lower boundary light attenuation in the water column. Variations in tidal range and light availability account for the variety exhibited in eelgrass range between different species and sites (Krause-Jensen et al. 2000, Herb and Stefan 2003). This range is usually determined at the upper boundary by the mean lower low water (MLLW) mark of the Puget Sound's two tides. Phillips found that while vegetative growth was observed from 1.8 m above MLLW to 30 m deep, the optimum range for reproductive and vegetative activity was from MLLW to 6.6. m below (Phillips 1984). A more detailed survey by the WA-DNR's ongoing Submerged Vegetation Monitoring Project (SVMP) has found that eelgrass depth range varies throughout the Sound (Fig. 1).

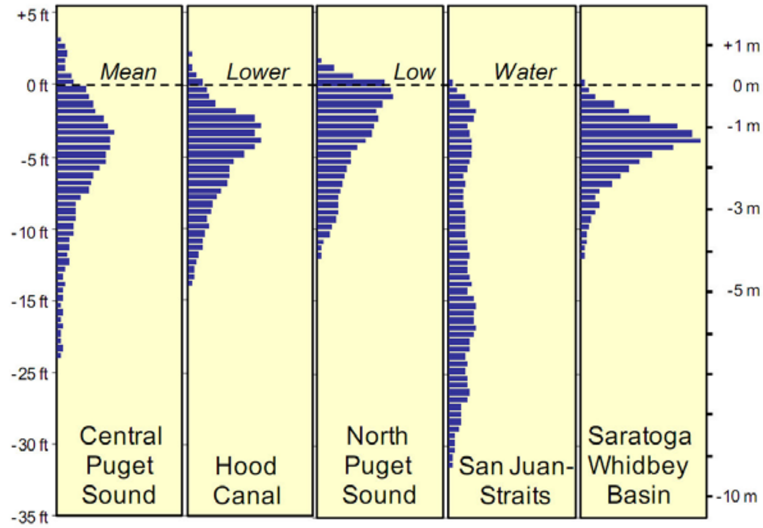

Fig. 1. Estimated depth profiles for Puget Sound eelgrass based on 2002-2004 Submerged Vegetation Monitoring Project data

Not all locations in Puget Sound are suitable for eelgrass growth. Southern Puget Sound is generally considered unsuitable habitat for eelgrass due to a large tidal range which at one extreme exposes eelgrass to desiccation and at the other extreme reduces light availability to unacceptable levels (Dowty 2011).

Overwater structures such as bridges, docks, piers, floats, and miscellaneous buildings cover large sections of shoreline in the Puget Sound. Any part of the shoreline that is in permanent shadow from an overwater structure will be unsuitable for photosynthesis and thus unsuitable for eelgrass growth.

Temperature and salinity. As with depth, eelgrass thrives best within a specific range of temperatures and salinities. A study of eelgrass restoration in the Columbia River estuary, where during low-flow conditions salinity intrusion can occur many miles upstream, found that eelgrass experienced optimal conditions within the salinity range 10-30 ppt (Judd 2009). This agrees with Phillips (1972) which showed that any salinity lower than 10 ppt resulted in stunted growth. Eelgrass will not grow in persistent fresh water (Phillips 1974).

Eelgrass species tolerate a wide variety of temperatures worldwide, from -6°C (21.2°F) in Alaska to around 27°C (80.5°F) in the Gulf of California, Mexico; however, there is some evidence that specific genotypes evolve with different temperature requirements determined by location. Thus temperature may affect the availability of transplants; the optimal temperatures for reproductive growth in the Puget Sound occurs in the temperature range 6°C – 12.5°C (42.8°F – 54.5°F) (Phillips 1984).

Substrate. Substrate is a strong factor influencing eelgrass success. All seagrasses, with the exception of surfgrass (*Phyllospadix*, which attaches to rocks) grow in unconsolidated substrates ranging from gravelly sand to fine muds and silts, with a general preference towards finer particle sizes (Kenworthy et al. 1977). Depth of sediment is also a factor: bedrock too near the surface (which might be exposed by currents) limits the distribution of some seagrasses (Fonseca et al. 1998). For this reason eelgrass tends to prefer a fairly protected level of wave exposure.

Substrate can also be a success factor for a restoration project. There are several approaches to anchoring the transplanted shoots to the substrate which have been used with varying degrees of success. Kopp and Short (2001) found in a study in New Bedford, MA, that a technique where eelgrass rhizomes were ‘stapled’ to the substrate with bamboo was less successful than a method where transplants were secured to the ocean floor by a metal frame for a period of one month. It was hypothesized that burrowing fauna such as crabs, which use eelgrass for shelter, dislodged the bamboo-stapled rhizomes from the loose sediment.

III. METHODS

AN EELGRASS SITE SUITABILITY MODEL

Puget Sound is a large and complex estuarine system of many interconnected waterways and significant variability in depth, tidal range, substrate, and development. In the current work potential eelgrass replanting sites were selected by examining available Geographic Information Systems (GIS) data on these variables and constructing a set of tables that included only those locations that matched a specific set of criteria.

This thesis aims to demonstrate how GIS can be used as a first step in selecting areas for eelgrass restoration in Puget Sound. As indicated above, a great many factors influence eelgrass success, and available GIS data sets do not enough information to select a site without additional field experimentation. It is unlikely that such a model could exist, given the sheer area under consideration and the necessary simplifications of a tabular data set. However, where pertinent information has been recorded, this information can be used to eliminate a great many sites on the basis of unsuitable substrate, for example. In this way the work differs from Short and Burdick’s computerized site selection model for the New Bedford Massachusetts area, which requires inputting field measurements to calculate site suitability. Recall from Section II that Short and Burdick produced a program where the users enter field measurements for salinity, turbidity, and fetch, and then see a GIS map which highlights likely eelgrass restoration sites.

In this thesis, the GIS output is based solely on the existing ShoreZone data set produced by the Nearshore Habitat Program of the WA-DNR, and requires field measurements of unconsidered factors (such as salinity and turbidity) be taken after the fact. In both models the aim is the same: to prioritize likely eelgrass restoration locations in order to facilitate restoration decisions that must be made with limited budget and resources.

GEOGRAPHIC INFORMATION SYSTEMS (GIS)

Geographic Information Systems (GIS) are a powerful tool for manipulating and analyzing spatial information. The great advantage of GIS is that data sets containing multiple attributes can be presented with reference to geographic locations. It is comparatively straightforward, therefore, to create a prioritization matrix based on a set of defined parameters and link the output to a map which can be easily visually interpreted.

SHOREZONE AND SVMP

This thesis builds its site-selection model primarily on data available from two publically available WA-DNR GIS data sets: the ShoreZone Inventory and the annual SVMP report. Data from the two data sets were combined in ArcGIS 9.3 and analyses and statistics were performed with Microsoft Excel. The SVMP data set is used only to delineate the regions in Puget Sound that are considered for this thesis. All of the data on local conditions, substrate, eelgrass presence, and shoreline modification are contained within the ShoreZone Inventory.

The ShoreZone Inventory. The Nearshore Habitat Program of the WA-DNR has produced a large GIS data set, known as ShoreZone, which contains an inventory of Washington's saltwater shorelines from the Canadian border to the Columbia River. This data set, compiled from data gathered over the period 1994-2000, contains information concerning shoreline morphology, substrate, wave exposure, and biota.

The ShoreZone Inventory divides the saltwater shore of Washington into 7365 individual units of approximately 0.5 miles in length where the primary geomorphology is consistent. A unit might be thus classified as a gravel beach, and abut a unit classified as a mud flat (or another gravel beach). The longest unit is 2.38 miles, while the shortest is 59 feet (Berry et al. 2001).

Each unit is characterized as possessing one of fifteen shoreline types, seven substrate types, and six wave exposure classes. Further information on each unit includes percentage of anthropogenic modification, primary, secondary, and tertiary kinds of modification, and degree of presence of eelgrass, seagrass, surfgrass, kelp, sargassum, dunegrass, and saltmarsh. Table 1 presents an example, in tabular form, of some of the data an individual unit might contain.

Attribute	Unit
Unit ID	2646
Length (ft)	1563.668
Shoreline Type	Sand flat
Substrate Type	Sand
Shoreline Modification	90%
Primary Modification	Wooden bulkhead
Secondary Modification	Rip Rap
Tertiary Modification	None
Exposure Class	Semi-protected
Surfgrass	Absent
Eelgrass	Continuous
Kelp	Absent
Sargassum	Absent
Dunegrass	Absent
Salt Marsh	Absent

Table 1. An example of some of the data available for each of the 7365 ShoreZone units

PSAMP and SVMP. In 2000, as part of its work with the multi-agency Puget Sound Assessment and Monitoring Program (PSAMP), the Nearshore Habitat Program of the WA-DNR created the Submerged Vegetation Monitoring Project, or SVMP. The intention of the SVMP is to monitor and track the health and extent of eelgrass using a statistically robust sampling design and underwater videography (Graekle et al. 2009). The SVMP provides both Sound-wide and regional data, dividing the Sound into six zones: North Puget Sound, San Juan Islands- Strait of Juan de Fuca, Central Puget Sound, Hood Canal, Saratoga Passage-Whidbey Basin, and Southern Puget Sound (Fig. 2).

Because tidal ranges and light availability vary within Puget Sound, each of the six SVMP zones under consideration demonstrates a different depth gradient where eelgrass is found. Southern Puget Sound, for example, due to extreme tide changes which desiccate eelgrass at low tide and place it outside the range of light it requires at high tide, does not support eelgrass except in very rare circumstances (Dowty 2011). The ShoreZone data list no eelgrass presence at all for the South Puget Sound.

