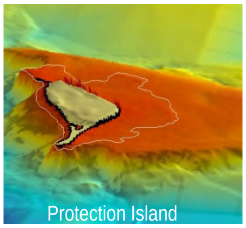
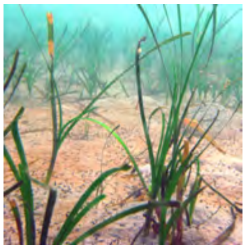
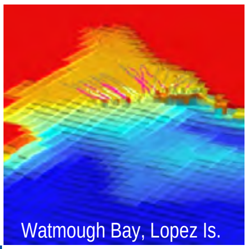
NATURAL RESOURCES

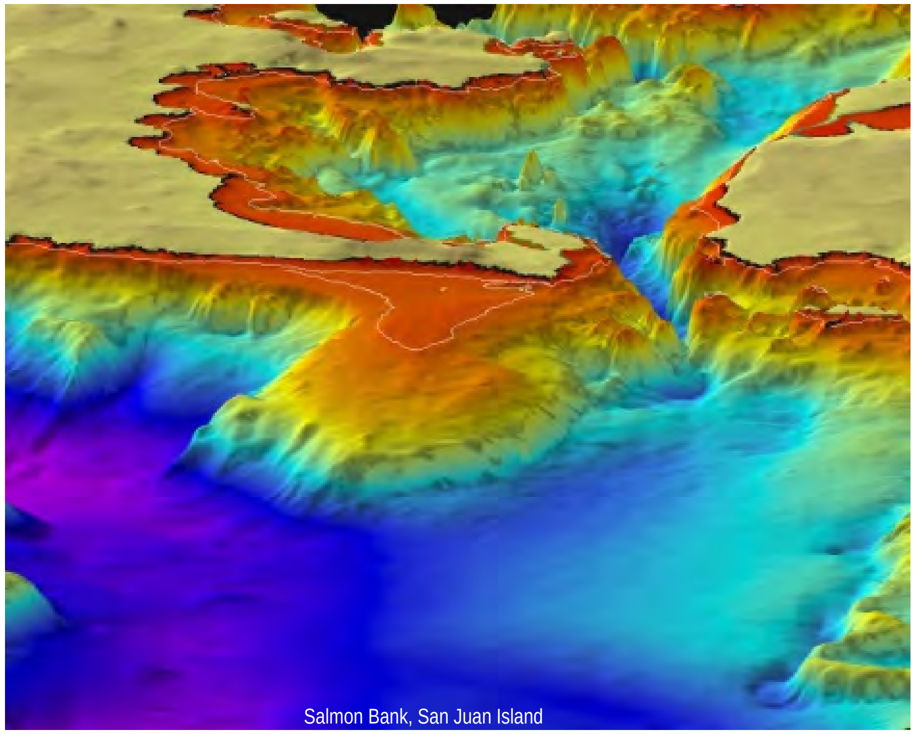


Protection Island





Watmough Bay, Lopez Is.



Salmon Bank, San Juan Island

Area of Eelgrass Depth Bands in Greater Puget Sound

March11, 2011

PSAMP
Puget Sound Assessment and Monitoring Program

WASHINGTON STATE DEPARTMENT OF
Natural Resources
Peter Goldmark - Commissioner of Public Lands

Cover Images (clockwise from upper left): (1) Protection Island with the lower limit of the eelgrass depth band approximated by the -20 ft bathymetric contour (white line); (2) Salmon Bank (San Juan Island) with the lower limit of the eelgrass depth band approximated by the -30 ft contour; (3) Watmough Bay (Lopez Island) showing the relatively course resolution of the 30 meter resolution Puget Sound DEM (Finlayson et al. 2000) and much higher resolution bathymetry retrieved from eelgrass monitoring transects; (4) Photo of eelgrass bed west of Dumas Bay (King County) (Photo: Helen Berry, DNR).

Area of Eelgrass Depth Bands in Greater Puget Sound

March 11, 2011

Pete Dowty

Nearshore Habitat Program
Aquatic Resources Division

PSAMP
Puget Sound Assessment and Monitoring Program

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Contents

EXECUTIVE SUMMARY

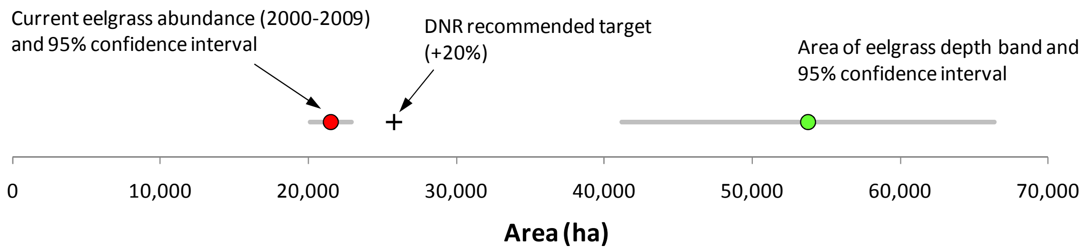
The Washington State Department of Natural Resources (DNR) is steward of 2.6 million acres of state-owned aquatic land. DNR manages these aquatic lands for the benefit of current and future citizens of Washington State. DNR's stewardship responsibilities include protection of eelgrass (*Zostera marina*), an important nearshore habitat in greater Puget Sound. In addition to its role as the 'indicator champion' for the Puget Sound eelgrass ecosystem indicator, DNR is contributing to the effort of the Puget Sound Partnership to set targets for key indicators, including eelgrass.

DNR has found that there is a need for more information on both the historical and potential distribution of eelgrass in greater Puget Sound to support target setting. The purpose of this report is to contribute in this area by presenting new estimates of the area within the eelgrass depth range in greater Puget Sound. This area is not equivalent to potential eelgrass area since, for example, many area within the depth band will rocky and will not support eelgrass which prefers sandy substrates. Nevertheless, the area of the depth band is a required starting point for developing estimates of potential eelgrass area.

The approach utilized available gridded bathymetry datasets and existing information on the distribution of eelgrass by depth. The project had substantial data processing requirements associated with transforming bathymetry data into the appropriate vertical datum (Mean Lower Low Water) and filling data gaps with new data.

Three bathymetry datasets were analyzed for this study. One was produced by the Washington State Department of Fish and Wildlife. The other two were produced by Dave Finlayson and colleagues at the University of Washington. Two sources were used to delineate eelgrass depth bands: the work of Ron Phillips from the 1970s based on field work from the 1960s, and the annual DNR eelgrass monitoring data collected since 2000.

The objectives of this study included the estimation of uncertainty in addition to the estimation of the area of the eelgrass depth band in greater Puget Sound. Results from the various bathymetry datasets were used to characterize uncertainty. The estimated area of the eelgrass depth band in greater Puget Sound was 53,785 ± 12,580 ha (95% confidence interval). This is a wider confidence interval than expected. Based on this estimate, the current regional percent cover of eelgrass is 40%. This estimate is shown in the figure below relative to the current eelgrass abundance and the DNR recommended eelgrass target that was adopted by the Puget Sound Partnership.



Current eelgrass abundance (2000-2009) and 95% confidence interval
DNR recommended target (+20%)
Area of eelgrass depth band and 95% confidence interval
0
10,000
20,000
30,000
40,000
50,000
60,000
70,000
Area (ha)

1 Introduction

The Washington State Department of Natural Resources (DNR) is steward of 2.6 million acres of state-owned aquatic land. DNR manages these aquatic lands for the benefit of current and future citizens of Washington State. Eelgrass (*Zostera marina*) is an important component of the public and private nearshore aquatic lands in greater Puget Sound. Eelgrass and other seagrasses are known to provide extensive ecosystem services worldwide (Costanza et al. 1997, Green and Short 2003, Larkum et al. 2006). In Puget Sound specifically, eelgrass provides spawning grounds for Pacific herring (*Clupea harengus* pallasi), out-migrating corridors for juvenile salmon (*Oncorhynchus* spp.) and important feeding and foraging habitats for waterbirds such as the Black Brant (*Branta bernicla*) and Great Blue Heron (*Ardea herodias*) (Phillips 1984, Simenstad 1994, Wilson and Atkinson 1995, Butler 1995).

In the legislation that created the Puget Sound Partnership (RCW 90.71.210), the new Science Panel was charged with identifying environmental indicators to measure the health of Puget Sound by July 31, 2008 (RCW 90.71.280 [3]) as well as benchmarks. This obligation was met on July 30, 2010 when the Leadership Council adopted the Dashboard of Ecosystem Indicators. Eelgrass was included as one of 20 indicators on the Dashboard and was placed on a short list of three indicators to be considered for initial target setting. DNR serves as the ‘indicator champion’ for the eelgrass indicator. The agency currently produces the state’s Puget Sound eelgrass indicator as part of its role in the Puget Sound Assessment and Monitoring Program (PSAMP).

DNR has found that there is a need for more information on both the historical and potential distribution of eelgrass in greater Puget Sound to support target setting for eelgrass (Dowty et al. 2010). The purpose of this report is to contribute in this area by presenting new estimates of the area within the eelgrass depth range in greater Puget Sound.

These estimates are not themselves estimates of potential eelgrass area – i.e. they do not represent the area that eelgrass could realistically occupy under current environmental conditions. Depth is only one of many environmental factors that constrain the distribution of eelgrass. Others include sediment type, temperature, salinity, and exposure. Potential eelgrass area will be the intersection of the tolerable limits of all these parameters. This will be a subset of the area of the eelgrass depth band. It is possible that as the Puget Sound system changes over time, the eelgrass depth band may shift.

The depth-based estimates reported here are intended to serve as useful reference points in assessing scenarios of eelgrass expansion and as a first step toward developing more realistic estimates of potential eelgrass area.

While the concept of finding the area within specific depth bands is straightforward, the task of calculating these areas was complicated by technical aspects of processing the available bathymetry data. For example, the available datasets used different vertical datums, or zero points for measuring depths. A Mean Lower Low Water (MLLW) datum is best for characterizing eelgrass depth because the elevation of MLLW is an important ecological constraint on eelgrass growth and survival. Above this elevation, there is periodic emersion at very low tides and it is a rough indication of upper limit of eelgrass growth. The depths of the shallow edge of eelgrass beds relative to Mean Sea Level (MSL) will vary widely across sites with different tidal ranges, thereby limiting the value of cross-site comparisons. In contrast, these depths would be relatively invariant when given relative to MLLW, thereby facilitating meaningful cross-site comparisons. Since the available bathymetry data were not all in a MLLW datum, transformations were necessary and this comprised a substantial portion of the overall effort in this study.

1.2 Objectives

The main objective of this work was to produce estimates of the area in greater Puget Sound within the depth band where eelgrass is found.

This work included the following sub-objectives:

- Convert existing bathymetry datasets from orthometric datums to a mean lower low water (MLLW) datum.
- Identify a depth band that generally represents the vertical distribution of eelgrass in greater Puget Sound, and find the area of this band.
- Estimate uncertainty associated with the area estimate for the eelgrass depth band.
- Assess sensitivity of the area of the eelgrass depth band to hypothetical elevation shifts associated with changing environmental conditions.
- Identify next steps to support eelgrass target setting and refinement, including develop of more realistic estimates of potential eelgrass area.

2 Methods

The approach utilized available gridded bathymetry datasets and existing information on the distribution of eelgrass by depth. The bathymetric data were converted to a MLLW datum when necessary, and then analyzed within a GIS to summarize the area within specific depth limits associated with eelgrass presence.

2.1 Bathymetry Datasets

Three bathymetry datasets were analyzed for this study. One was produced by the Washington State Department of Fish and Wildlife. The other two were produced by Dave Finlayson and colleagues at the University of Washington. Other datasets were available but were not included because of limited spatial extent or resolution. These include datasets for Puget Sound proper (NOAA National Ocean Service 2008; 30 m resolution), the coastal U.S. (NOAA Geophysical Data Center 2010; 90 m resolution), and the entire earth (Amante and Eakins 2009; 1.8 km resolution).

2.1.1 WDFW PSAMP Bathymetry (1999)

The Marine Bird and Marine Mammal Component of PSAMP produced a digital bathymetry dataset for all Washington State marine waters in 1999 (Nysewander et al. 2005). The dataset was created through a contract with Environmental Consultants Inc. (ECI) of Portland, Oregon. Point soundings from NOAA's National Ocean Service (NOS) Hydrographic Survey Data CD product v3.3 and Canadian sources were used to create a gridded surface. The vertical datum of this dataset is MLLW, so no datum conversion was necessary. Specifics of the interpolation algorithm used by ECI are not given in the metadata accompanying the dataset, but it produced clear point artifacts in the dataset. There is also limited coverage in the shallow areas of some embayments (Figure 2-1).

DNR obtained the original dataset, which contained two products – a "nearshore" version in a State Plane projection and a complete version in UTM Zone 10 projection. DNR has updated this dataset as agency GIS standards have changed. The nearshore version used for this study has the characteristics shown in Table 2-1.

2.1.2 Finlayson et al. 2000 Augmented

The Finlayson et al. 2000 dataset combines bathymetry and topography for the entire Puget Sound basin. The bathymetric portion was generated from soundings in the NOAA National Ocean Service (NOS) GEODAS database (Figure 2-2). This dataset is distributed by the University of Washington with the characteristics shown in Table 2-2. The elevation values were transformed to a MLLW datum prior to analysis using

NOAA's VDatum tool, version 2.3.2 (Parker et al. 2003, NOAA 2010). The raster data was first converted to a series of ASCII x,y,z triplets (51,224,000 triplets) to meet VDatum input requirements. In order to make the dataset more manageable, the nearshore portion was extracted (between +15 m and -30 m NGVD29) and only these nearshore *z*-values were transformed to a MLLW datum (4,792,584 triplets).

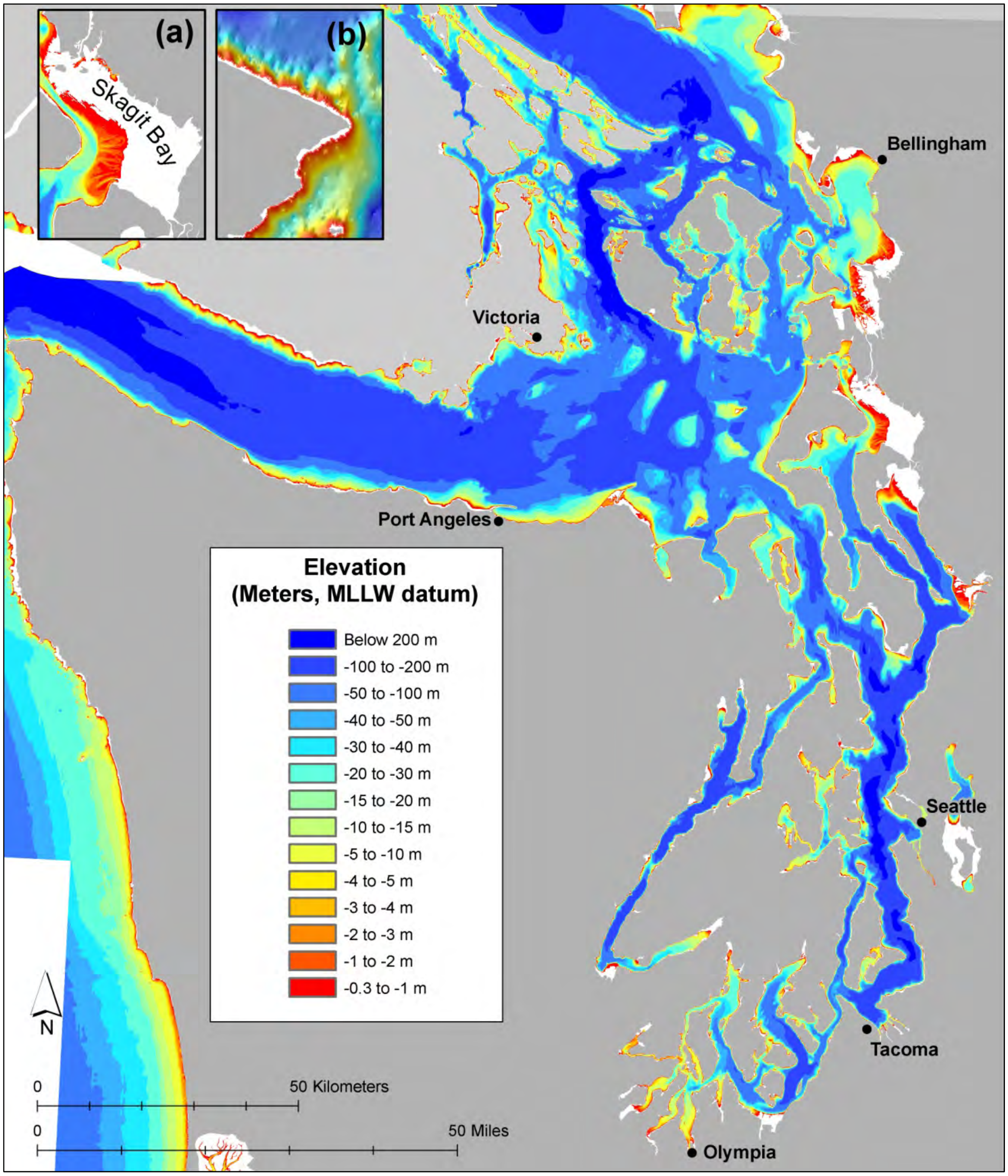


Figure 2-1. The nearshore version of the WDFW PSAMP bathymetric dataset with 19.8 m (65 ft) resolution. The inset maps show (a) an example of the limited coverage in the shallow areas of some embayments, and (b) an example of point artifacts – a dimpled appearance - likely associated with limitations of the interpolation algorithm (note that colors on this inset map do not correspond to the legend).

Table 2-1. Parameters of the WDFW PSAMP bathymetry dataset.

Parameter	Value
file format	ERDAS Imagine raster (13,195 x 22,636 pixels) 16-bit unsigned integer (greater depths are larger positive numbers)
projection	State Plane, Washington South Zone
horizontal datum	NAD83 HARN
horizontal units	US survey feet
horizontal resolution	65 feet (19.8 meters)
vertical datum	MLLW
vertical units	feet

The *z*-values output from VDatum were real numbers (floating point) in decimeters. These values were rounded to integer decimeters. The raster grid was then reconstructed from the transformed MLLW *z*-values and the original *x*,*y*-values in a UTM projection. The manipulations of ASCII data (triplets, ASCII grid) were conducted with Python programs run on Sun Solaris computers. VDatum is a Java program available as a jar file that had to be run on a Microsoft Windows computer for the program to handle the NAD27 and NGVD29 datums correctly. A bug in the UNIX version of VDatum has since been fixed in version 2.3.3. Additional detail on vertical datums is given in Appendix A (p. 45).

This dataset has a major area of missing data east of the San Juan Islands (Figure 2-2). The dataset was augmented with hydrographic survey data from NOS to fill this area of missing data (NOAA National Ocean Service 2010). A total of 210,954 soundings from seven surveys were retrieved from the NOS database. Six surveys were conducted between 1998 and 2004 (H10766, H10887, H10922, H10792, H11268, H11269) and one older survey was from 1955 (H08331). All survey data used a MLLW vertical datum. Several points were added to these soundings using elevations from the surrounding transformed Finlayson data to expand coverage of the point data and improve continuity. Ordinary kriging (ArcGIS Spatial Analyst 9.3) with 12-point interpolation was used to create a bathymetric surface in the area of missing data with 30 m horizontal resolution with depths in integer centimeters. More details on the use

Table 2-2. Parameters of the Finlayson et al. 2000 dataset.

Parameter	Value
file format	ESRI ASCII grid (6,740 x 7,600 pixels) signed integers (greater depths are more negative numbers)
projection	UTM Zone 10 North
horizontal datum	NAD27
horizontal units	meters
horizontal resolution	30 meters
vertical datum	NGVD29
vertical units	decimeters

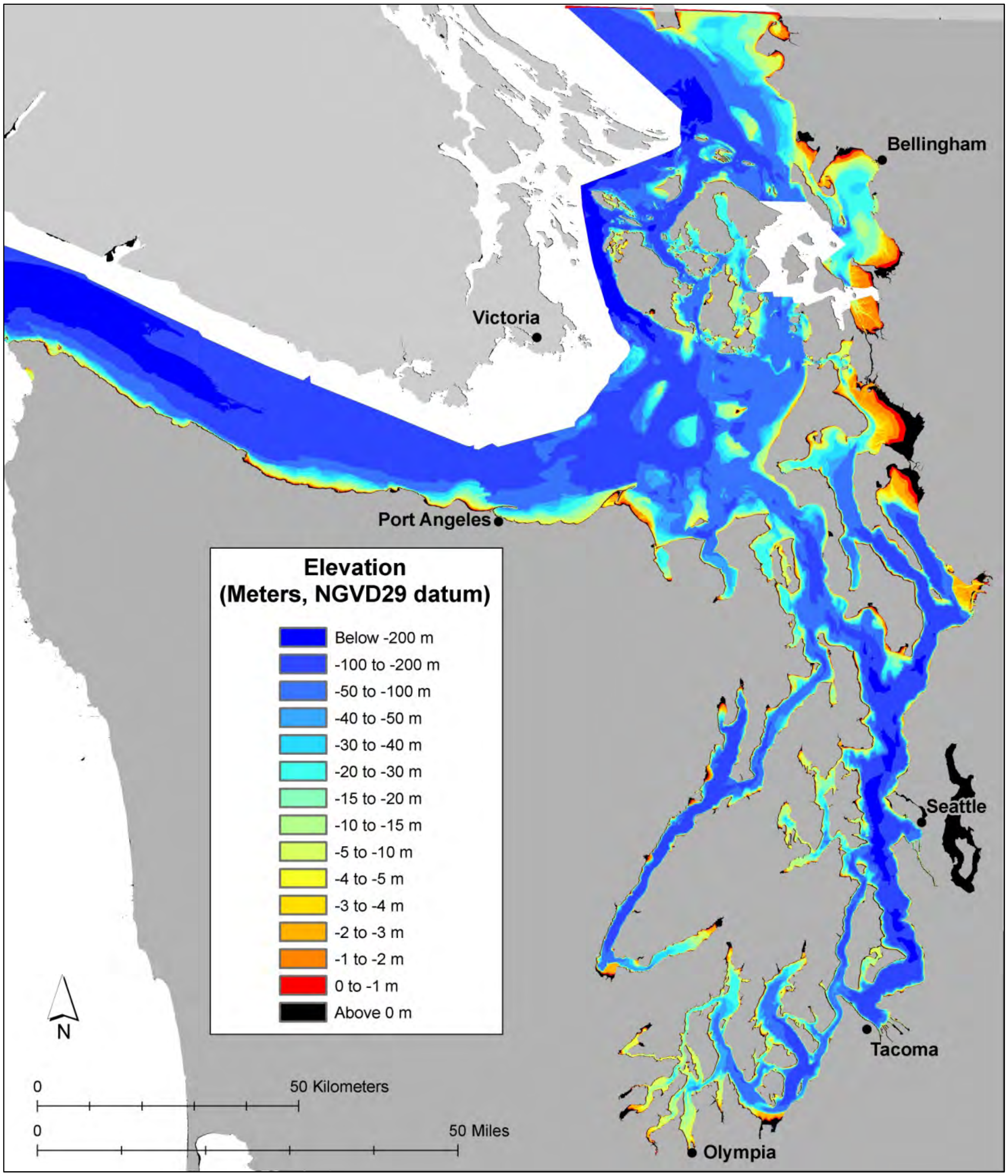


Figure 2-2. The bathymetric portion of the Finlayson et al. 2000 dataset with 30 m resolution.

of the NOAA soundings is given in Appendix B (p. 49).

2.1.3 Finlayson 2005

The Finlayson 2005 dataset improved the resolution of the 2000 dataset and incorporated additional data sources including multibeam sonar and water-penetrating LIDAR (Finlayson 2005). However the spatial extent of this dataset is much more restricted and no longer covers the greater Puget Sound study area (Figure 2-3).

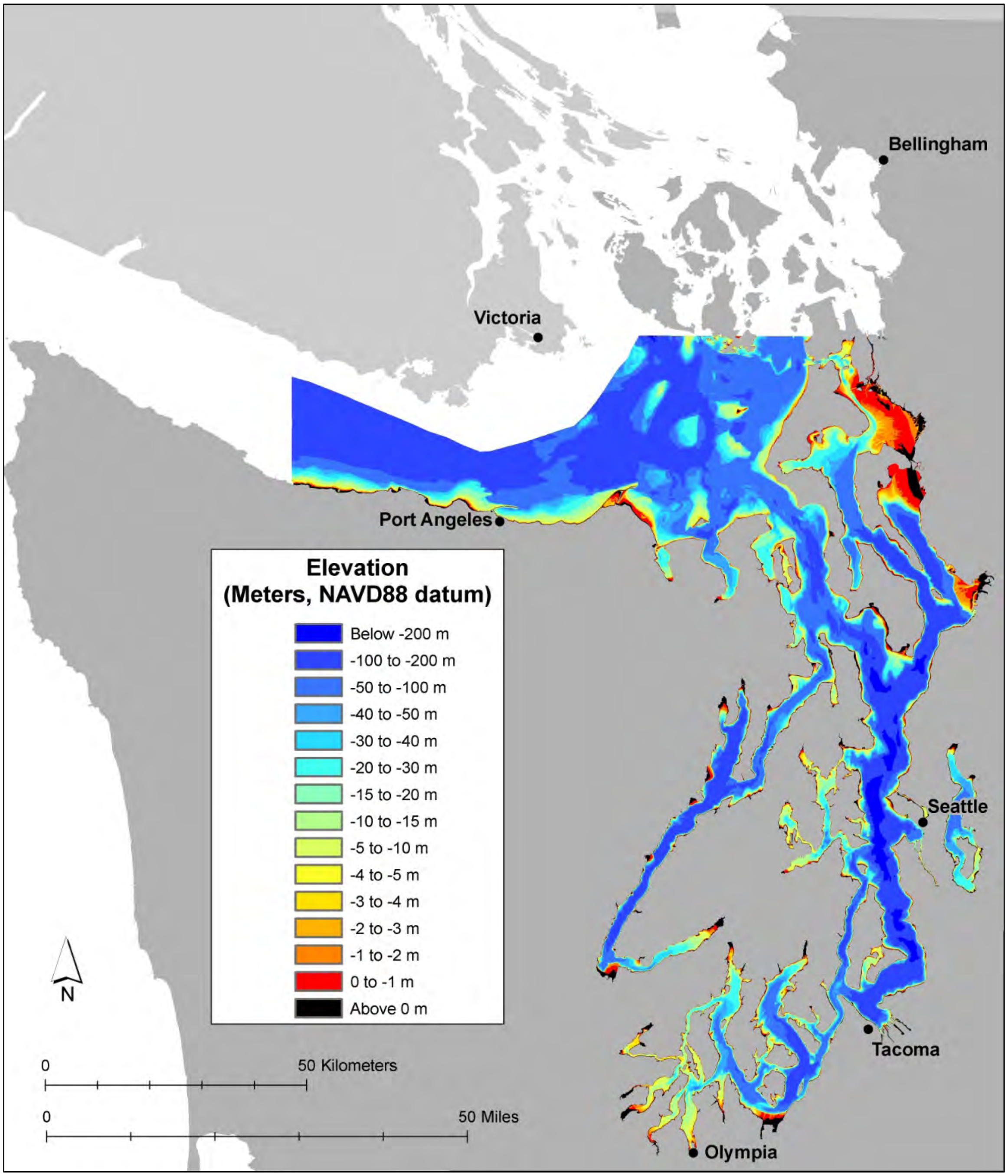


Figure 2-3. The bathymetric portion of the Finlayson 2005 dataset with 9.1 m (30 ft) resolution.

This dataset is distributed by the University of Washington with the parameters given in Table 2-3.

The elevation values were transformed to a MLLW datum prior to analysis using NOAA's VDatum tool, version 2.3.2 (Parker et al. 2003, NOAA 2010). The raster data was first converted to a series of ASCII x,y,z triplets (305,600,952 triplets). Because of the size of this dataset, the nearshore portion was extracted (between

+15 m and -30 m NAVD88) and only this portion was transformed (30,111,930 triplets). These nearshore ASCII triplets were divided into 31 separate files to make the processing times more manageable for each file. The triplets were imported into ArcGIS as point shapefiles and the *x,y* coordinates were projected to UTM to meet VDatum input requirements. The UTM *x,y* coordinates were exported back to ASCII triplets and VDatum was then used to convert the *z* values to a MLLW datum. The *z*-values output from VDatum were real numbers (floating point) in feet. These values were rounded to integer feet. The raster grid was then reconstructed from the MLLW *z*-values in feet and the original *x,y*-values in State Plane projection. The manipulations of ASCII data (triplets and ASCII grid) were conducted with Python programs run on a Sun Solaris computer. Processing within ArcGIS was conducted with ArcToolbox models constructed with ModelBuilder. VDatum is a Java program available as a jar file. VDatum was run on a Sun Solaris computer for the processing of this dataset. More details on the use of the NOAA soundings are given in Appendix B (p. 49).

Table 2-3. Parameters of the Finlayson 2005 dataset.

Parameter	Value
file format	ESRI ASCII grid (16,406 x 18,692 pixels) signed integers (greater depths are more negative numbers)
projection	State Plane, Washington North Zone
horizontal datum	NAD83 HARN
horizontal units	US survey feet
horizontal resolution	30 feet (9.1 meters)
vertical datum	NAVD88
vertical units	feet

2.2 Depth Bands

2.2.1 Phillips' Observed Depth Band

Ron Phillips conducted field surveys of 101 sites in 1962-63 within Puget Sound proper. Sixty-five sites were surveyed using SCUBA with the remainder sampled by dredging (Phillips 1972, pp. 26, 30). Phillips concluded from these surveys that "virtually all measurements made in Puget Sound demonstrate that *Zostera* is restricted to a belt from MLLW (mean lower low water) to a depth of -22 feet (-6.6 meters)" (Phillips 1972, p.34). This is referred to here as the Phillips depth band.

Phillips distinguished between this depth band and the wider band that encompasses infrequent observations at extreme shallow and deep depths. His extreme observations were +1.5 m MLLW at the shallow end and -6.9 m MLLW at the deep end (Phillips 1974, p.34).

2.2.2 McClellan (Phillips' Modeled Depth Band)

Phillips relied on the bathymetry-area analysis of McClellan (1954) to model the area of his eelgrass depth band across Puget Sound proper. Phillips was forced to use a depth band that differed from his observed band because the depth increments used by McClellan (1954) did not match his depth band limits. The McClellan depth band used by Phillips' to model the regional eelgrass depth band was MLLW to -3 fathoms (-5.5 m = -18 ft).