Puget Sound SVMP Zones

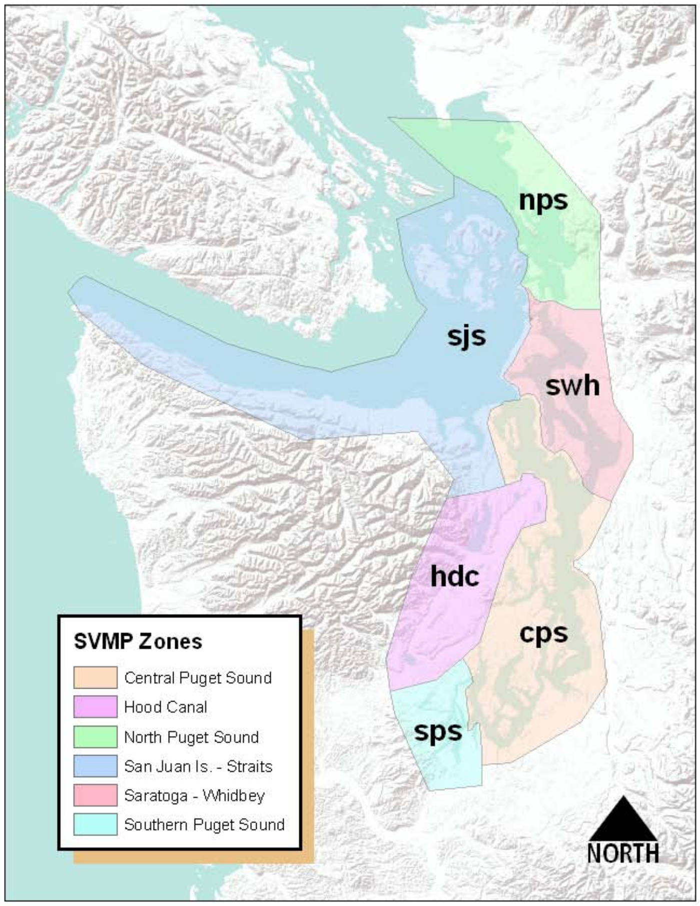

Fig. 2. The six zones determined by the DNR's Submerged Vegetation Monitoring Project

MANIPULATION OF DATA SETS

Limiting the ShoreZone data set to the regions included in the SVMP data set. As previously stated, the ShoreZone data set includes all of Washington's saltwater shorelines from the Canadian Border to the mouth of the Columbia River. In order to provide statistically meaningful data for eelgrass presence in the Puget Sound alone, all data referencing regions outside of Puget Sound were eliminated from the ShoreZone inventory. This was done with ArcGIS 9.3 by clipping the ShoreZone data to areas that fell within the regions delineated by the SVMP data set. After the irrelevant regions had been clipped from the ShoreZone Inventory, 6460 of the original 7365 units remained for analysis. All further analysis was performed on the ShoreZone data and no other data from the SVMP data set was required.

Data normalization. Before performing any statistics on the ShoreZone features of eelgrass presence or absence, substrate, wave exposure, and shoreline modification, we accounted for the relative occurrence of each feature. For example, a key indicator for eelgrass success is substrate. ShoreZone lists seven substrate categories (more on this below) but each substrate is not equally abundant in Puget Sound. When correlating *Continuous* eelgrass presence to substrate (to determine if eelgrass shows a significant presence for a substrate type) the ratio was based off the relative abundance of the substrate and not the actual number of counts of that particular type.

FACTORS CONSIDERED FROM SHOREZONE

Not all data in ShoreZone was considered in the construction of this model. Due to different substrate/ habitat requirements, surfgrass, sargassum, kelp, and dune grass were not considered in competition for space with eelgrass and were eliminated. Shoreline type was considered less important than substrate type and was not considered. Pete Dowty at the WA-DNR had previously combined eelgrass presence data with beach width and found no clear association (personal communication, January 2011). In the end, it was decided that eelgrass success was to be predicted using substrate type, percent and type of shoreline modification, and wave exposure class.

Eelgrass presence. The ShoreZone inventory contains three categories of eelgrass presence: *Continuous*, *Patchy*, and *Absent*. For this study only *Continuous* eelgrass presence was considered, because it was the strongest way to relate eelgrass health with the factors considered (substrate, shoreline modification (extent and type), and exposure class). Analysing the *Absent* category produces much the same data, only inversely. That is to say, *Continuous* eelgrass is strongly correlated to a sandy substrate and very weakly to a rocky substrate. *Absent* eelgrass shows a strong correlation to a rocky substrate and a weak correlation to a sandy substrate. It was decided to only use data that reflected eelgrass success, as indicated by *Continuous* eelgrass presence.

The presence of *Continuous* eelgrass is used in two ways: to determine existing correlations between eelgrass and environmental factors, and to determine which locations have no need of replanting. Clearly, if a unit shows *Continuous* eelgrass presence, restoration is not required.

Proximity to existing *Continuous* eelgrass beds is also a factor to consider in selecting a site for replanting. In their site-selection model for eelgrass transplantation in the northeastern US, Short et al. include a buffer of 100 m from natural eelgrass beds to insure that transplanting is taking place outside an area that would otherwise be naturally revegetated by seed dispersal (Short et al. 2002). Local field tests may indicate that such seed dispersal is not possible due to water currents, but that data must be collected in the field and is outside the scope of this model. It should also be considered that proximity to donor beds can be an important factor in the actual practical work of obtaining donor eelgrass shoots, which should ideally be done on the same day as replanting to prevent desiccation.

Substrate Type. Substrate type is the single strongest factor included in the ShoreZone data set for eelgrass success. To some extent this is self-explanatory: as stated above, all seagrasses with the exception of surfgrass grow in unconsolidated substrates ranging from gravelly sand to fine mud and silts. The ShoreZone data set includes seven substrate classes. They are, ranging from coarsest to finest: *Man-Ma*de; *Rock*; *Gravel*; *Rock, Gravel, and Sand*; *Gravel and Sand*; *Sand*; *Mud and Fines*. By correlating the occurrence of *Continuous* eelgrass presence with the occurrence of each kind of substrate and then normalizing for percentage of each substrate type, eelgrass was shown to statistically demonstrate a strong preference for *Sand* substrate type (Fig. 3). Therefore, only shore units that had a *Sand* substrate class were considered as potential sites for eelgrass replanting (even if, in the real world, it might have been possible to replant in several of the other substrate types).

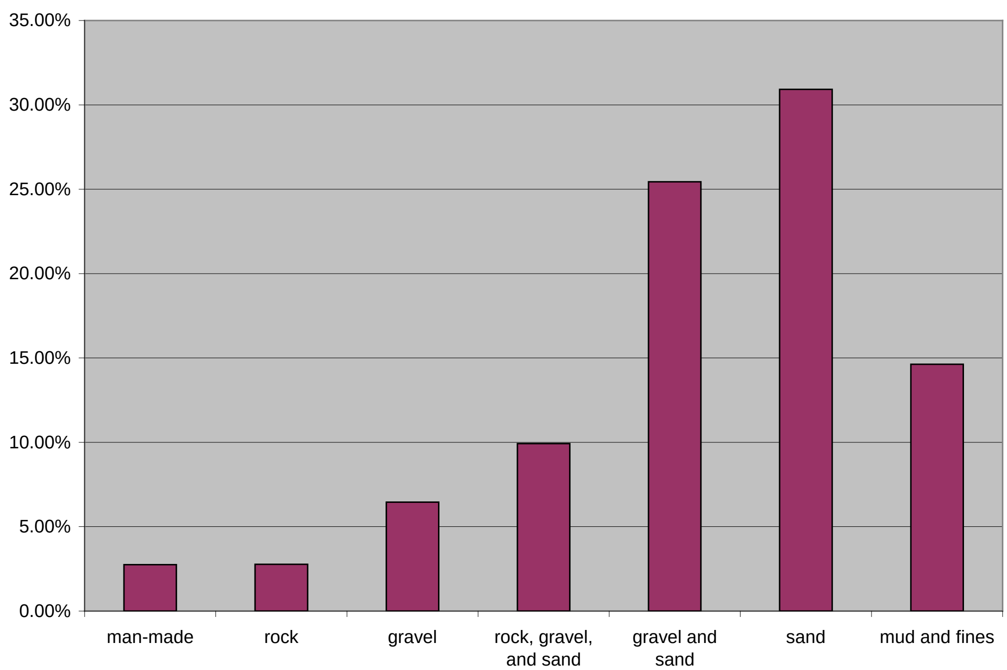

Fig. 3. Percent continuous eelgrass presence (all regions) by substrate type

Shoreline Modification. ShoreZone contains both ordinal and nominal data concerning shoreline modification. The percent modification per unit and the primary, secondary, and tertiary type of modification is listed. The categories considered are *Boat Ramp*, *Concrete Bulkhead*, *Landfill*, *Rip Rap*, *Sheet Pile*, *Wooden Bulkhead*, or *None*, presenting some difficulties for analysis as the percent modification has different significance for each type of modification, and the types of modification vary widely in quantity. For example, in the North Puget Sound zone, there are one hundred and sixty-four counts of rip rap (armoring) and only four boat ramps. *Continuous* eelgrass occurs at fifty-nine of the sites with rip rap (36%) but at three of those four with boat ramps (75%). This does not imply that eelgrass shows a preference for boat ramps over rip rap.

The sample size can be increased by considering all regions simultaneously, but even then chi-square tests show that eelgrass demonstrates no significant preference for percentage of shoreline modification. The data are just too general. Yet it is known that eelgrass cannot survive in places shadowed by overwater structures (which inhibit photosynthesis). Additionally, it has been established that coastal armoring negatively affects habitat on sandy beaches by increasing erosion and reducing beach width (Dugan et al., 2008). It is reasonable to avoid areas that have been too heavily modified for replanting projects. For the purposes of this model, a shoreline modification percentage of 35% or less was considered preferable. This does not take into account type of shoreline modification (e.g. rip rap, boat ramps, etc) as the available data is too broad to be of significance. It seems reasonable, though, that a lower level of shoreline modification implies less general anthropogenic disturbance and traffic.