2.2.3 SVMP Region Depth Bands

The 2000-2008 SVMP dataset contains detailed information on eelgrass distribution by depth across the SVMP study area. To date, regional scale analysis of the depth data has been restricted to:

(a) Tracking the overall shallowest and overall deepest observations of eelgrass within each SVMP region (Gaeckle et al. 2009). The extreme values over 2000-2008 are indicated in Figure 2-5.

(b) A compilation and analysis of histograms showing the frequency of eelgrass observations by depth within each SVMP region based on 2002-2004 data encompassing 88 sites (Selleck et al. 2005) (Figure 2-4).

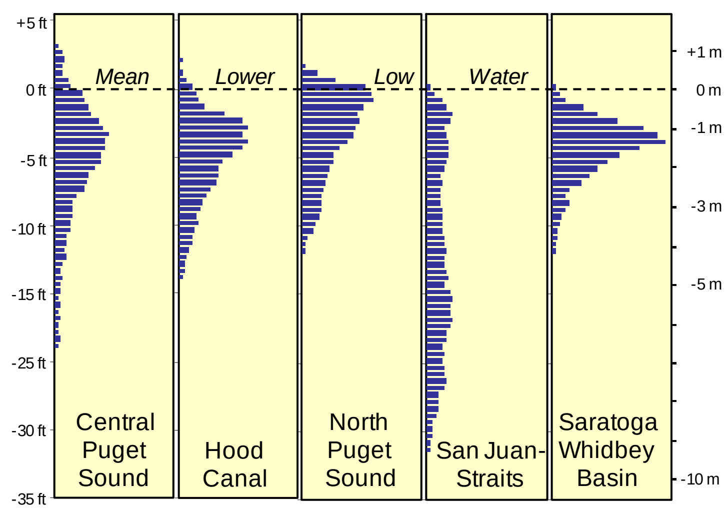


Figure 2-4. Depth profiles of eelgrass within the five SVMP regions based on 2002-2004 SVMP data (data from Selleck et al. 2005).

The histograms of Selleck et al. (2005) were used to develop separate eelgrass depth bands for each of the five SVMP reigons (see Figure 2-6, p. 14). The histograms have depth bins of width 15 cm (0.5 ft), and this is subsequently the vertical resolution of the depth bands. The approach followed Phillips (1972) in that the few eelgrass observations at extreme elevations (shallow and deep) were not included in the depth bands. This avoids expanding the bands to include habitat depths that do not support eelgrass except in rare circumstances. This was done by isolating the histogram depth bins that encompassed roughly 98% of the eelgrass observations within each region.

The bins that included observations of approximately the extreme 1% on each of the shallow and deep tails of the histogram were not included. These depth bands are referred to as the 1-99 percentile bands. The resulting depth bands are compared to the Phillips' observed depth band and the McClellan depth band in Figure 2-5.

The southern reaches of Puget Sound that are outside the SVMP study area (Figure 2-6) were effectively treated as a sixth region, Southern Puget Sound (SPS), and were essentially assigned a null depth band. Eelgrass is virtually absent in this area and so there was no depth that was considered to support eelgrass.

2.3 GIS Analysis

Once the bathymetry raster layers had been prepared (Section 2.1), analysis was conducted in ArcGIS 9.3.1. First, the derived datasets were examined to assess the effects of the datum transformations. Also, the data used to augment the transformed data from Finalyson et al. 2000 was examined for discrepancies when compared to the adjacent data in Finlayson et al. 2000.

Following this initial data review, the distribution of area by depth was examined with frequency histograms. These historgrams were developed in the original vertical units of each dataset (feet or meters). The 'zonal histogram' function in Spatial Analyst was used to produce histograms of pixel counts by depth within zones specified by a vector data layer. The output is in the form of a dbf table which was then processed in Excel by summing pixel counts across the depth bins for each eelgrass depth band. Pixel counts were converted to area values using the dataset pixel size.

Analysis was conducted at three spatial extents by using different vectors layers to define the zones. The three spatial extents include (Figure 2-6):

- Puget Sound proper
- Greater Puget Sound
- SVMP study area

The definition of Puget Sound proper used here was that of McClellan (1954). In relying on McClellan's bathymetry-area analysis, Phillips (1972) in effect adopted this definition, although his text describes a slightly different boundary at the northern end of Admiralty Inlet. Puget Sound proper was included in the analysis here so that comparisons could be made to the estimates of Phillips (1972, 1974) and Thayer and Phillips (1977). Greater Puget Sound includes all marine waters out to the western-most SVMP sampling site at Point Flattery. The SVMP study area is equivalent to greater Puget Sound except that the southern reaches beyond Dana Passage and Pickering Passage as well as Henderson Inlet are excluded. Native eelgrass (*Zostera marina*) observations in these areas are very rare.

Once the area of the eelgrass depth bands was determined, several hypothetical scenarios were considered that perturb the existing depth bands because of changing environmental conditions. The areas of the perturbed depth bands was determined under these scenarios. First, the effect on depth band area was determined as the

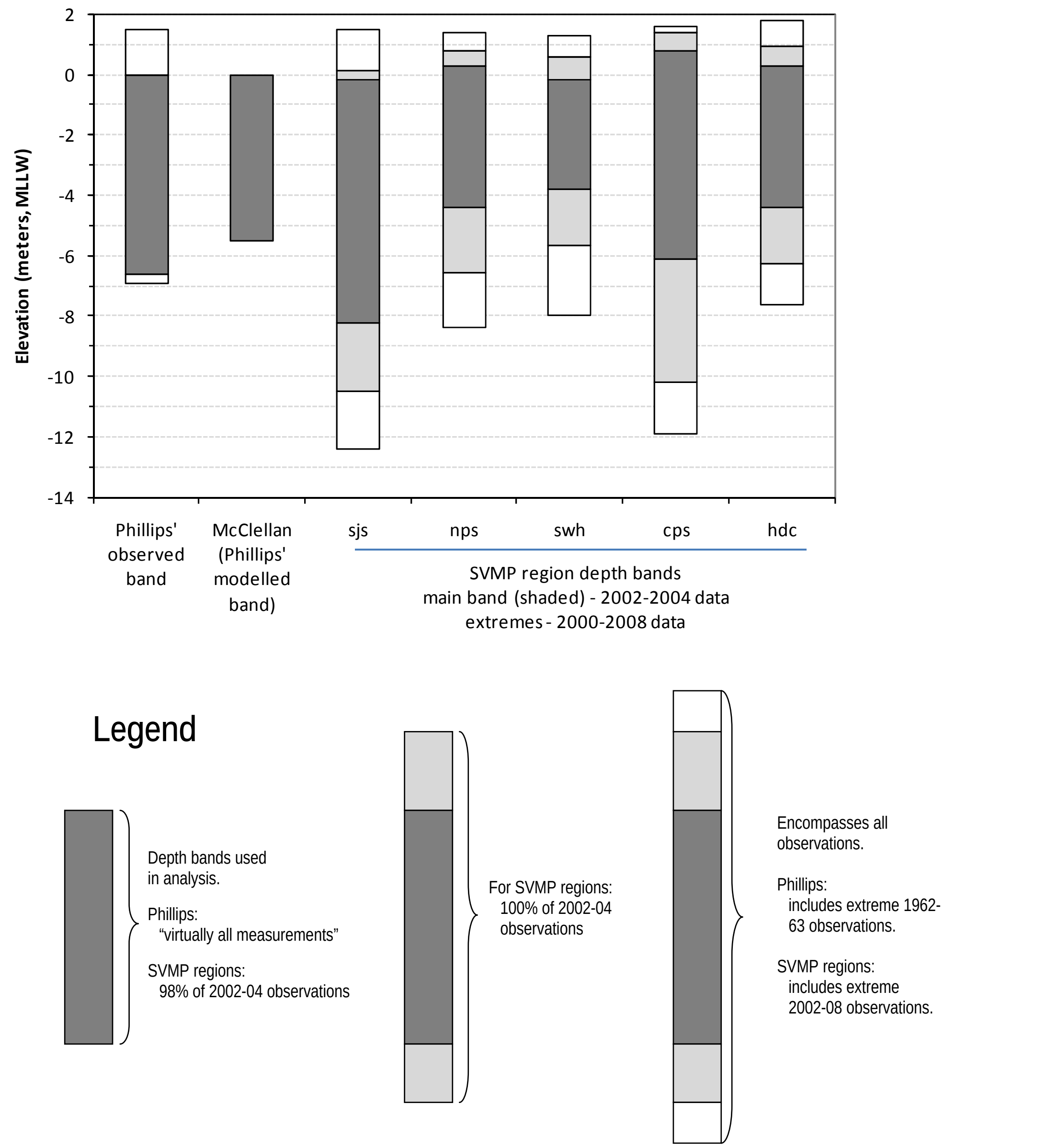


Figure 2-5. Eelgrass depth bands. The dark shaded bars represent the primary depth bands used in the analysis presented in this report. The dark shaded bars for the SVMP regions are based on 2002-04 data and exclude the extreme one percent of the observations in both the lower and upper observations. The light shaded bars for the SVMP regions show the 2002-04 depth ranges associated with these one percent tails that were excluded. The hollow bars indicate the overall shallowest and deepest observations in Phillips' observations and, for the SVMP regions, in the 2002-2008 SVMP dataset.

shallow and deep margins of the depth bands expand and contract up to 0.5 vertical meters. These scenarios are intended to represent changes in the different controlling factors that limit eelgrass distribution at the shallow and deep margins.

Second, simple scenarios of sea-level rise were assessed by raising the deep and shallow margins of the depth bands by equal amounts. Predictions of sea-level rise over the next 50-100 years for Puget Sound vary from 8 cm (low) to 15 cm (medium) and 55 cm (very high) (Mote et al. 2008). The scenarios investigated here all reached at least 50 cm. The WDFW dataset was not included in this analysis because of the limited coverage in shallow water (Figure 2-1, p. 6).

Third, the depth distribution of the flats potential eelgrass habitat as delineated for SVMP monitoring was compared to the eelgrass depth bands. This analysis was motivated by concerns that the depth distribution of the SVMP flats could be significantly broader than the eelgrass depth bands and that this could introduce a positive bias into eelgrass area estimates or reduce precision.

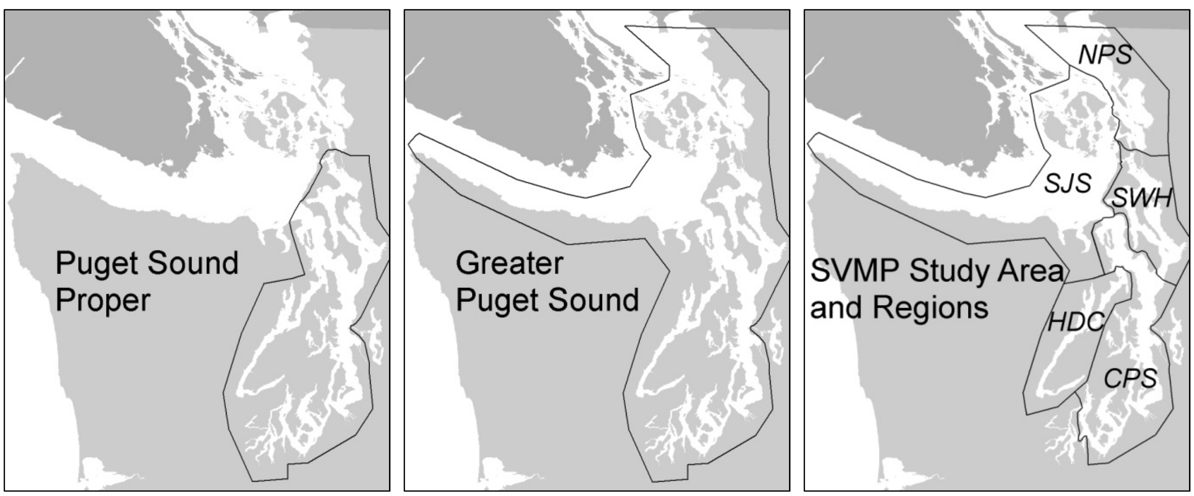


Figure 2-6. The different spatial extents used to summarize area of eelgrass depth bands in this study. The SVMP regions include North Puget Sound (NPS), San Juan Is. – Strait of Juan de Fuca (SJS), Saratoga Passage – Whidbey Basin (SWH), Hood Canal (HDC) and Central Puget Sound (CPS). The Greater Puget Sound area also includes the southern reaches of Puget Sound that are referred to in this study as the Southern Puget Sound (SPS) region.

3 Results

3.1 Derived Bathymetry Datasets

The datasets derived from the Finlayson et al. 2000 and Finlayson 2005 datasets are shown in Figure 3-2 and Figure 3-3, respectively. These data reflect the restriction to the nearshore zone as well as the effects of the transformations to a MLLW datum.

3.1.1 Effects of Datum Transformations

The effect of datum transformation can be seen more clearly at finer spatial scales. Figure 3-1 shows the effect of transformation from NAVD88 to MLLW of the Finalyson 2005 dataset at Nisqually Flats. In this area, the difference between the datums is roughly one meter and the transformation essentially shifts the depth bands shown by one band at the shallow depths.

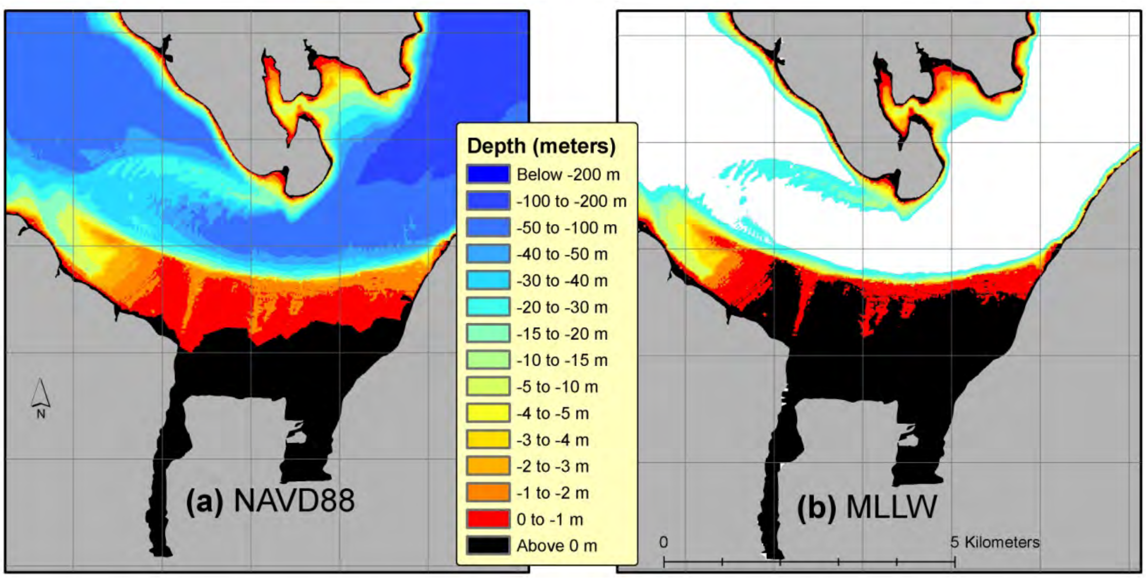


Figure 3-1. The effect of datum transformation on the Finalyson 2005 dataset at Nisqually Flats. (a) shows the original Finlayson 2005 dataset with a NAVD88 vertical datum. (b) shows the derived dataset transformed to a MLLW datum.

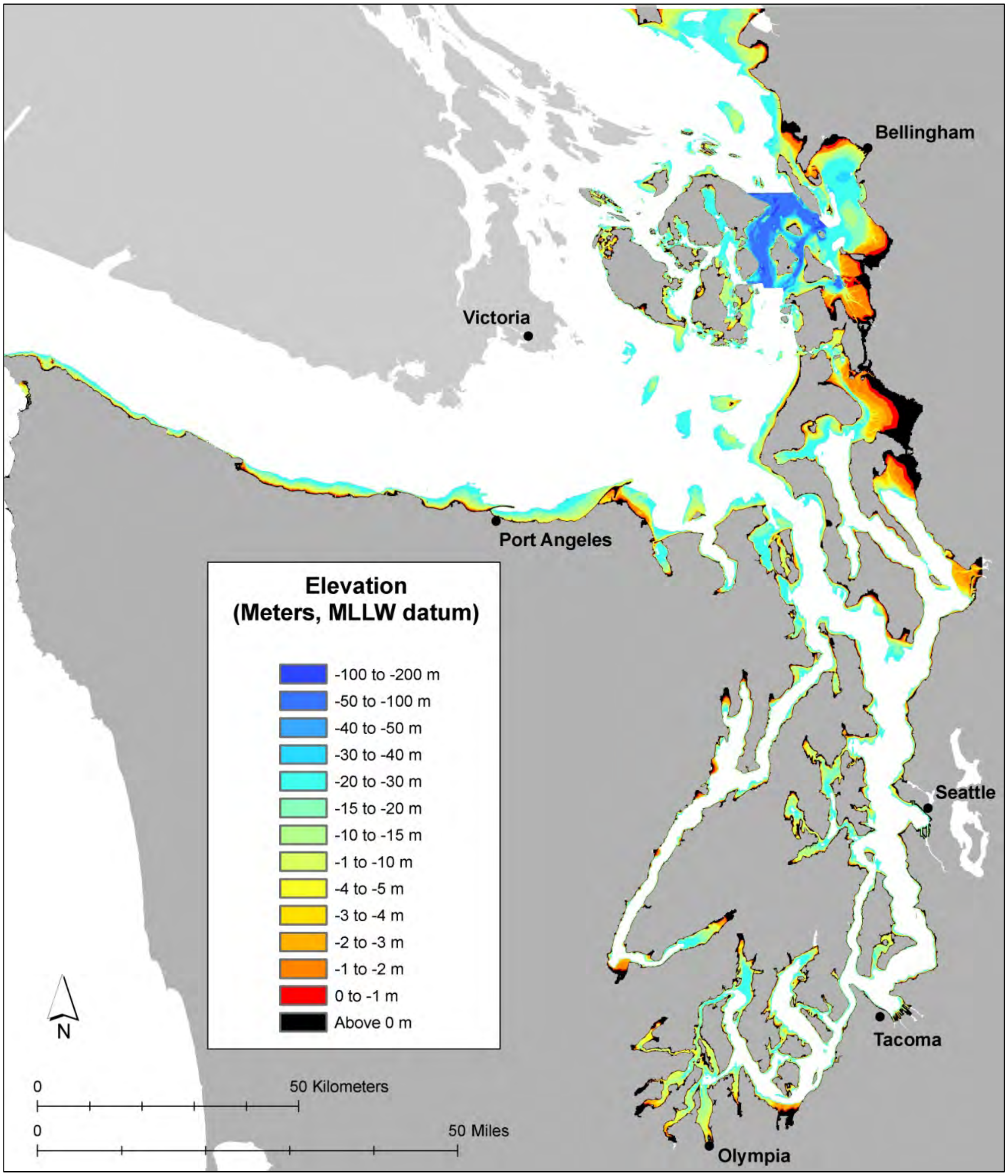


Figure 3-2. The nearshore bathymetry derived from Finlayson et al. 2000 by transformation to a MLLW datum and augmentation with interpolated NOAA soundings in the area of missing data.

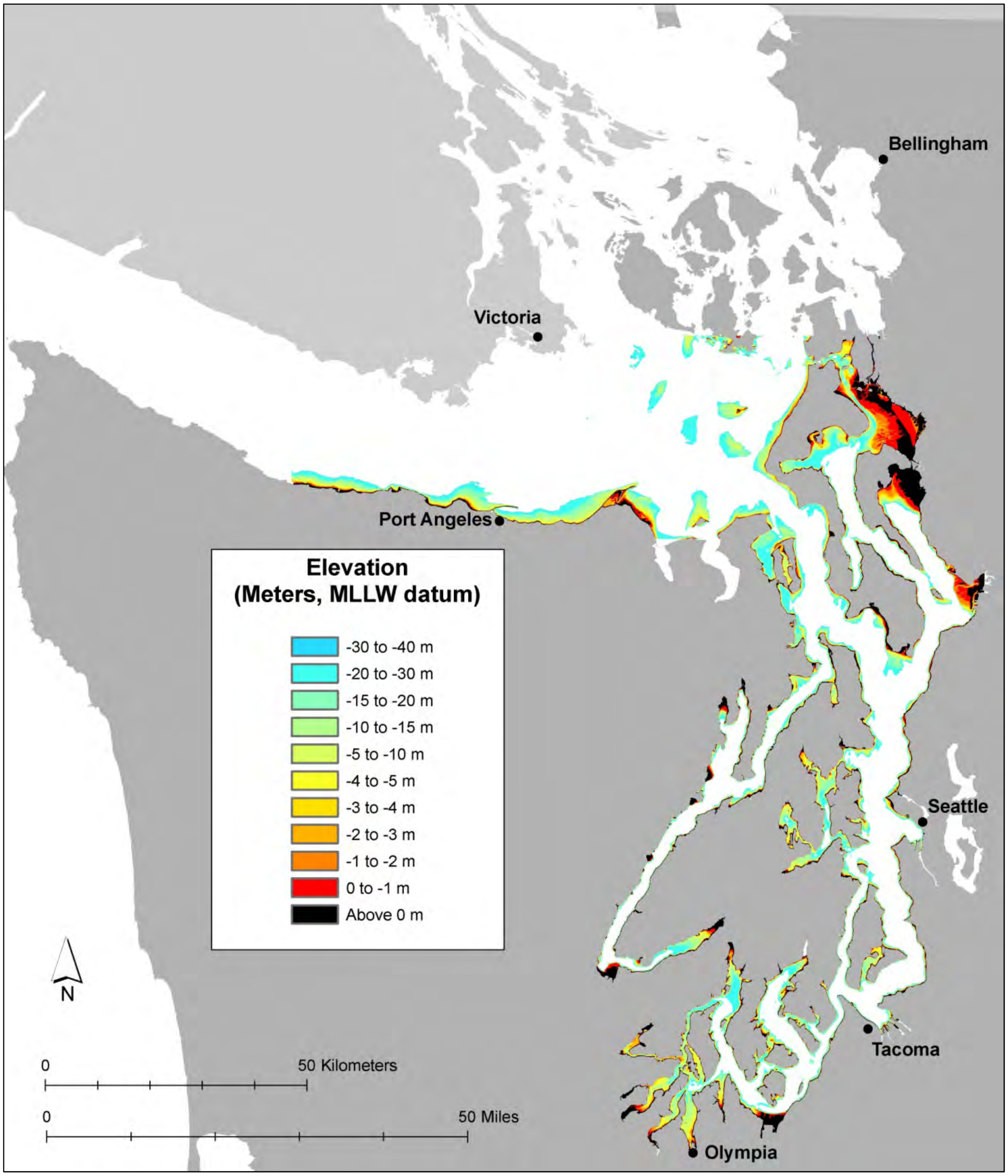


Figure 3-3. The nearshore bathymetry derived from Finlayson 2005 by transformation to a MLLW datum.

The effect of the datum transformations vary across greater Puget Sound. To assess the magnitude of the transformations across the study area, the datums were related at several points using VDatum. The NGVD29 datum is relatively close to MSL with some divergence in the areas of high tidal range (Figure 3-4). The NGVD29 datum is 28 cm below MSL at Olympia.

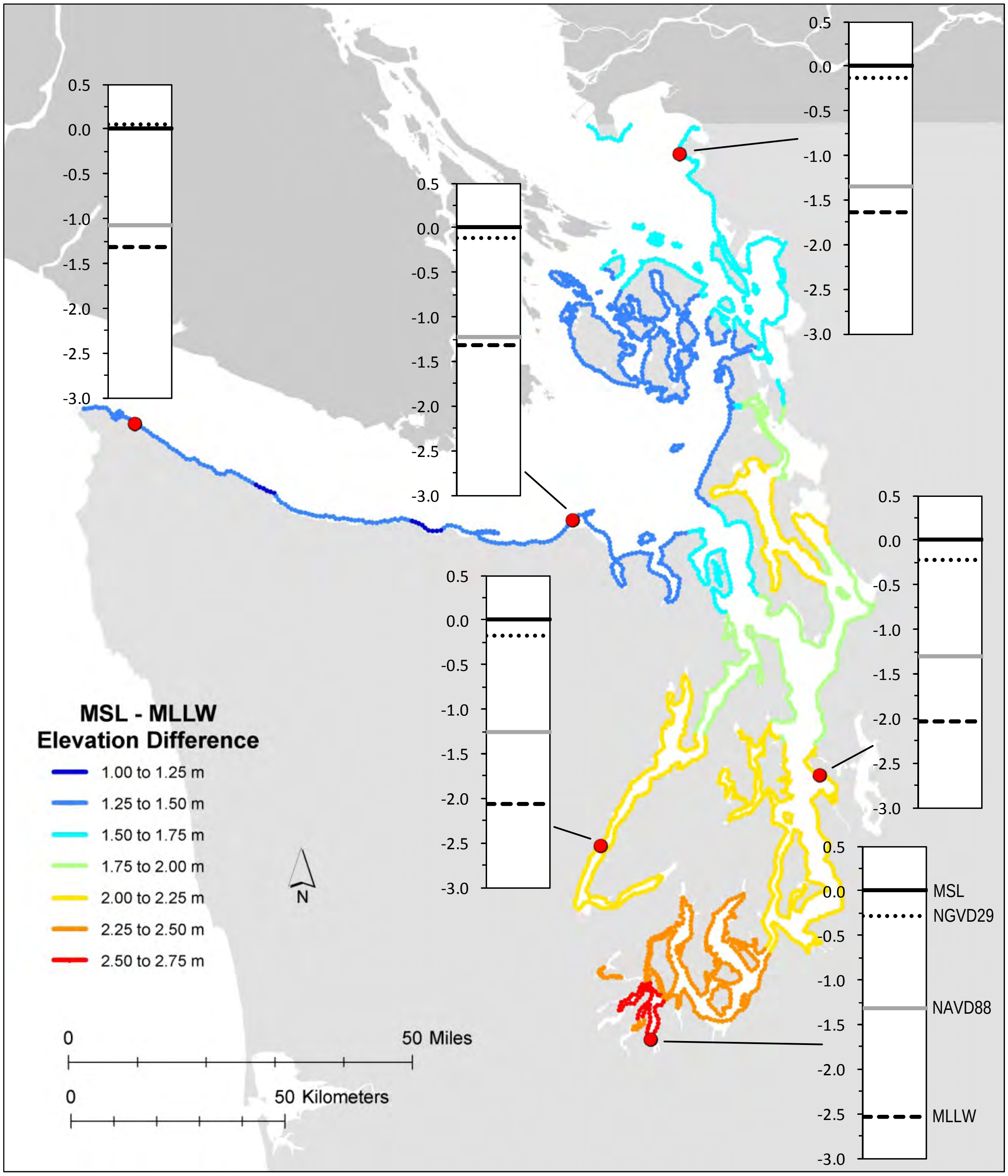


Figure 3-4. The relationship between four vertical datums at points with different tidal ranges. Each graph shows the datums relative to MSL in units of meters. The tidal ranges (elevation difference between MSL and MLLW) are shown in the map along the -20 ft (-6.1 m) contour. All datum relationships were calculated with VDatum.

The NAVD88 datum is below MSL in all areas ranging from 1.1 meters below in the Strait of Juan de Fuca to 1.3 meters below at Olympia. When transforming to a MLLW datum, there is a greater shift from NGVD29 than from NAVD88. The shift from NGVD29 to MLLW reaches 2.3 meters at Olympia.

3.1.2 Augmentation of Finlayson et al. 2000

The data generated to augment Finlayson et al. 2000 in the area of missing data is shown in Figure 3-5. There are clear discrepancies in comparison to the Finlayson data where they meet, particularly in Padilla Bay. These discrepancies led to an error assessment that is discussed in more detail in Appendix B. Elevation differences in Padilla reach 1-2 meters which is on the order of error expected between different bathymetric surveys (section B.3.5, p. 56). Much larger discrepancies (up to 30 meters) were found in areas with steep beach profiles (see section B.2, p. 51).

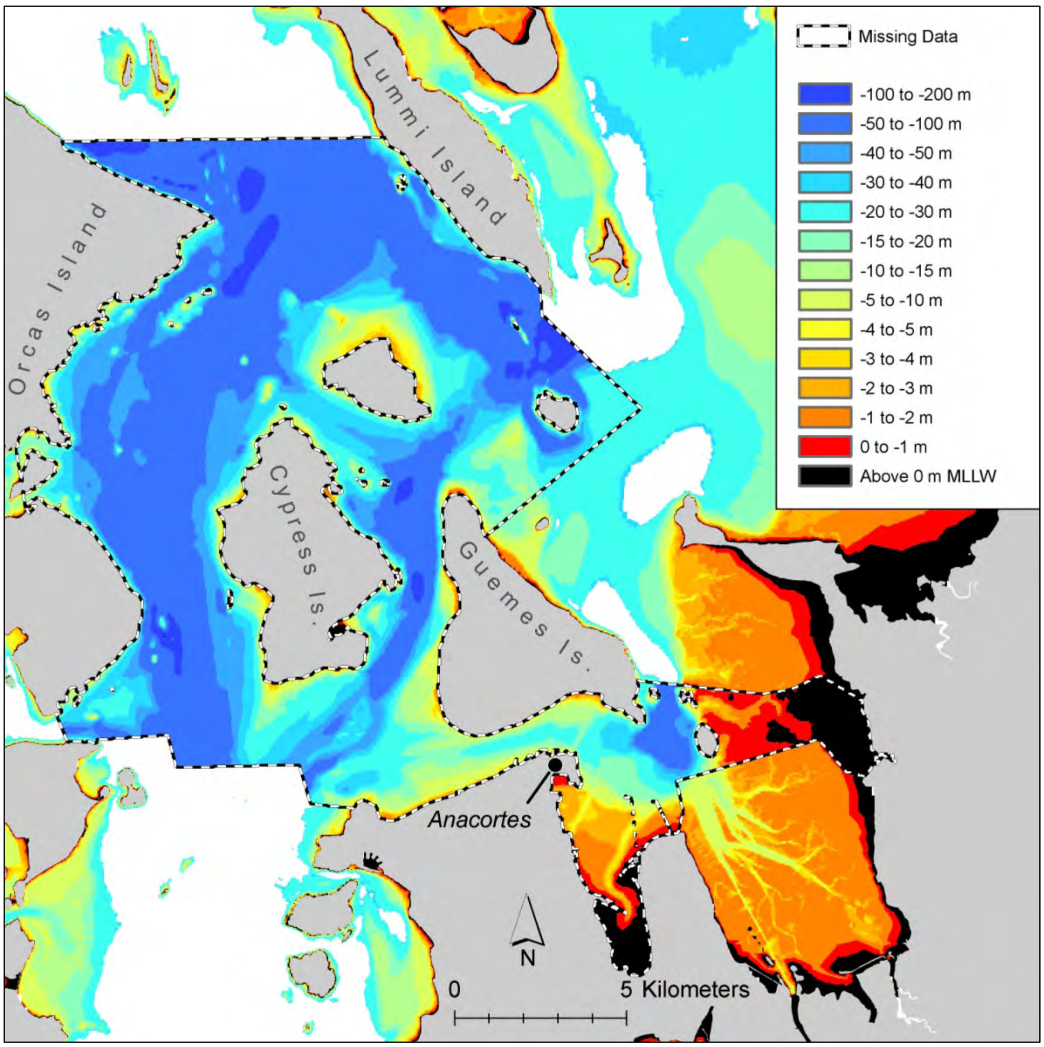


Figure 3-5. The data derived from Finlayson et al. 2000 in the area where NOAA soundings were used to fill missing data in the original Finlayson et al. dataset.