Exposure Class. ShoreZone classifies all of the Puget Sound in terms of six levels of exposure class: *Very Exposed*, *Exposed*, *Semi-Exposed*, *Semi-Protected*, *Protected*, and *Very Protected*. The class for any unit was calculated by combining an exposure model that computed fetch characteristics with wave exposure data determined on site by a geomorphologist. In the 6460 units encapsulated by the SVMP zonal regions, none are classified as *Very Exposed*, only one as *Exposed*, and only 3 as *Semi Exposed* (all *Very Exposed* regions lie in the ShoreZones on the Pacific Coast, which are out of the range of the SVMP regional zones). Thus, for all intents and purposes, all of Puget Sound can be considered to fall under the classifications of *Semi Protected*, *Protected*, and *Very Protected* and severe wave energy can be discarded as a limiting factor for this model.

With regards to eelgrass requiring a certain level of water movement to facilitate nutrient and oxygen mixing and seed dispersal, the data show eelgrass demonstrating an approximately three times greater preference for *Semi-Protected* and *Protected* zones over *Very Protected* (table 2). As before, this was normalized by figuring in the relative abundance of each exposure class.

ALL REGIONS EXPOSURE CLASS	TOTAL COUNTS eelgrass	class	EELGRASS % OF TOTAL	CLASS % OF TOTAL
very exposed	0	0	0.00%	0.00%
exposed	0	1	0.00%	0.02%
semi exposed	3	253	1.19%	3.92%
semi protected	365	1814	20.12%	28.08%
protected	845	3447	24.51%	53.36%
very protected	68	945	7.20%	14.63%

Table 2. Normalized data indicating eelgrass preference for protected exposure class

Overwater structures. Overwater structures such as bridges, docks, piers, floats, marinas, floating homes, and miscellaneous buildings cover large sections of shoreline in the Puget Sound. Any part of the shoreline that is in permanent shadow from an overwater structure will be unavailable for photosynthesis by eelgrass and thus unsuitable for replanting. The WA-DNR has made available a shapefile of all overwater structures in the Puget Sound at their GIS Data Centre website[1]. This file was digitized from 3-foot resolution color orthophotos taken between 2002 and 2006 by either the WA-DNR or the United States Department of

[1] http://fortress.wa.gov/dnr/app1/dataweb/dmmatrix.html, retrieved January 2011

Agricultural National Agriculture Imagery Program (NAIP). The data is classified so that overwater structures can be referenced based on structure type or size.

Not all overwater structures will eliminate the possibility of eelgrass replanting. Small, recreational family-use docks do not shade much area and may even be helpful to a replanting team. Large industrial docks, on the other hand, not only shade large areas but indicate substrate disturbance and a hazard for replanters and should be eliminated. To illustrate, Fig. 4 shows a Bainbridge Island marina. The overwater structures are clearly visible. Fig. 5 provides the same information depicted as a GIS output of the ShoreZone data. The GIS map shows that both locations where continuous eelgrass is present (deep in the marina and just outside the mouth) have relatively light or absent overwater structures. If this area becomes a candidate for replanting, we would first have to find units where there is currently no eelgrass and a sandy substrate. These two locations are shown in blue in Fig. 5. However, it is clear from both the photograph and the GIS map that these locations are in areas of dense construction, and are thus unsuitable for replanting. Of the other locations where eelgrass is absent, none have suitable substrates. This marina is thus an unsuitable location for eelgrass replanting.

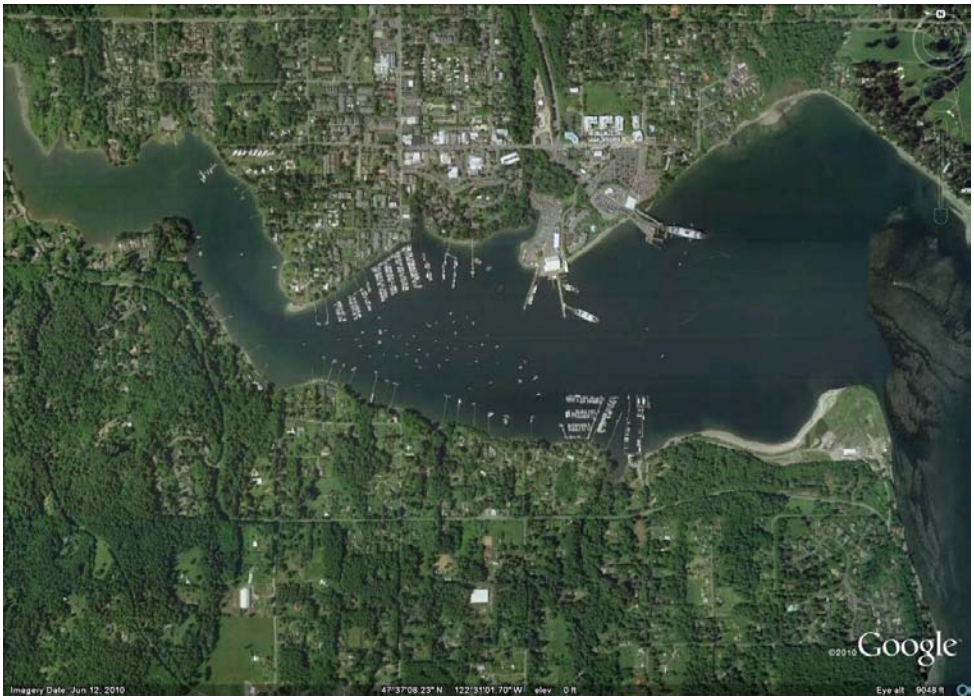

Fig. 4. Bainbridge Island marina showing overwater structures. Image courtesy of Google Earth, retrieved 3/01/11

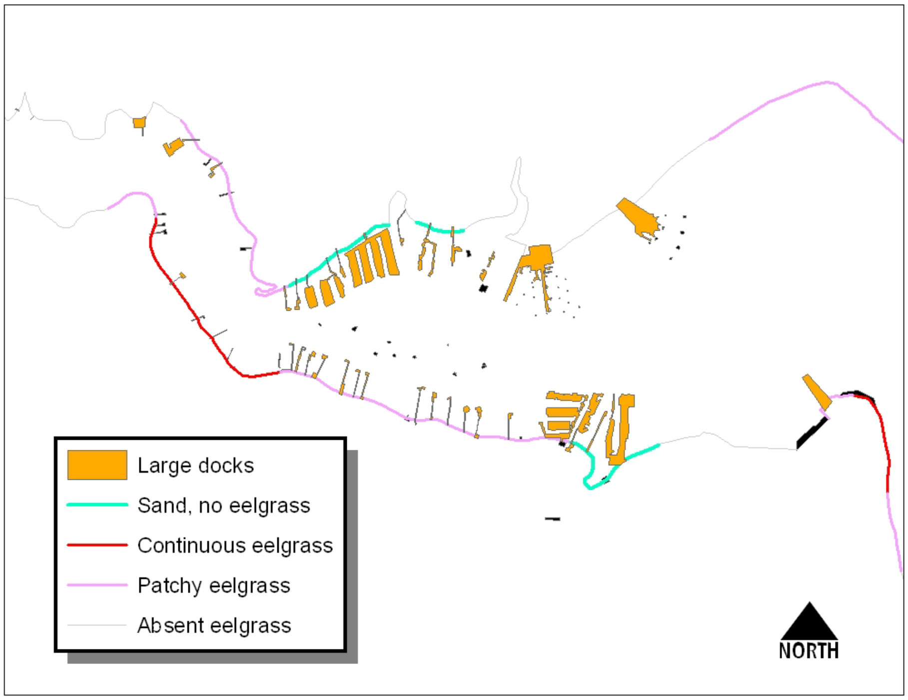

Fig. 5. Bainbridge Island marina as represent by GIS model

The overwater structures data suffer from the same limitations as the shoreline modification nominal data: they are too broad in nature to be a strong indicator for eelgrass presence. The types of overwater structures listed are *Bridge*, *Building*, *Buoy/Float*, *Dock/Pier*, *Fill* or *Other*. The size of any listed structure is given in acres, hectares, and square feet and varies from about 35 to 260,000 square feet. Attempting to correlate *Continuous* eelgrass to both structure type and size would probably be unnecessarily complex and fruitless. However, as seen in the Bainbridge Island marina images above, it seems reasonable to assume that large docks over a shore unit imply less light availability and more anthropogenic traffic and disturbance. The data includes a “Complexity” category, which estimates dock usage based on the size of the structure. *Simple* docks are interpreted to mean small docks for family or recreational use, whereas *Complex* docks are for community, commercial, or industrial use. For this model, shore units with a *Complex* dock presence were eliminated for consideration for replanting.

CREATION OF SITE SELECTION OUTPUT

ShoreZone data on *Continuous* eelgrass presence was correlated to the factors of substrate type, exposure class, and shoreline modification (extent and type). This was done by joining the eelgrass attribute table to each of the above layers in order. The Select by Attributes tool was used to create a selection linking *Continuous* eelgrass presence with each of the above criteria both by individual SVMP region and all the regions as a whole. While the entire region-wide data was sufficient to discover any correlation, individual zones were considered for practical purposes and the ability to practically represent the data on a map.

When the attribute tables were linked, simple if-then statements were used in the Select by Attributes tool to return a count of units that fit the criteria. For example, for the North Puget Sound SVMP zone, the following statement was used to return a value of *Continuous* eelgrass presence in areas with between 5% and 35% shore modification:

“eelline.EELGRASS” = “CONTINUOUS” AND
“shoremod.SM_TOT_PCT” > = 5 AND “shoremod.SM_TOT_PCT” < 36

where “eelline.EELGRASS” is the column in the eelgrass attribute table that contains the values of Continuous, Patchy, or Absent, and “shoremod.SM_TOT_PCT” is the column in the shoreline modification attribute table that contains the percentage of total modification. The previous statement returned 21 records out of 591, indicating that out of 591 North Puget Sound ShoreZone Units where shoreline modification was between 5% and 35%, 21 out of 591 (3.55 %) showed continuous eelgrass presence. Fig. 6 shows an image of the tool.