The error assessment suggests that interpolation error associated with the kriging may be the main source of error leading to these large discrepancies (section B.3.4, p.54).

Error associated with multiple datum transformations appears to be smaller but still important. The error associated with the source soundings includes a small error associated with depth measurement (~ 1 cm) and a much larger error associated with the adjustment of sounding depth to a MLLW datum (up to 45 cm).

3.2 Bathymetry-Area Relationships

The breakdown of total nearshore area by SVMP region is similar across the three datasets analyzed (Figure 3-6). The greatest areas are in the NPS, SJS and CPS regions, with lesser areas in SWH, HDC and SPS. Histograms of nearshore area by depth also reflect broad similarities across the three datasets (Figure 3-7, Figure 3-8, Figure 3-9). There are peaks in area at shallow depths (above -5 m MLLW) that are seen in each dataset. These presumably represent broad flats. Also, the SPS region has a unique distribution with a sharp drop-off in area below -10 to -12 meters that is clearly seen in each dataset.

The three datasets also have similarities that appear to be artifacts associated with the source NOAA soundings. There are sharp peaks in area at regularly spaced depths in the SJS, NPS and CPS regions in the -20 to -30 m depth zone. These peaks were investigated in the NPS region and found to be linked to a coarser vertical resolution at depth which leads to increased areas at the recorded depths. In the NPS region this was most prominent in Bellingham Bay (Figure 3-10). The fact that the same coarse vertical resolution is seen in each dataset suggests that this pattern originates from the NOAA soundings used to generate the gridded bathymetry, rather than the processing of any particular dataset.

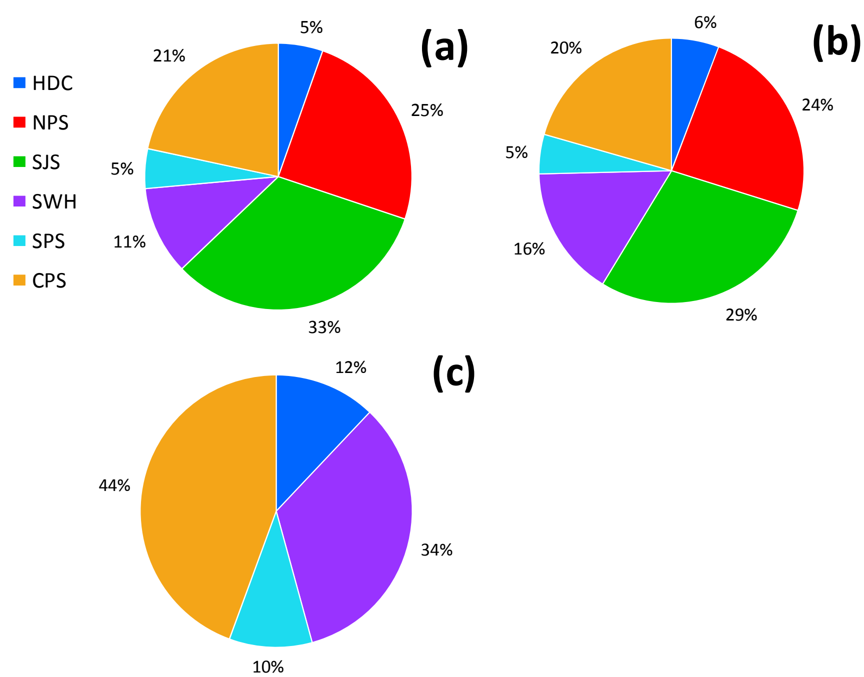


Figure 3-6. Breakdown of total nearshore area by SVMP region for (a) the WDFW PSAMP dataset, (b) the dataset derived from Finlayson et al. 2000 and (c) the dataset derived from Finlayson 2005, excluding the regions with partial coverage.

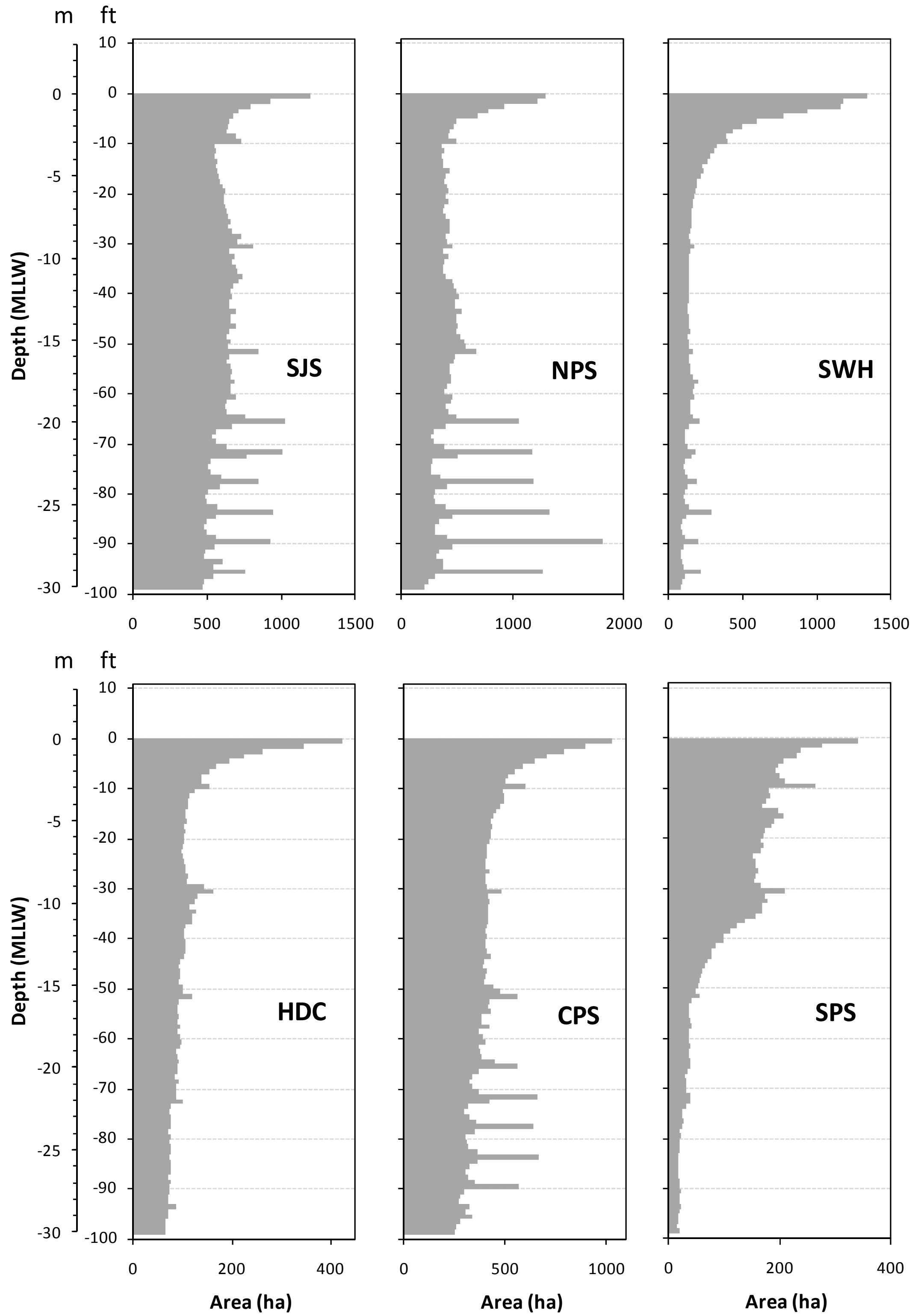


Figure 3-7. Distribution of area by depth for the WDFW PSAMP dataset. The histogram bins are in units of feet with a one foot bin width.

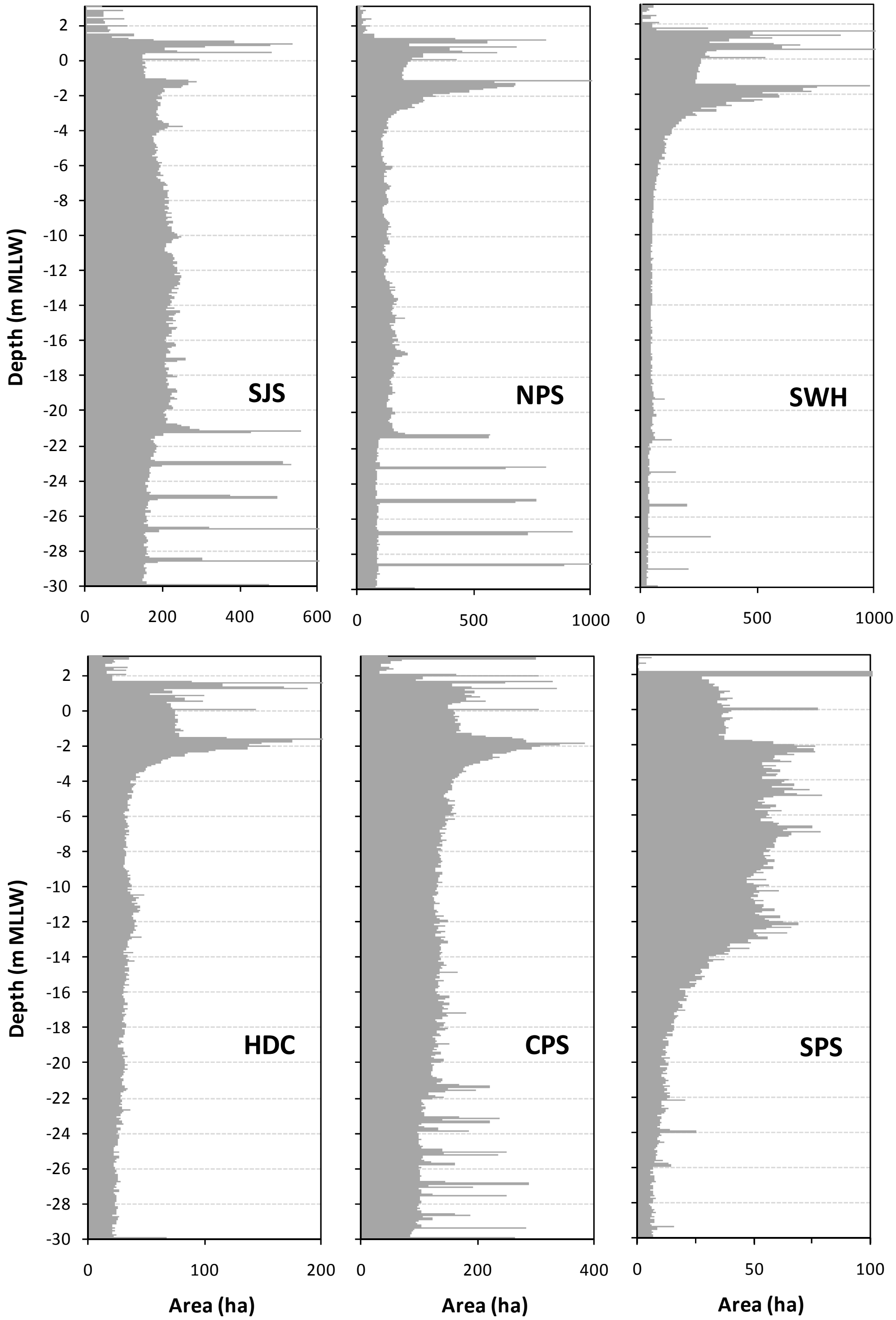


Figure 3-8. Distribution of area by depth for the dataset derived from Finlayson et al. 2000. The histogram bins are in units of meters with a one decimeter (10 cm) bin width. The areas within several bins are off the scales shown: NPS: the area at -1.2 m reaches 1012 ha; HDC: the area at +1.5 m is 267 ha and at -1.7 m is 245; SPS: the area at +2.1 m is 351 ha.

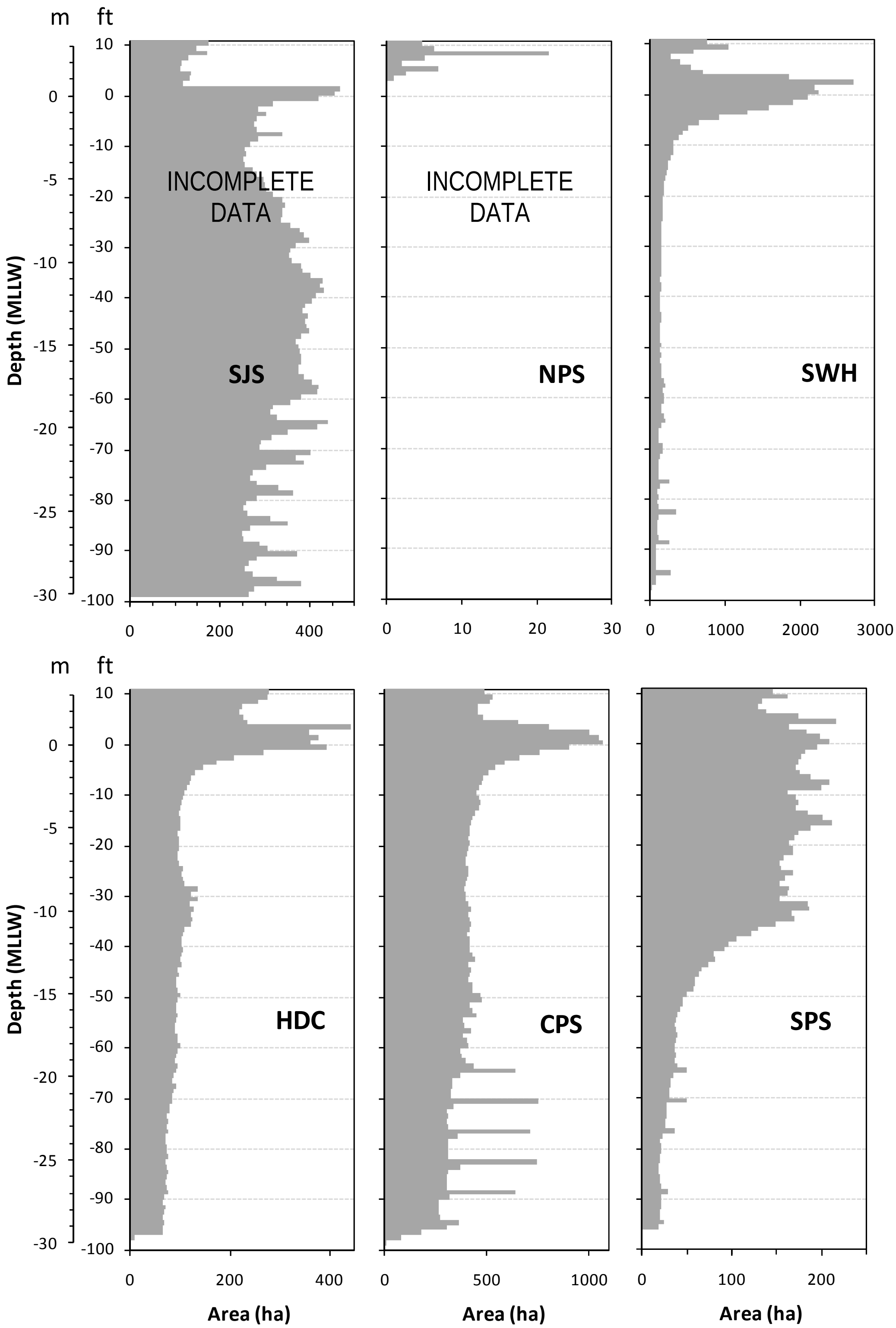


Figure 3-9. Distribution of area by depth for the dataset derived from Finlayson 2005. The histogram bins are in units of feet with a one foot bin width. Due to the limited extent of this dataset, the histograms for the SJS and NPS regions are incomplete and not directly comparable to the other regions and to the results from the other datasets.