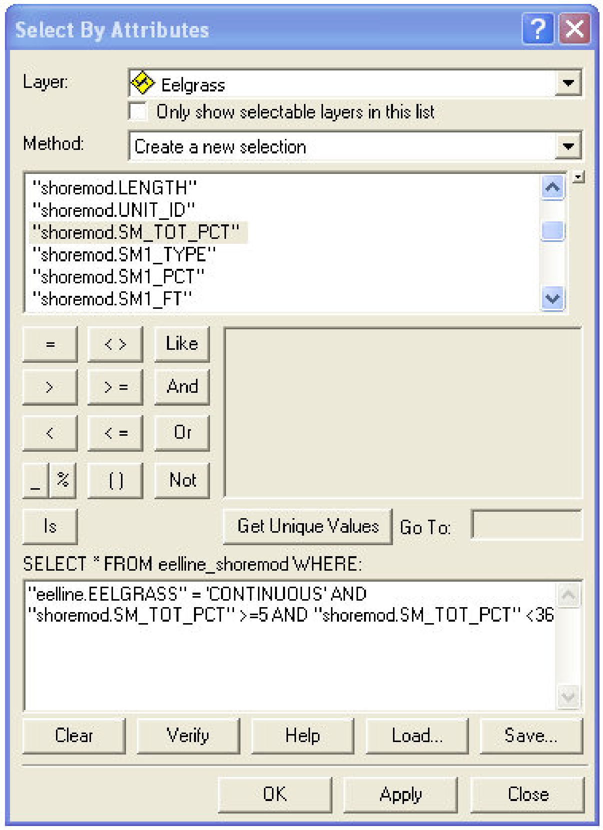

Fig. 6. ArcGIS 9.3 'Select by Attributes' tool as used

to restrict records to those fitting the selection criteria

Continuous eelgrass presence for each of 6460 units was correlated in this fashion to the following criteria from ShoreZone:

SUBSTRATE TYPE: *Man-Made*; *Rock*; *Gravel*; *Rock, Gravel, and Sand*; *Gravel and Sand*; *Mud and Fines*

EXPOSURE CLASS: *Very Exposed*; *Exposed*; *Semi-Exposed*; *Semi-Protected*; *Protected*; *Very Protected*

SHORELINE MODIFICATION (PERCENT): <5; 5-35; 36-65; 66-95; >95

Applying the Model Parameters. The criteria for determining optimum sites for eelgrass replanting were as follows:

- *Absent* existing eelgrass beds
- *Sand* substrate
- Shoreline modification >36%
- *Protected* exposure class
- No *Complex* large docks in the shore unit

A formula with these criteria was applied to every one of the 6460 ShoreZone shore units and the output was returned as 'Optimal Sites.' This is represented visually in the maps of each region given in Section IV.

IV. RESULTS

MODEL OUTPUT OF POTENTIAL REPLANTING SITES

The maps below were produced when the model was applied to the five SVMP zones in question. Sites selected as optimal for potential replanting are highlighted in bright blue. These sites show an ideal substrate, low levels of modification, absence of commercial or otherwise large overwater structures, no current *Continuous* eelgrass, and a *Protected* exposure class.

Areas that display current continuous eelgrass presence are highlighted in bright red for comparison. Aside from giving a visual impression of the extent of eelgrass in the zone and the consequent need (or lack of need) for replanting, proximity to existing eelgrass beds may be a factor when eliminating potential replanting sites, as dense local eelgrass might eliminate a site on the basis that natural recruitment is likely. Conversely, replanting sites too far away from existing eelgrass may cause logistical difficulties when it comes to obtaining donor shoots, which should for preference be done on the day of the transplanting to prevent shoot desiccation. For clarity, narrative interpreting each map has been incorporated into the captions for each map.

Since the zone maps are of a fairly small scale, close-up maps of areas of particular interest in each zone are included. These larger scale maps include place names in order to aid location, though any mapping program (such as Google Earth) should be sufficient to locate the replanting zones.

Table 3 below summarizes the relative abundance of eelgrass by region and the area available for replanting according to the model output. Note that this represents a linear measure of eelgrass presence along the shoreline and not an estimation of entire area colonized, and so cannot be compared with the estimates of eelgrass area in Section II.

Region	Length of shoreline (ft)	Length Continuous Eelgrass (ft)	Percent Continuous Eelgrass	Length Available (ft)	Percent Available
CPS	3,856,624	523,304	13.57%	211,514	5.48%
HDC	1,284,400	440,463	34.29%	207,834	16.18%
NPS	1,314,357	438,784	33.38%	68,137	5.18%
SJS	3,551,901	537,441	15.13%	101,239	2.85%
SWH	1,786,296	303,704	17.00%	66,379	3.72%
All Regions	11,793,578	2,243,695	19.02%	655,104	5.55%

Table 3. Continuous eelgrass and optimal replanting area by region

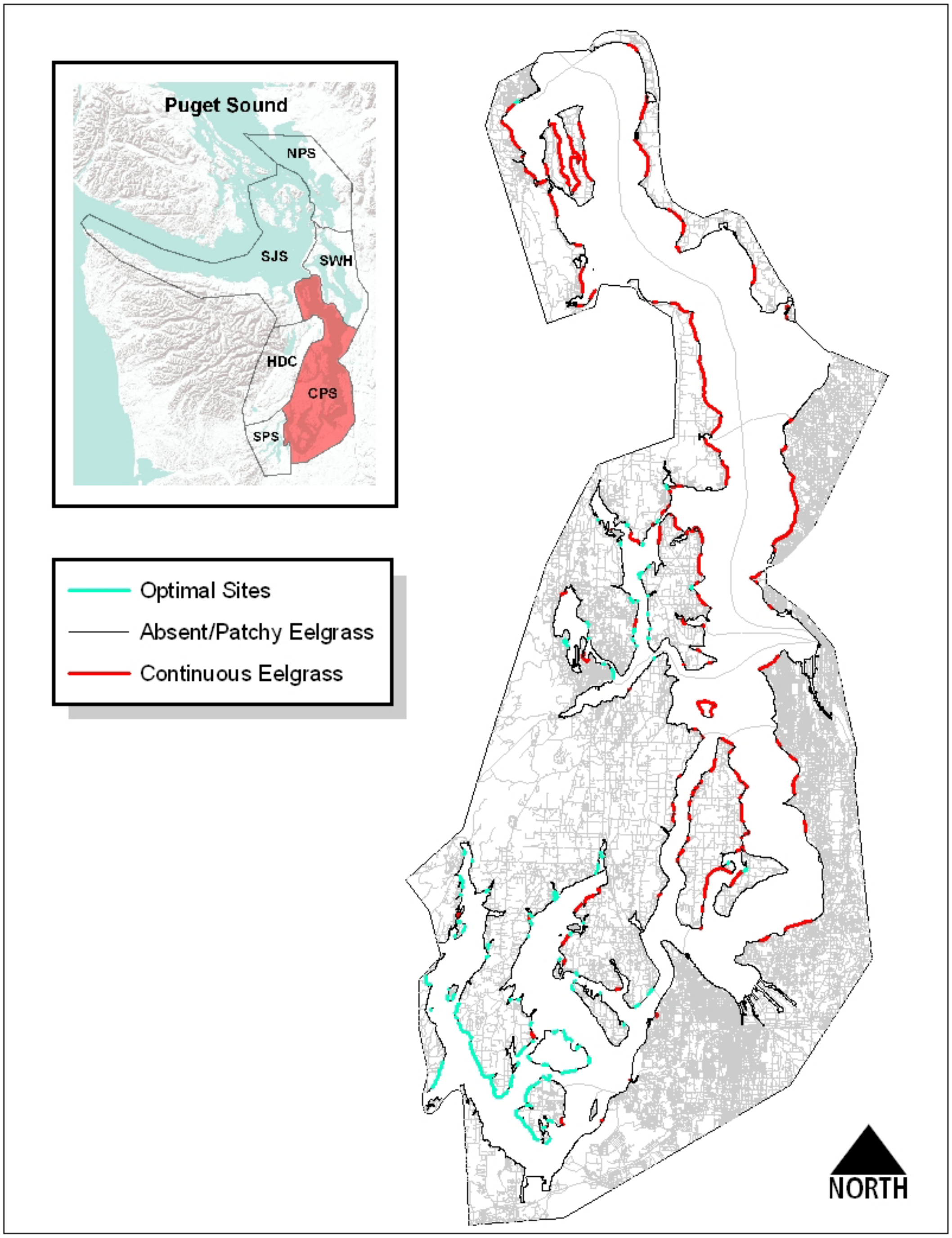

Fig. 7. Priority areas for Central Puget Sound

Since the southern area of this map has a high density of 'optimal' sites, one must question why eelgrass has not naturally recruited to the area. Due to the length of the inlets, it may be that the tidal range of the area is too extreme. This could be determined by supplemental field tests, but in the meantime it might be

better to focus on a location with more of a balance between absent and continuous eelgrass presence, such as the Bremerton area at the middle of the zone. A close up of the area follows.

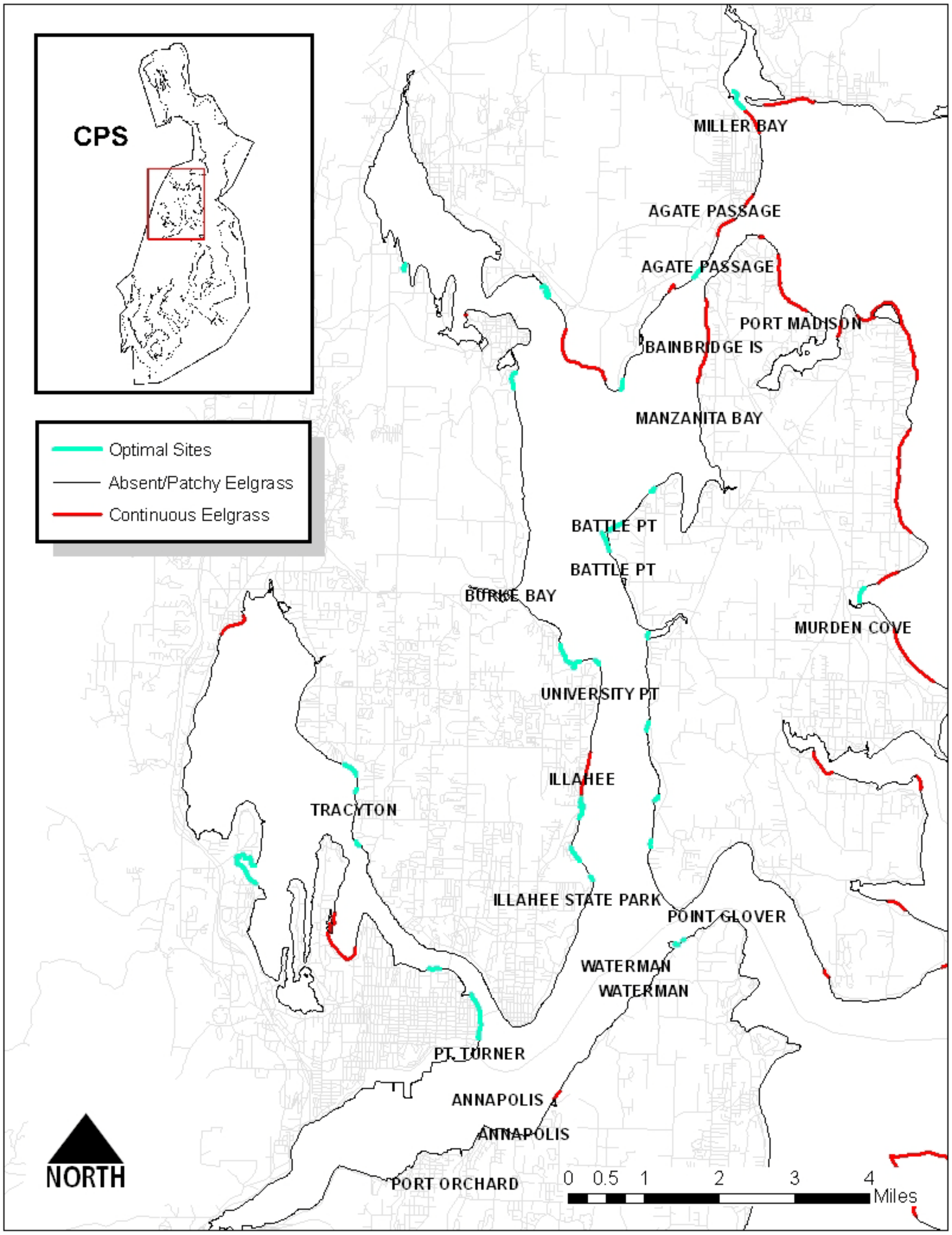

Fig. 7a. Priority areas for North Bremerton

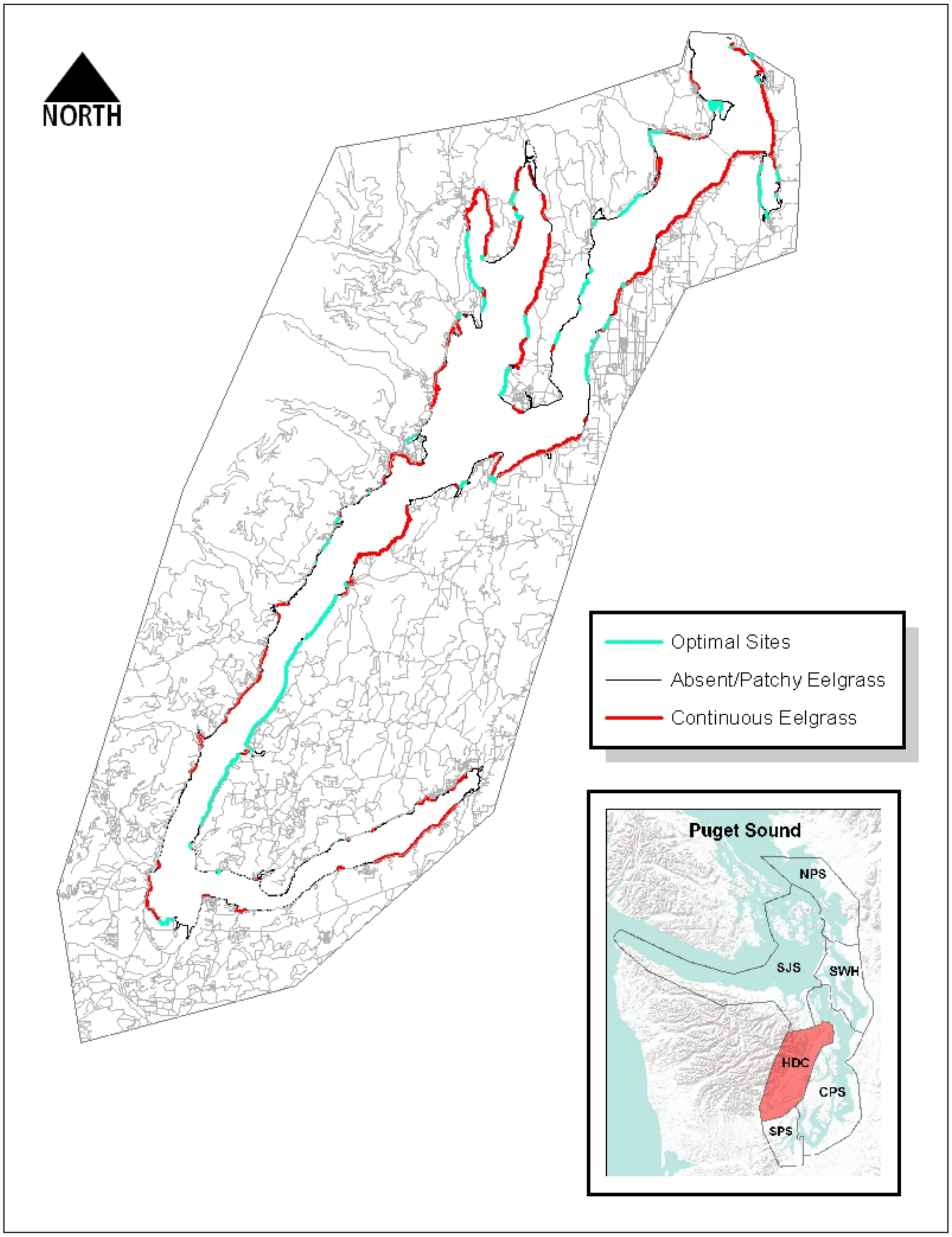

Fig. 8. Priority areas for Hood Canal

Again we see a large open area in the southern part of Hood Canal which appears to be ideal for eelgrass, as it may well be (the opposite shoreline demonstrates considerable eelgrass presence). Of more interest is the northern section where we see a good mix of available sites and donor sites.

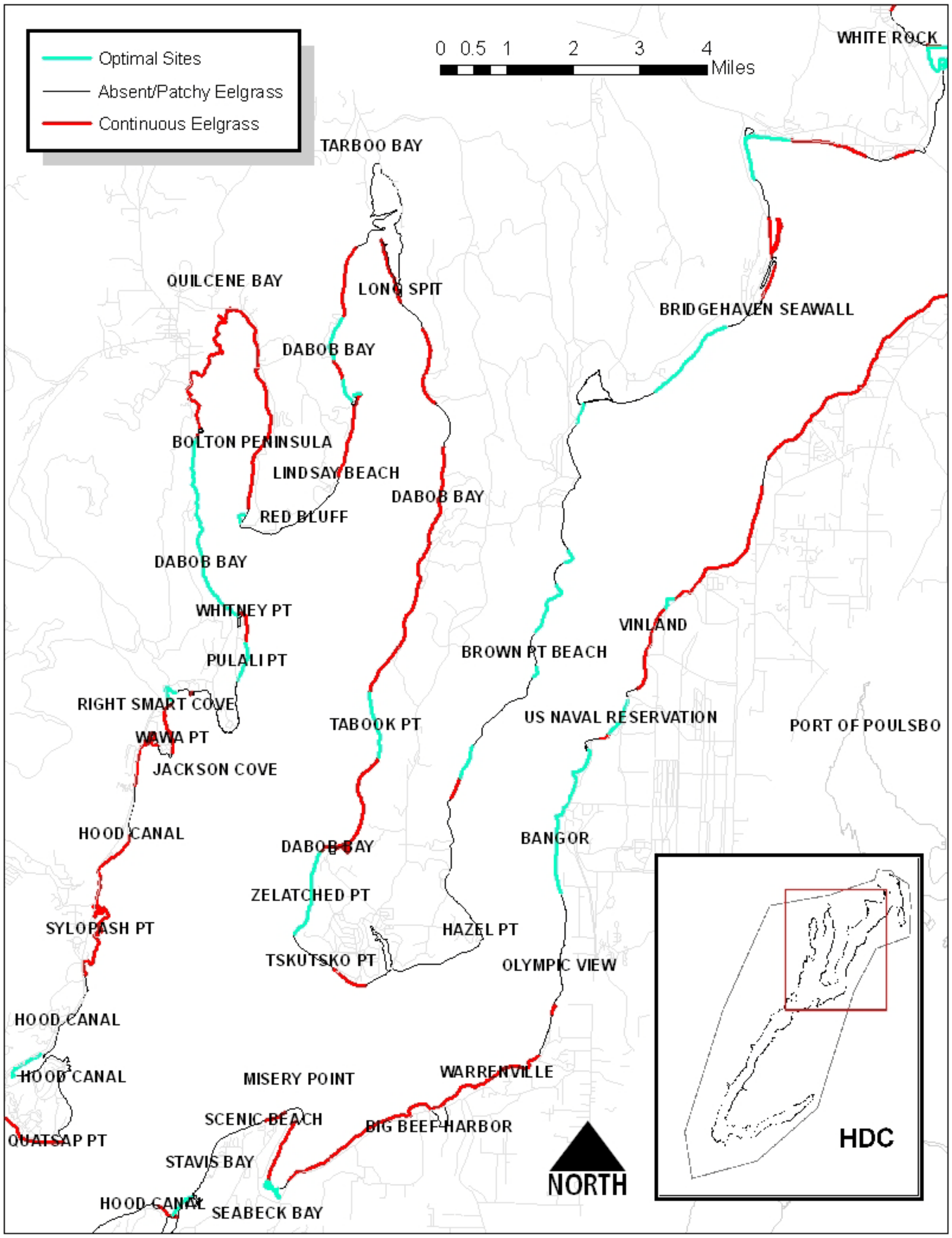

Fig. 8a. Priority areas for Quilcene-Poulsbo

There is a good mix here of eelgrass presence and absence although care should be taken to avoid replanting in areas that field tests indicate will likely experience natural recruitment.