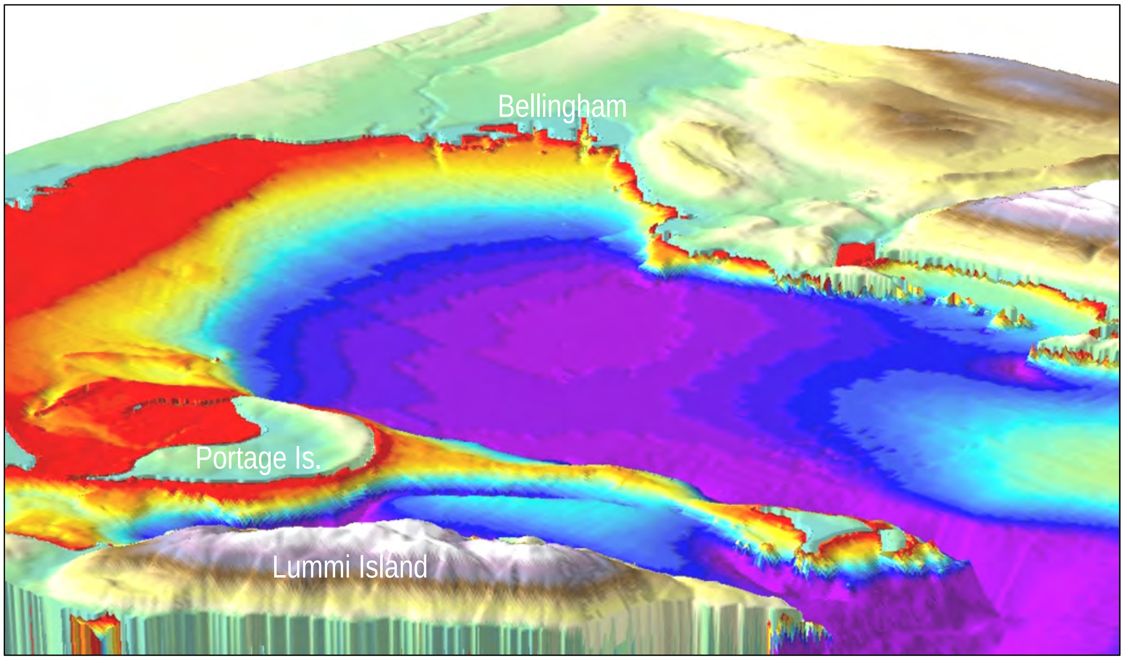


Figure 3-10. Bellingham Bay as seen in the Finlayson et al. 2000 dataset showing the coarser vertical resolution at depth in the center of the bay which leads to large areas at regular depth increments.

There are discrepancies between the dataset derived from Finlayson et al. 2000 and the other two datasets. This is most clearly seen at shallow depths (< 5 m) where the Finlayson et al. dataset has multiple peaks in area in each region whereas the other datasets for the most part have single peaks. It appears that the dataset derived from Finlayson et al. 2000 has a depth offset relative to the other datasets that shifts the histogram to greater depths. This allows features at higher elevations to appear that are above the scale shown for the other datasets. The additional peaks seen at the shallowest depths presumably appear at higher elevations not shown for the other datasets.

This explanation was tested by comparing the depths of the artifacts at deeper elevations – i.e. the sharp peaks associated with the coarser vertical resolution at depth. The depths of the maximum area for each peak in the CPS region confirm that the dataset derived from Finlayson et al. 2000 is shifted downward by approximately 1.4 m relative to the mean of the other two datasets (Figure 3-11).

3.3 Area of Eelgrass Depth Bands

3.3.1 Comparison of Estimates

The estimates of area within the various eelgrass depth bands are given in Table 3-1 and Figure 3-12. The estimates for Puget Sound proper (23,000 to 38,000 ha) are clearly lower than those for the SVMP study area and greater Puget Sound (49,000 to 66,000 ha). The results from the Finlayson et al. 2000 dataset are consistently greater than the WDFW estimates for each spatial extent and each depth band.

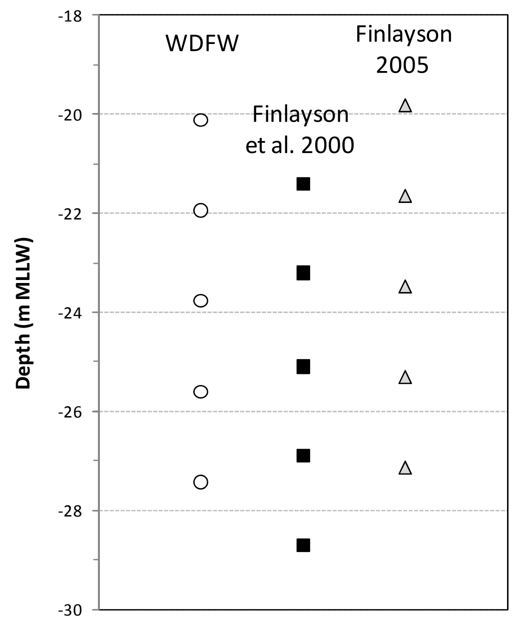


Figure 3-11. Depths of the regularly spaced peaks in area for each dataset. The peaks associated with coarser vertical resolution. These points correspond to the peaks seen in the histograms for the WDFW dataset (Figure 3-7), and the datasets derived from Finlayson et al. 2000 (Figure 3-8) and Finalyson 2005 (Figure 3-9).

Table 3-1. Estimates of the area in eelgrass depth bands. For comparison, the column at the far right includes estimates based on the McClellan (1954) bathymetry study – both the value of Phillips (1972) that appears to be in error and the revised value produced by DNR (Dowty et al. 2010).

Spatial Extent	**Depth Band**	**WDFW 1998 (ha)**	**Finlayson et al. 2000 (augmented) (ha)**	**Finlayson 2005 (ha)**	**Estimates based on McClellan (1954) bathymetry-area study (ha)**
Puget Sound proper	Phillips	31,063	38,136	34,414	46,647 (Phillips 1972) 29,429 (Dowty et al. 2010)
	McClellan	27,503	33,831	30,876	
	SVMP regions	22,870	30,367	27,974	
Greater Puget Sound	Phillips	57,197	65,789		
	McClellan	49,608	57,526		
	SVMP regions	48,835	58,735		
SVMP study area	Phillips	52,673	62,003		
	McClellan	45,763	54,501		
	SVMP regions	48,835	58,735		

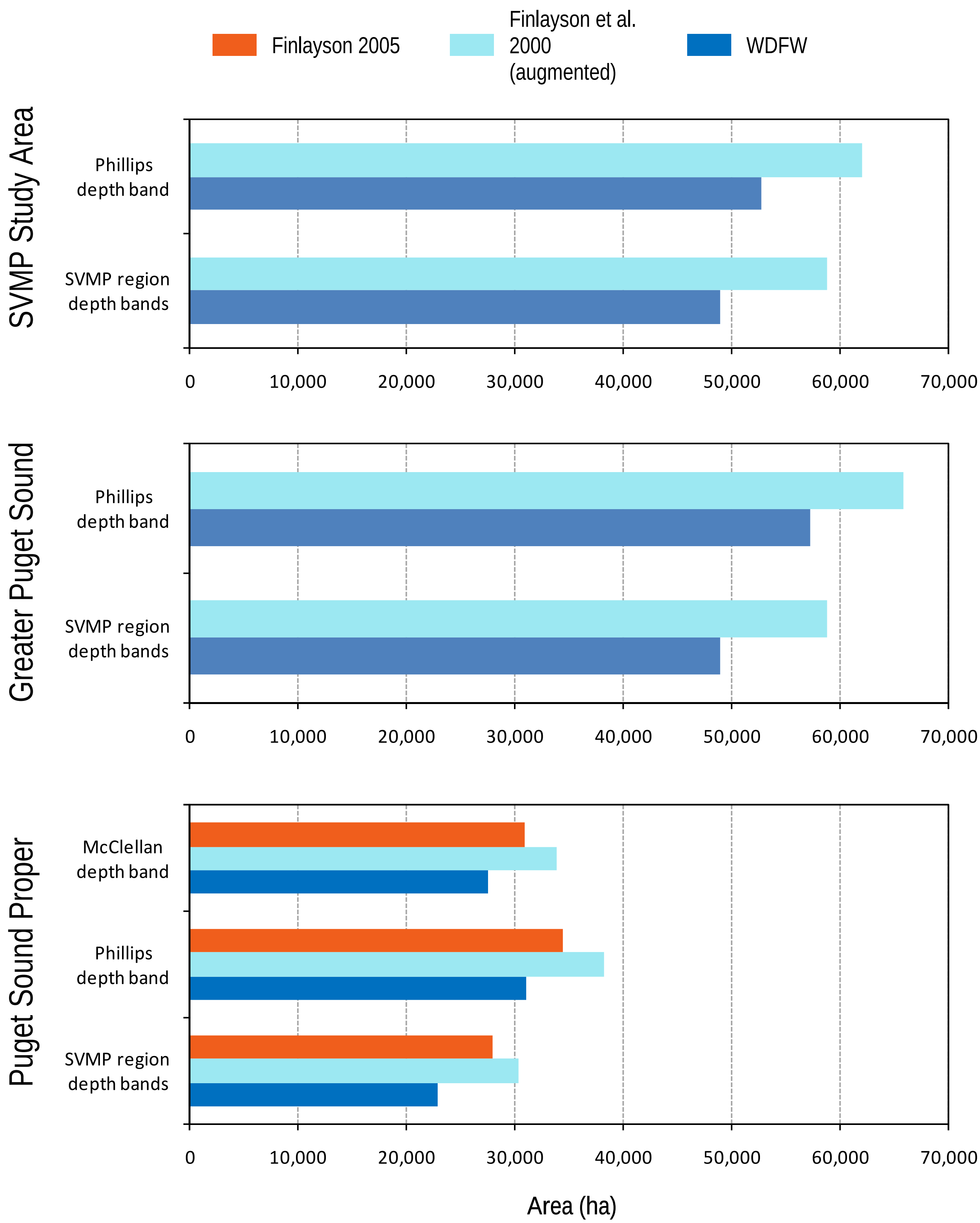


Figure 3-12. Estimates of area within eelgrass depth bands for the SVMP study area (top), greater Puget Sound (middle) and Puget Sound proper (bottom). Separate estimates are shown for different eelgrass depth bands and the different datasets analyzed.

Results from the Finlayson 2005 dataset are only available at the Puget Sound proper scale, and here they are intermediate between area estimates from WDFW and Finlayson et al. 2000. Since there is no SVMP depth band for the SPS region, the SVMP depth band results are identical for the greater Puget Sound and SVMP study area scales.

The results at the region scale reflect strong differences between the regions as well as an interaction between the specific depth bands and the region bathymetry (Figure 3-13). The HDC and SPS regions have only a fraction of the area of the other regions in the Phillips' depth band. There is no area in SPS under the SVMP depth bands because there is virtually no eelgrass in this region. In some regions, the Phillips' depth band gives a greater area than the SVMP band (e.g. SWH), but in others the SVMP band gives the larger area (e.g. SJS).

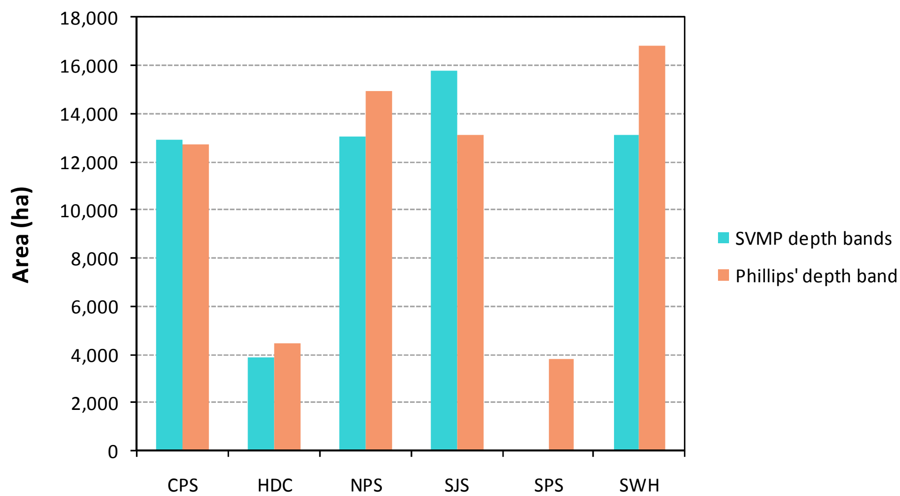


Figure 3-13. The areas associated with the SVMP and Phillips' depth bands by region. These results are based on the augmented Finalyson et al. 2000 dataset.

3.3.2 *Scenarios of Eelgrass Depth Band Expansion and Contraction*

Results of the depth band expansion and contraction scenarios are presented in Figure 3-14 for the datasets derived from Finlayson et al. 2000 and Finlayson 2005. Due to the limited data coverage at shallow depths, only the deep limit of the depth bands was tested on the WDFW dataset (Figure 3-15).

There are strong differences between regions in response to changes in the eelgrass depth bands. For example, if the deep margin of the region depth bands shifted 0.5 m deeper, the HDC region would gain 185 ha within the depth band (Figure 3-14 a). In contrast, the SJS region would gain 1050 ha. Regions that had a strong response under contraction also had a strong response under expansion, and vice versa. In general, HDC has the smallest response in area to shifts in shallow and deep margins for each dataset analyzed. At the deep margin, SJS and CPS were the most responsive. At the shallow margin, NPS and SWH were the most responsive.