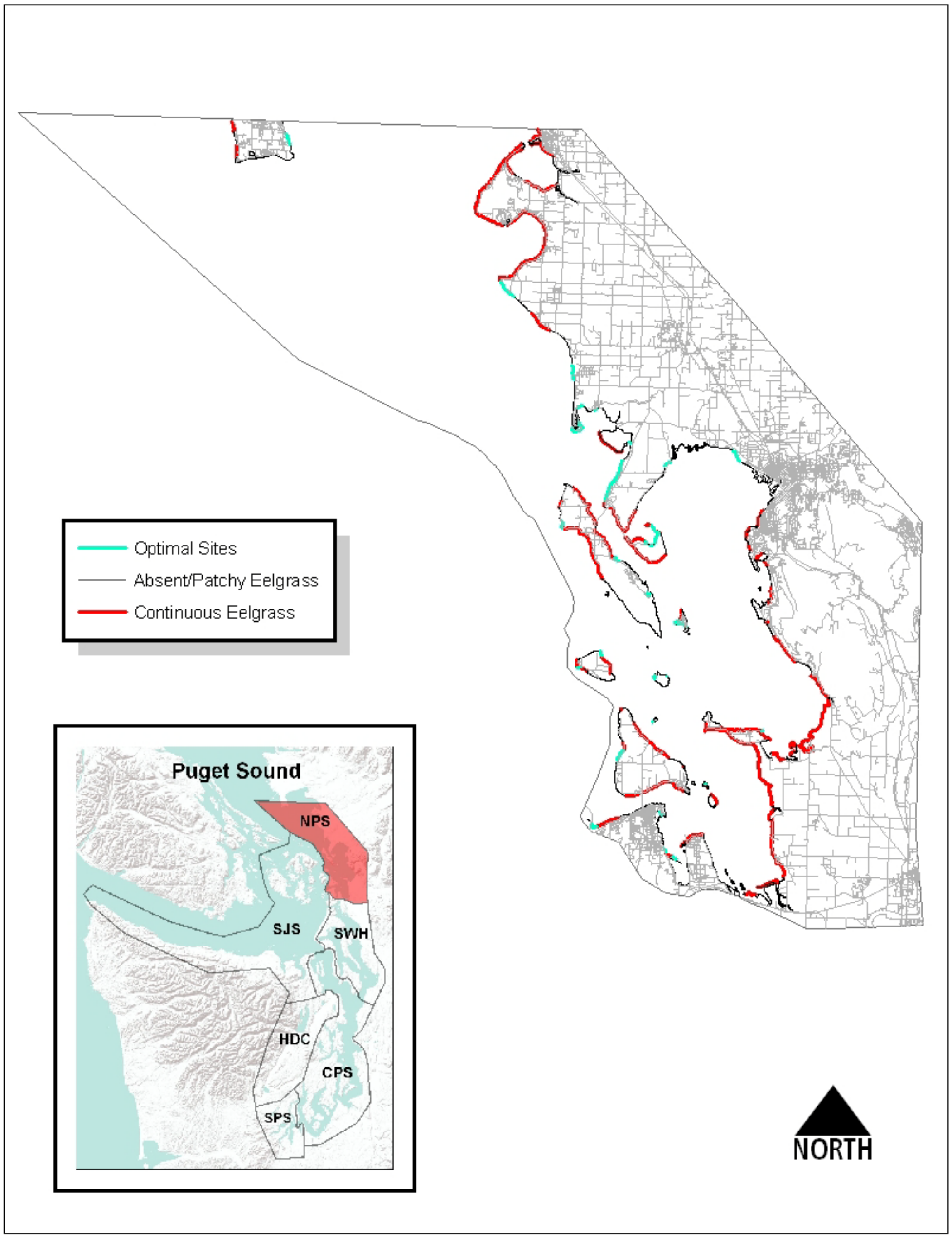

Fig. 9. Priority areas for North Puget Sound

North Puget Sound is already well populated with eelgrass and may not need restoration. The dominance of continuous beds indicate natural recruitment is likely. Some areas around Bellingham could pose potential sites.

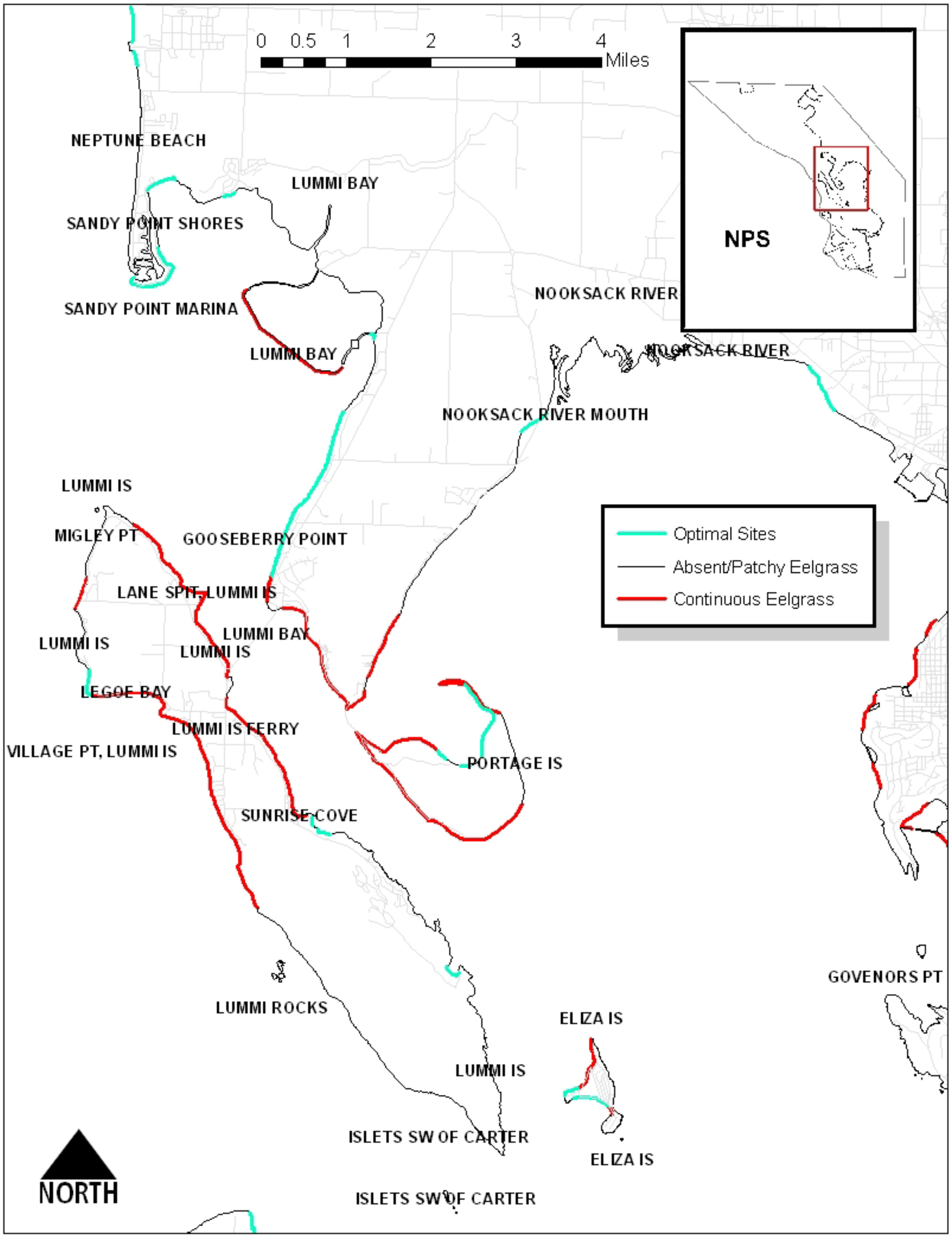

Fig. 9a. Priority areas for Bellingham area

Large stretches near Gooseberry Point and Sand Point are good candidates for eelgrass replanting. The sites near the Nooksack River mouth may not be suitable due to the influx of fresh water lowering local salinity to unacceptable levels.

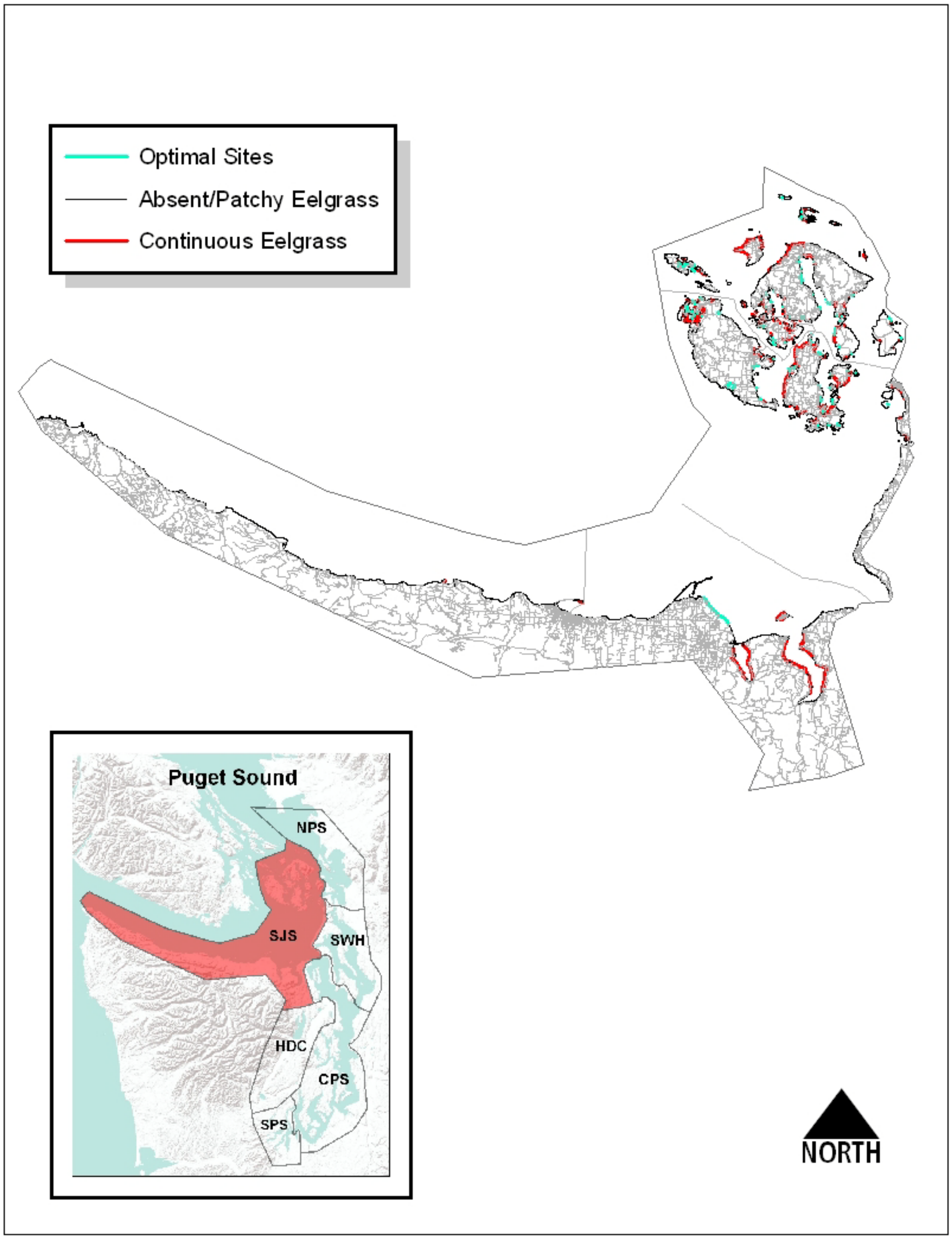

Fig. 10. Priority areas for San Juan Islands - Strait of Juan de Fuca

In this map the chief area of interest is the San Juan Islands, which experience a high degree of anthropogenic disturbance. There are no sites at all along the top of the Olympic Peninsula.

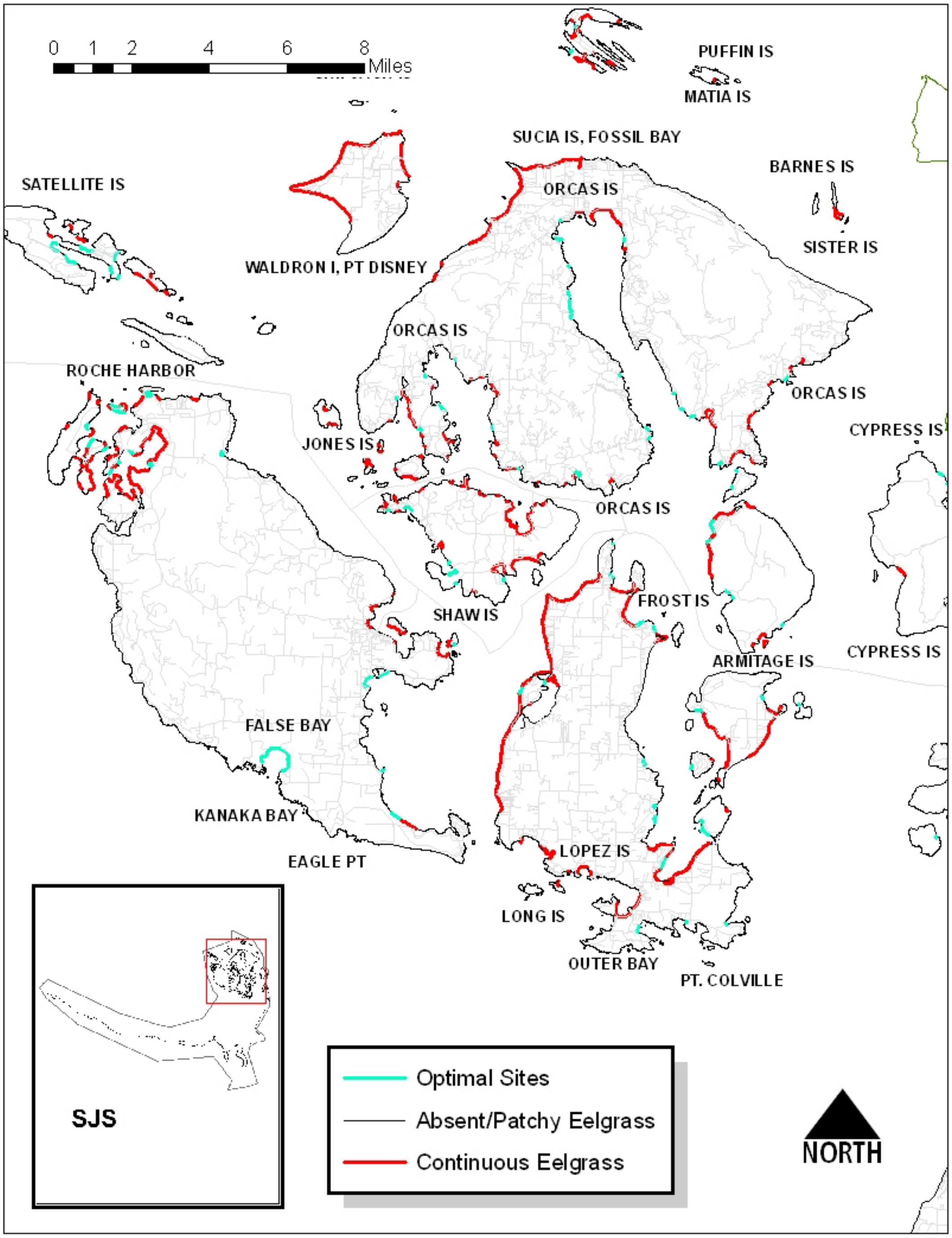

Fig. 10a. Priority areas for San Juan Islands

There are relatively few available sites on the San Juan Islands, implying that eelgrass has successfully recruited to all suitable areas already. Replanting efforts should perhaps be directed elsewhere.

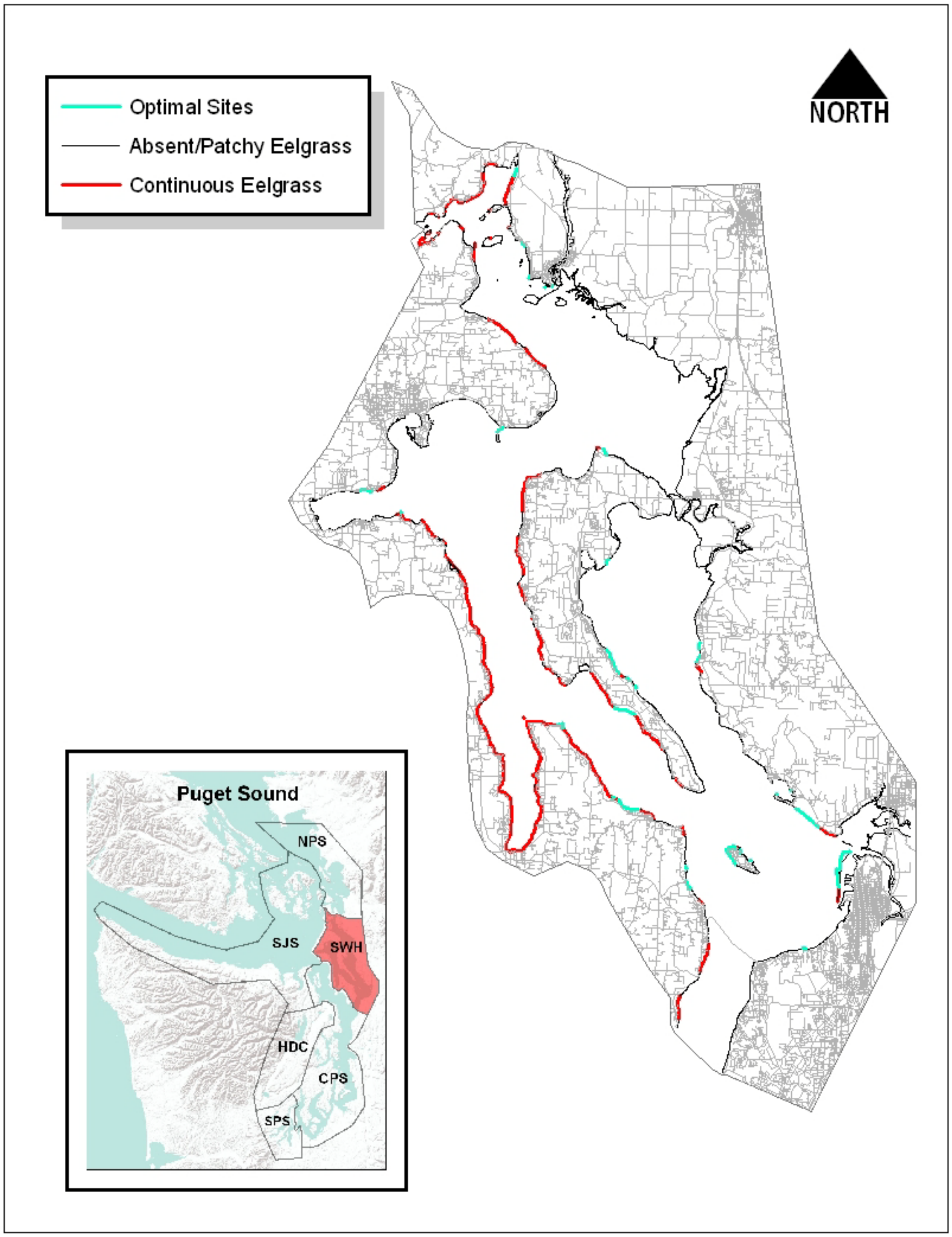

Fig. 11. Priority areas for Saratoga Passage - Whidbey Basin

Certain parts of this area are densely populated with eelgrass, leaving few sites with ideal conditions. Again, natural recruitment might be the best option. However, the area around Everett has some potential sites.