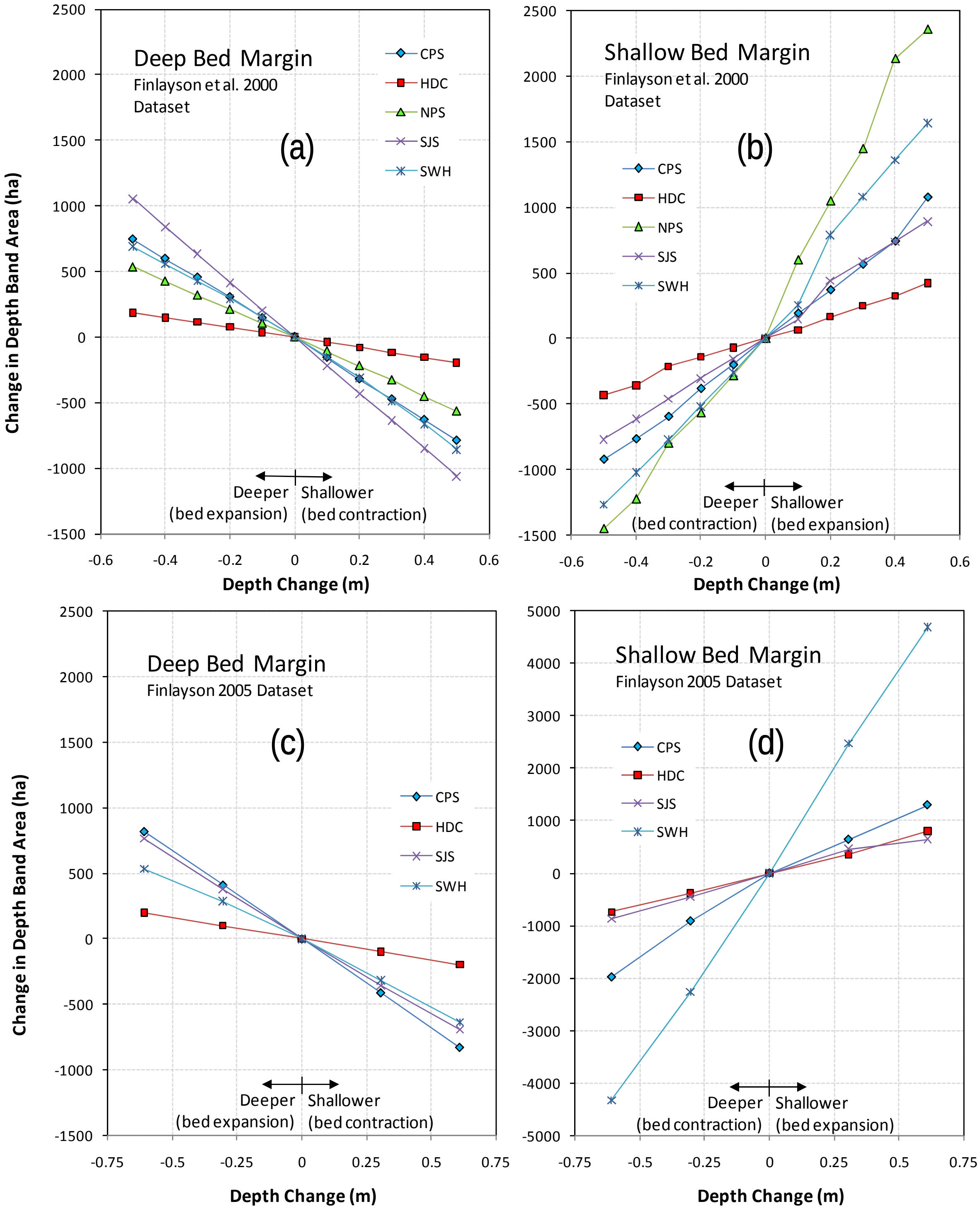


Figure 3-14. Results of eelgrass expansion and contraction scenarios using the Finlayson et al. 2000 (a and b) and Finlayson 2005 (c and d) datasets. Note the expanded *y*-axis in d.

There was a strong difference in results obtained from the Finlayson et al. 2000 and Finlayson 2005 datasets at the shallow margin of the depth bands. For SWH, an expansion upward by 0.5 m increased the depth band area by 1640 ha in one case (Finlayson et al. 2000, Figure 3-14 b) and about 3900 ha in the other (Finlayson 2005; Figure 3-14 d).

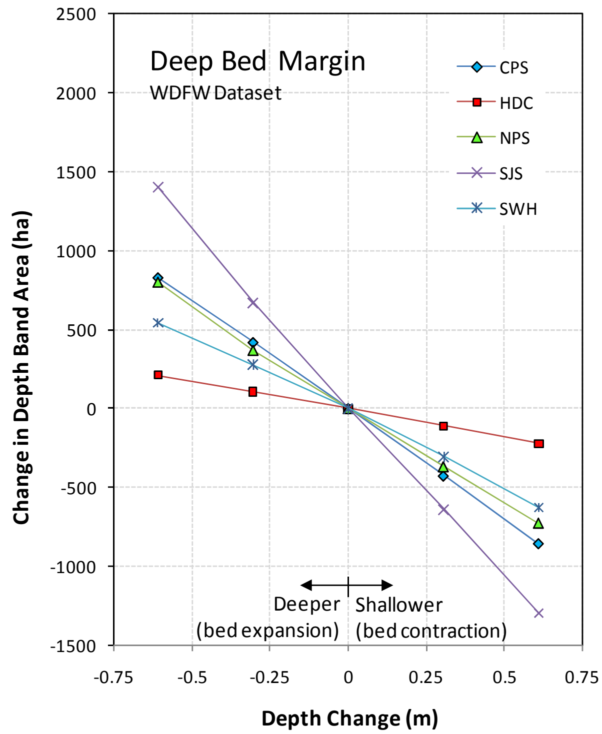


Figure 3-15. Results of eelgrass expansion and contraction scenarios using the WDFW PSAMP dataset.

3.3.3 Scenarios of Sea-Level Rise

All sea-level rise scenarios increased the area within the eelgrass depth bands except in the SJS region (Figure 3-16). The SJS region had an increase in area for sea-level rise up to 20-30 cm, with a decrease in area as sea-level rise continued. The NPS and SWH had the largest increases in area under the scenarios studied.

Again, there were strong differences between the results obtained with the two datasets. With 50 cm of sea-level rise, analysis of the dataset derived from Finlayson et al. 2000 in the SWH region produced an increase of 783 ha in the area within the eelgrass depth band. In contrast, analysis with the dataset derived from Finlayson 2005 produced an increase of about 3400 ha (interpolated).

The responses in the HDC and CPS regions were similar and showed a relatively modest gain in depth band area under sea-level rise.

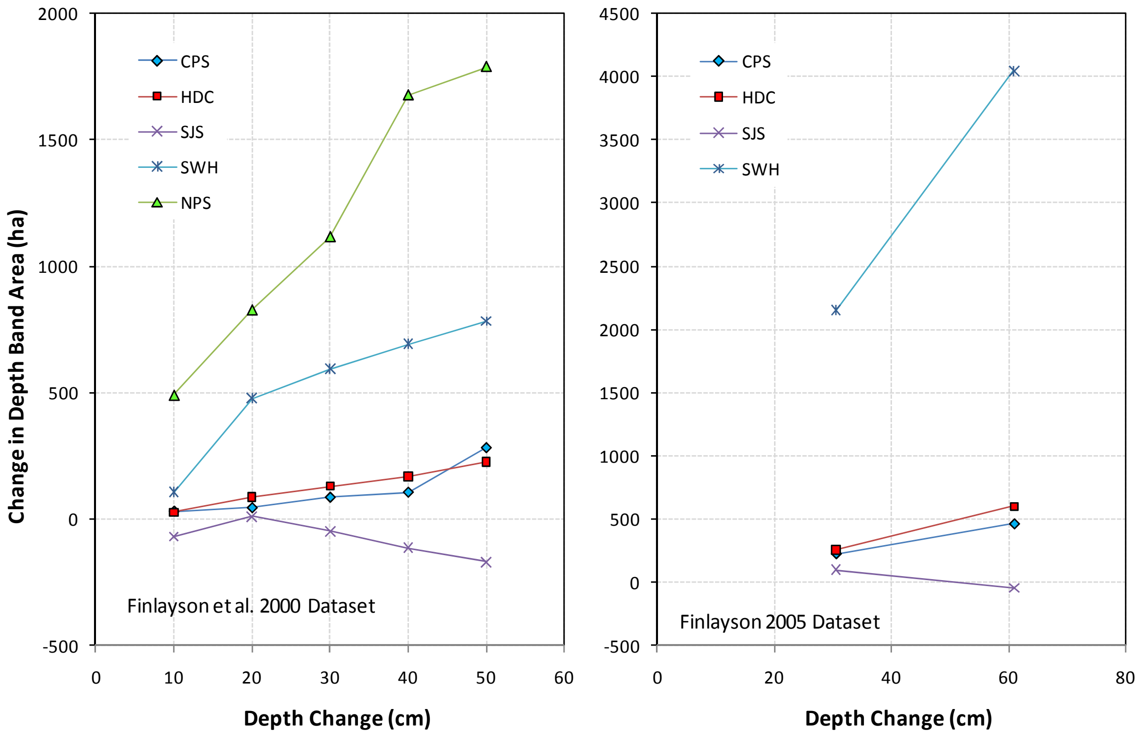


Figure 3-16. Changes in the area of eelgrass depth bands under sea-level rise scenarios ranging from +10 cm to +61 cm. On the left are results obtained with the dataset derived from Finlayson et al. 2000 and to the right results obtained with Finlayson 2005.

3.3.4 Implications for SVMP Sampling Frames

The SVMP eelgrass depth bands are related to the depths represented in the SVMP flats sites in Figure 3-17. In each region, a substantial area in the flats sites falls outside the eelgrass depth bands on both the deep and shallow ends. In the most extreme case, only 52% of the flats sites area falls within the region eelgrass depth band (HDC). Region SJS has the highest correspondence with 80% of the flats sites area falling within the region depth band.

Based on these results, the 2005 eelgrass area of the SVMP rotational flats stratum was re-calculated with the flats sites areas reduced by 50% and 75%. To increase the contrast between the scenarios, a calculation was also included with flats sites areas increased by 25%. These manipulations had no effect on the estimated stratum area and associated variance. Clearly, the estimators for flats stratum area and variance are not sensitive to large changes in site areas. The effects investigated were large, but they were uniformly proportional to site area. If site areas were adjusted based on the actual bathymetry profile at each individual site, some effect on the estimates would be expected, but the results here suggest this effect would not be large.

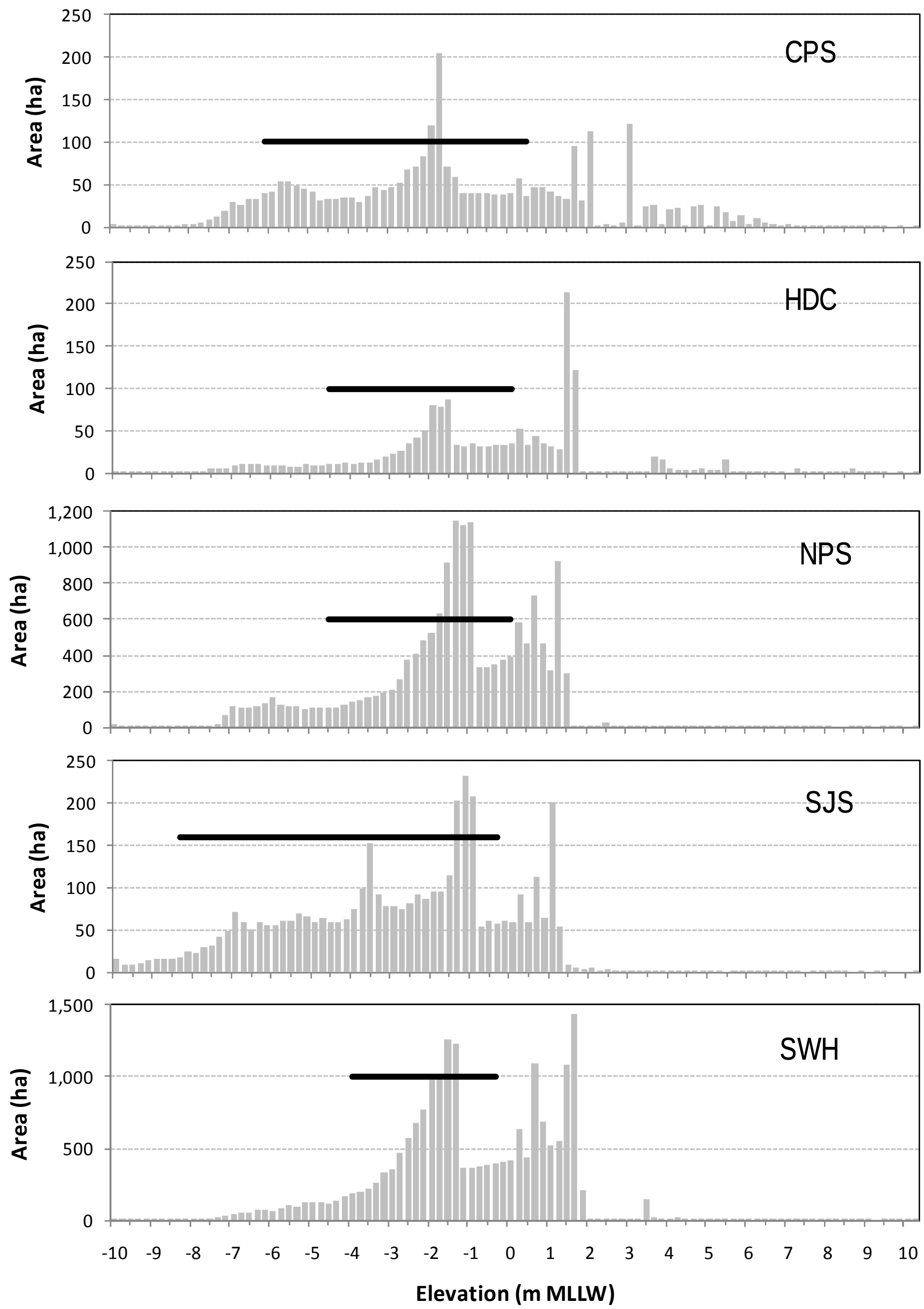


Figure 3-17. The SVMP region depth bands (horizontal lines) and the distribution of flats potential habitat area by depth for each region. Based on the dataset derived from Finlayson et al. 2000.

4 Discussion

The primary purpose of this study was to bring new information to the eelgrass target-setting effort for greater Puget Sound. The area of the eelgrass depth band was intended to be used as a reference point to help assess target values, as well as to serve as the initial steps needed to produce additional reference points in the form of potential eelgrass area estimates.

To best achieve this purpose, the many estimates of the area of the eelgrass depth band (Figure 3-12, p. 26) need to be reduced to a clearer result. The fact that eelgrass depth bands vary strongly between sub-basins (Figure 2-5, p. 13) suggests that the SVMP region depth bands should provide the best characterization of the eelgrass depth limits within greater Puget Sound. It is reasonable to assume that estimates based on the SVMP region depth bands will be more accurate than estimates based on the single Phillips depth band applied across these different regions. This narrows the focus to just two estimates for greater Puget Sound that rely on the SVMP region depth bands – one from the WDFW dataset (48,835 ha) and one from the dataset derived from Finlayson et al. 2000 (58,735 ha). The mean of these two values (53,785 ha) provides the best point estimate of area of the eelgrass depth band in greater Puget Sound. This approach does not include area from the southern reaches of Puget Sound (SPS region) where eelgrass is absent today. The SVMP depth band for the SPS region can be thought of as a null. This region accounts for 6% of the total area under the application of the Phillips depth band.