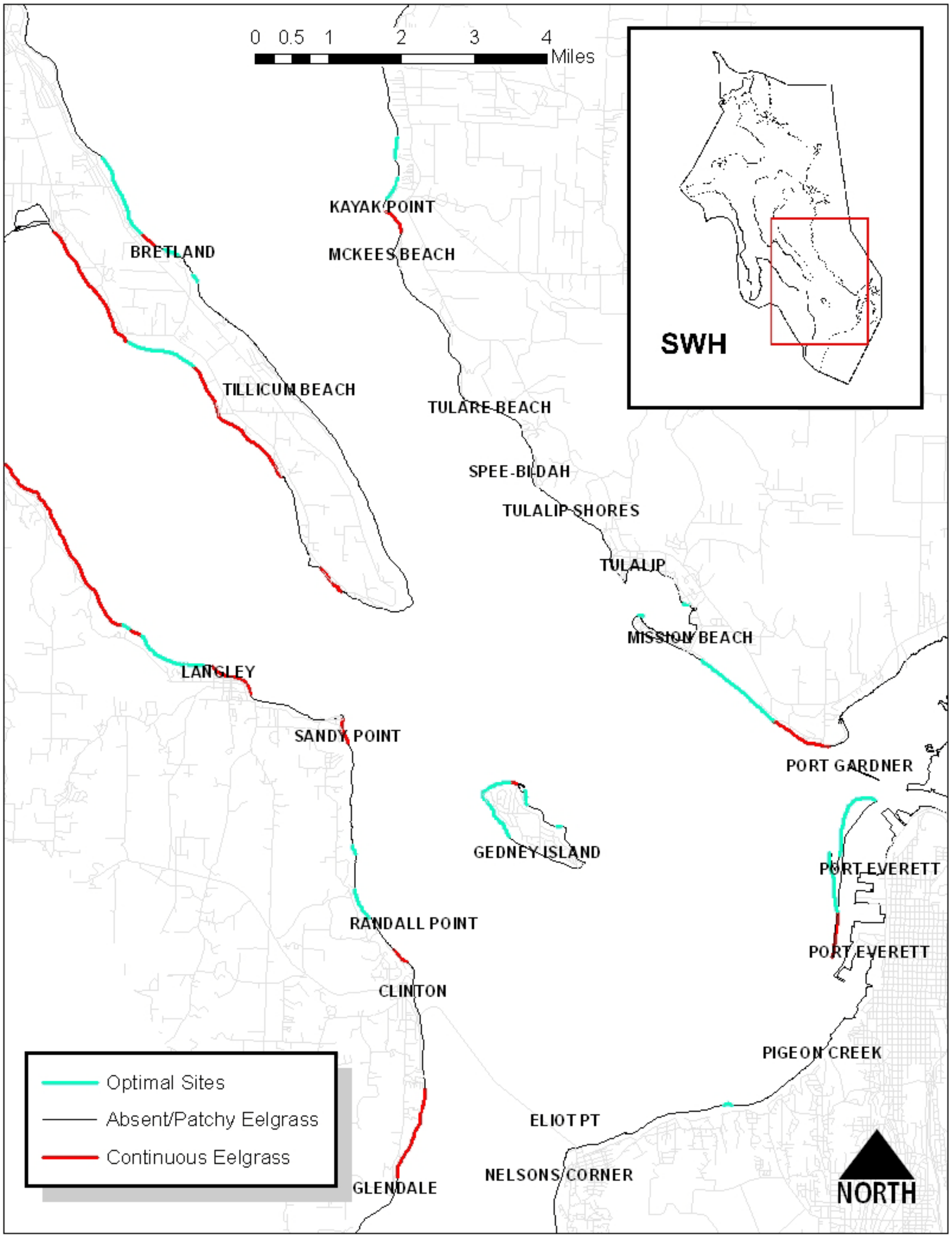

Fig. 11a. Priority areas for Everett area

Mission Beach, Kayak Point and Bretland all have stretches of approximately one mile that could be good sites for replanting.

V. DISCUSSION AND CONCLUSIONS

This work prioritizes locations in the SVMP regions of Puget Sound as the most suitable for further investigation for eelgrass replanting projects. These areas are recommended to practitioners as areas where transplanting resources should be focused. Because this model is based on a single, albeit complex, data set, it cannot make any claim of completeness without supplemental field data. Nevertheless, it provides a valuable starting point by narrowing down the vast length of Puget Sound shoreline into a few particularly likely locations. At this point, field research as well as the common sense of the restoring team must come into play.

Prioritization models have been used with success in other parts of the country, but Puget Sound still lacks a unified model. As with many environmental restoration efforts, reestablishing eelgrass beds is a political, economic, and scientific endeavor. Eelgrass restoration is a labor intensive and expensive process, usually requiring many workers and SCUBA divers, and restoration dollars are limited. What dollars are available must be spent wisely. An effective prioritization model for restoration site selection must be developed so that resources can be efficiently distributed.

The output of the model demonstrates the location of sites that, according to five basic but important parameters, appear to have near-ideal conditions for eelgrass growth. The question that must follow is, why has eelgrass not colonized these areas naturally? Only in some of the cases can the absence of eelgrass be explained by anthropogenic disturbance. Other limiting factors must be considered, such as inappropriate tidal ranges. For example, fig. 12 shows a map of Erlands Point in Bremerton where the 'optimal' site the model has selected for eelgrass replanting is highlighted in blue. Although it is not in the range of this map, continuous eelgrass grows in the area, indicating good general conditions. Fig. 13 is a photograph of the same area. A quick visual examination reveals this inlet is extremely shallow and thus experiences a tidal range that would most likely result in eelgrass desiccation. It must be eliminated from the model. Field experience is the best way to judge the locations the model selects as 'optimal.' In this case, an inlet is rejected in favor of a more open stretch of coastline.

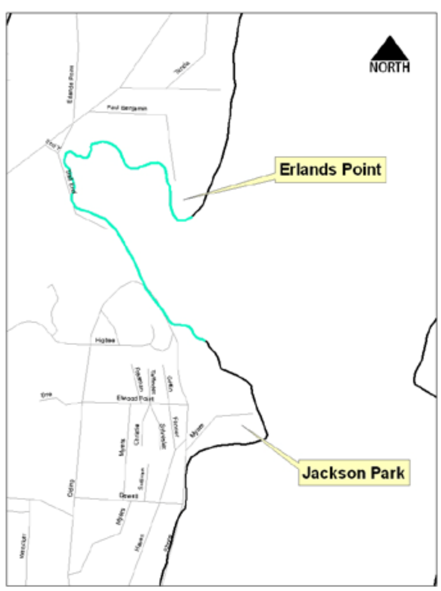

Fig. 12. Area in Bremerton showing model-selected 'optimal' site (blue)

Fig. 13. Erlands Point. Image courtesy of Google Earth. Retrieved 3/11/11. Image taken 7/9/07.

The findings of the model are preliminary at best and, as the above example demonstrates, require field tests to determine their real-world suitability in terms of tidal range, temperature, salinity, turbidity, as well as accessibility, proximity of donor beds, and the terms of the local coastal management plan. Additionally, as Thom et. al conclude, it is necessary to understand the reason behind the initial absence of eelgrass and correct it (Thom et al. 2008). The best current source for field test guidelines is the *Guidelines for the Conservation and Restoration of Seagrasses in the United States and Adjacent Waters* by Fonseca et al. (1998).

The ShoreZone Inventory is extensive but it was never intended to be superior to site-specific surveys (Berry et al. 2001). Most of the information contained within the data set was collected by helicopter using video imagery with locational information (GPS). A geomorphologist and a marine ecologist aboard the helicopter recorded continuous data on the physical and biological features of the shoreline. The wave exposure was estimated by combining the observed geomorphological data with a computer model that returned a modified effective fetch based on the GIS data of the shoreline characteristics. Eelgrass presence (classed as *Continuous*, *Patchy*, or *Absent*) was determined by the marine ecologist based on the aerial video. As such, the data produced is of a relatively low-resolution status. As Berry et al. put it in *The Washington State ShoreZone Inventory User's Manual,* when determining what features were included in the data, one should ask "Could I have seen the feature from the window of a helicopter traveling at 60mph and 300 feet above the ground?" (Berry et al. 2001)

Additionally, Puget Sound is a dynamic environment and the ShoreZone data set is at least ten years old. A certain amount of shoreline development, not included in the data set, will inevitably have occurred. Beaches and sandbars shift over time, particularly in response to shoreline armoring (Dugan et al. 2008). Eelgrass itself is not confined to the lines delimited by a data set but recruits over areas naturally (and existing beds die off).

GIS is a powerful tool for manipulating spatial data, but, like any other system, is only as good or up to date as the data input to it. While the ShoreZone data set is not continually updated, one of the great advantages of using GIS in creating models of the kind described in this thesis is that further surveys and updated data can be integrated into existing maps as those data are completed and made available. Any two data records that contain a common attribute, such as overlapping geographical location, can be related in GIS and an analysis performed. The model reported in this thesis could be made more effective by adding tidal range or turbidity data, for example. As an ever-increasing wealth of GIS data becomes available freely online from government agencies, a restoration team could produce a study similar to this one by using similar data and using this thesis as an exemplar. In that case, I would first recommend checking what data are available from the local Department of Natural Resources or equivalent body.

The Nearshore Habitat Program of the WA-DNR is currently (as of 2011) at work on a more comprehensive survey of eelgrass meadows using underwater videography, but this work is not expected to be completed for several years. Once it is complete we will have detailed knowledge of the extent of existing eelgrass meadows and can plan our restoration efforts accordingly, but that should not prevent us from acting now to restore this crucial habitat using the data we have.

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