The value of this point estimate by itself is limited. An interval, or uncertainty, estimate is needed to properly apply the results in a target-setting context. The assessment of proximity and separation between this estimate and other reference points depends upon a reasonable confidence interval. It is challenging to produce a confidence interval that integrates all the known uncertainties. It is difficult enough to characterize the uncertainty in the source bathymetry data (see section B.3, p. 51), but it is even less clear how this uncertainty would propagate to the area estimates.

A provisional confidence interval was found by using the spread in the multiple area estimates to characterize uncertainty and by assuming the sampling distributions are normal. The two estimates used above to calculate the mean are not sufficient to calculate a standard deviation. To deal with this, it was assumed that the spread of the two estimates about the mean, and the spread of the three corresponding estimates at the Puget Sound proper scale (i.e. the three SVMP depth band estimates, Figure 3-12) share the same coefficient of variation (CV). This allowed five estimates to be used to calculate the joint CV. This approach is expedient but does not address the fact that the five data points are not completely independent. The greater Puget Sound estimates reflect the same Puget Sound proper bathymetry that is summarized in the Puget Sound proper estimates. The effects of this dependency are not considered.

To illustrate this approach, Figure 4-1 shows the five estimates and the two sampling distributions (Puget Sound proper and greater Puget Sound) that have the same CV. The joint CV is calculated by normalizing each estimate by the mean of its respective sampling distribution. This eliminates the effects of different means and allows all five points to be placed together about the normalized mean of one (Figure 4-2). The fact that the points from the two distributions are interspersed on the normalized area axis suggests that the assumption of the same CV value is reasonable. The CV calculated with the five values is 0.12. When this value is used to calculate standard deviation for the two sampling distributions (Puget Sound proper and greater Puget Sound), the distributions shown in Figure 4-1 result.

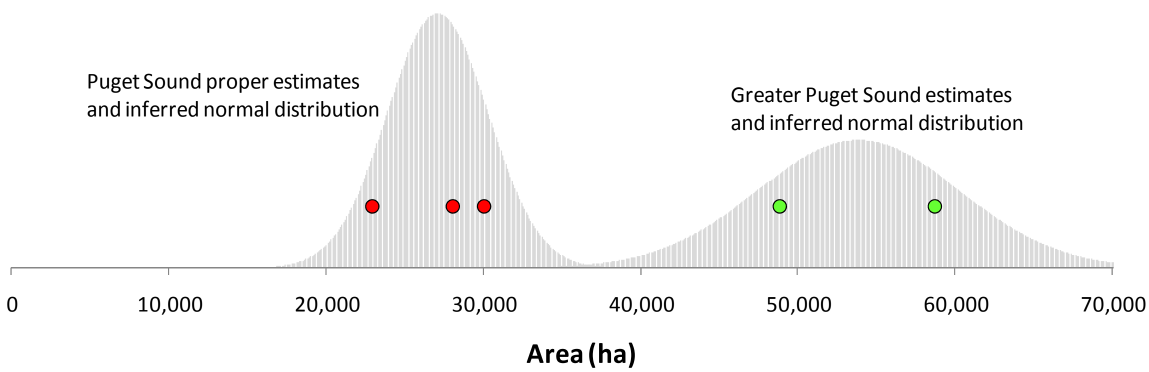


Figure 4-1. The sampling distributions for the area of eelgrass depth bands in Puget Sound proper and greater Puget Sound under two assumptions: (1) the sampling distributions are normal and (2) the two distributions have the same CV (i.e. the same dispersion when adjusted for differences in means).

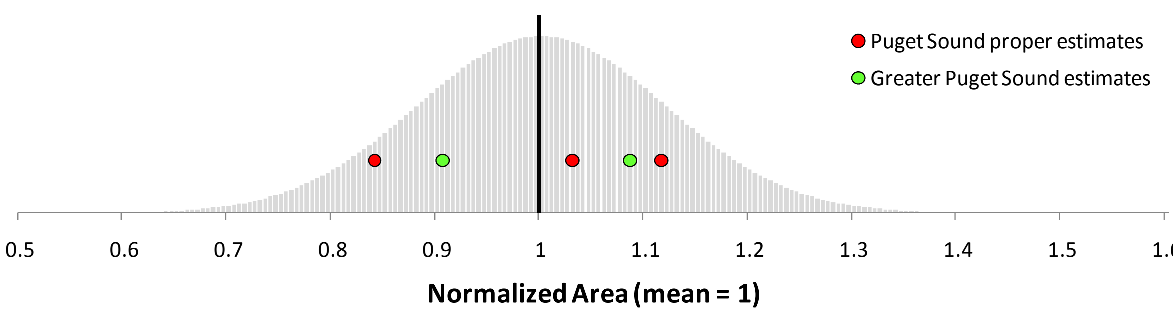


Figure 4-2. The distribution of the five estimates of normalized area of the eelgrass depth band relative to the joint normalized mean of one. The Puget Sound proper estimates were normalized by the mean of these three estimates. The SVMP study area estimates were normalized by the mean of these two estimates. It was assumed that all five points come from distributions with the same CV, in which case the CV can be calculated using all five points on this normalized axis. The resultant CV (n=5) is equivalent to the standard deviation (since mean = 1) and is equal to 0.12. The associated normal distribution (μ=1, σ=0.12) is shown as a histogram.

Under the assumption of normality, the calculated standard deviation can be used to generate a 95% confidence interval (1.96 × standard deviation) of ±12,580 ha. The combined estimate of the area of the eelgrass depth band in greater Puget Sound is then

$$\text{Eelgrass depth band area} = 53{,}785 \pm 12{,}580 \text{ ha}$$

This is shown graphically in Figure 4-3 relative to the values of the eelgrass target recommended by DNR (Goldmark 2010) and current eelgrass abundance as estimated by DNR's eelgrass monitoring (2000-2009 decadal average, Gaeckle et al. 2011). Relative to the point estimate of the area of the eelgrass depth band, the current abundance of eelgrass represents 40% cover and the DNR target represents 48% cover. These are higher values of regional percent cover than anticipated, but there are no other existing numbers for comparison for greater Puget Sound, either contemporary or historical. These results do present an opportunity for comparison of regional percent cover from other estuaries where eelgrass, or other seagrasses, is monitored. These comparisons would provide additional reference points that would be particularly valuable if cover from relatively intact, degraded and recovering estuaries could be obtained.

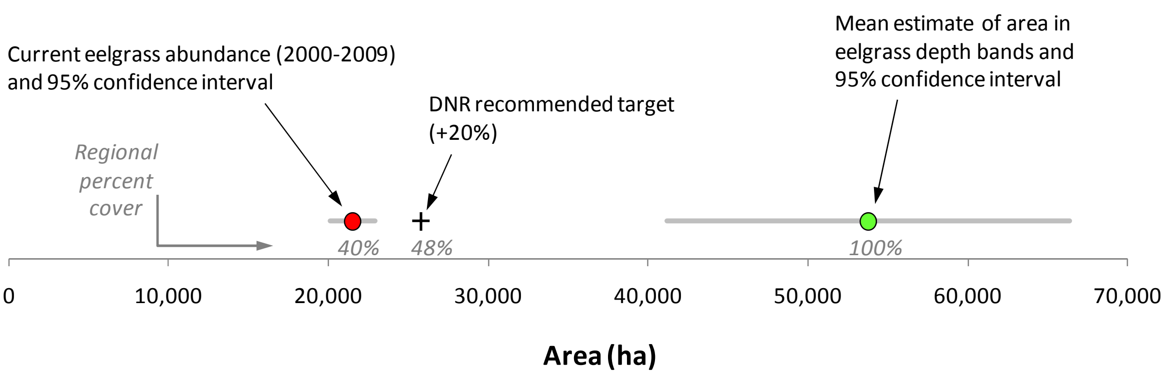


Figure 4-3. Relationship of the current eelgrass abundance and DNR recommended target to the 'best' estimate of area in the eelgrass depth bands. The current abundance is the decadal mean from DNR's SVMP monitoring (2000-2009). The best estimate is the mean of the estimates for greater Puget Sound using the WDFW and modified Finlayson et al. 2000 bathymetry datasets, and the SVMP region depth bands. The horizontal gray bars are the 95% confidence intervals. For the current abundance, the confidence interval is calculated from the monitoring data. For the eelgrass depth band area, the confidence interval is calculated as described in the text based on all five points shown in Figure 4-1. The regional percent cover shown is the area value as a percentage of the area of the eelgrass depth band point estimate.

The confidence interval on the estimate of eelgrass depth band area is wider than anticipated. The real interval is likely wider, since the error associated with the eelgrass depth band delineation has not been considered. The interval produced here only reflects the uncertainty in the underlying bathymetry data. The wide interval therefore reflects the fact that error in the bathymetry data is larger than anticipated.

This has implications for studies that rely on this bathymetry data, such as eelgrass habitat suitability modeling. This type of work predicts the suitability of locations for eelgrass growth and survival based on environmental parameters such as water clarity, temperature, salinity and dissolved oxygen, wave and current energy, sediment texture and geochemistry, as well as depth.

The wide confidence interval suggests that efforts to estimate potential eelgrass area based on environmental factors will be limited by uncertainty in the bathymetry data. Efforts to develop robust relationships between habitat suitability for eelgrass and sediment or water column parameters will have diminishing returns as uncertainty in bathymetry becomes the primary limitation on overall uncertainty.

5 Future Work

This section includes recommendations for future work. The tasks identified would build on the work completed here and provide useful contributions to the target-setting and assessment activities for eelgrass in Puget Sound.

Comparative Study of Seagrass Cover in other Estuaries

Past work has turned to other estuaries to provide reference points for eelgrass target setting when Puget Sound information is lacking. While historical seagrass estimates have been central to setting targets elsewhere (Dowty et al. 2010), such estimates do not exist for Puget Sound. In this case, records from other estuaries were useful in characterizing the rates of seagrass recovery that may be achieved when the goal is expansion of seagrass area.

This study has produced estimates of regional eelgrass cover as a percentage of the area of the eelgrass depth band for both the current population and for the Partnerhip's eelgrass target. Regional percent cover of eelgrass (or other seagrasses) from other estuaries could provide valuable reference points for assessing Puget Sound eelgrass targets in terms of percent cover.

> Recommendation 1: Compile existing estimates or conduct analysis to generate new estimates of seagrass percent cover in estuaries that conduct monitoring and have set management targets. Estimates are needed for both current abundance and the management target.

Assess Habitat Suitability Modeling

A meaningful estimate of potential eelgrass area that considers key environmental parameters in addition to depth will have to rely on some form of habitat suitability modeling. There is a substantial body of existing work that could be assessed for applicability in Puget Sound (Short et al. 2002; Phillips et al. 2006 and references therein). Initial work suggests that the ability to predict eelgrass presence is low with existing regional datasets (Dowty et al. 2005). Nevertheless, it is likely that such a modeling approach will be increasingly useful as eelgrass management and restoration progresses in Puget Sound.

> Recommendation 2: Conduct a literature review of habitat suitability models and their applications. Assess the feasibility of application in Puget Sound on a pilot basis.

Inventory Permanently Lost Eelgrass Habitat

Efforts to set seagrass targets in other estuaries have explicitly considered areas considered to be permanently lost as potential eelgrass habitat due to nearshore development (see Dowty et al. 2010). In these cases, seagrass targets are set based on consideration of both historical abundance and permanently lost habitat.

Mechanisms of habitat loss could include dredging and filling, as well as construction of overwater structures. A comparison of the magnitude of this area in Puget Sound relative to the area of increase associated with an eelgrass target will be instructive for ongoing project-level permitting and authorizations. The comparison will provide guidance for assessing the significance of project-level habitat loss and ensuring project-level decisions are consistent with the soundwide management goals as embodied in the current soundwide eelgrass target, as well as future sub-basin scale targets.

> Recommendation 3: Map areas of permanently lost eelgrass habitat due to nearshore development.

Improved Eelgrass Depth Bands

The delineation of specific depth bands was central to the work in this report. However, the SVMP region depth bands utilized data from only 2002-2004. The SVMP dataset now extends through 2010 and covers many additional sites. This provides an opportunity to improve the depth bands through a new analysis of the entire dataset.

> Recommendation 4: Generate new eelgrass depth histograms based on the complete 2002-2010 SVMP dataset. From these histograms, isolate new eelgrass depth bands for each region.

Develop Depth-Specific Targets and Change Scenarios

The scenarios studied in this report (sections 3.3.2, p. 27, and 3.3.3, p. 29) examine the effect on area if the shallow and deep margins of the depth band shift up or down. This approach does not consider the fact that the likelihood of eelgrass presence is much lower at the depth band margins than in the central area of the band (Figure 2-4, p. 11). The addition of a unit area to the margins of the eelgrass depth band does not represent an opportunity for expansion of eelgrass area in proportion to the size of the increment of area.

This concept can come into play in another context. The effect of error in the depth band delineation was not addressed in this study. This error could have been assessed by repeating the area calculations for bands that encompass all eelgrass observations rather than the depths corresponding to the 1 and 99 percentiles of the observations.

However, the inclusion of the extreme 1% of the observations, especially on the deep end, would have expanded the depth bands substantially (see Figure 2-5, p. 13). These expanded depth bands would lead to large differences in area, suggesting that there is a very large error associated with depth band delineation. This would not accurately capture the true error.

These considerations suggest a different approach to treating eelgrass and depth. Rather than conceptualizing a depth band as a binary present/absent distinction, the data is available to drive a more sophisticated approach. The overall depth band could be divided into smaller depth bins, each with a cover as a percentage of the area within the depth bin. This 'regional percent cover' (in contrast to traditional percent cover, such as in Braun-Blauquet methodology) reflects the measured abundance within that bin and the available habitat based on available bathymetry data. Change scenarios and targets could then be cast in terms of changes in percent cover within depth bins. For example, a scenario of improved water clarity that leads to eelgrass expansion at depth could be modeled as an increase in the very low cover currently found at depth. This could be a more meaningful representation than lowering the deep margin of the depth band so that a large area is added (large response) even though the cover achieved would be anticipated to be very low (small actual response). Targets based on depth bin cover would be too complex to serve, for example, as a 'Dashboard' indicator, but they could be valuable in relating change to mechanisms and devising management actions in response to observed change.

Recommendation 5: Estimate eelgrass percent cover in depth bins for each SVMP region and track as annual monitoring results. Devise and analyze scenarios of change based on depth bin cover.

Improved MLLW Bathymetry

While there are existing high-quality bathymetry datasets for the region, each has important limitations for the study of eelgrass over greater Puget Sound. These limitations include limited spatial extent (Finlayson 2005), limited coverage at shallow depths (WDFW), missing data (Finlayson et al. 2000) and inappropriate datums for the study of eelgrass (Finlayson et al. 2000 and Finlayson 2005).

The effort to fill the missing data in Finlayson et al. 2000 showed that more recent NOAA soundings are available for some areas (section B.1, p. 49). It also showed that large interpolation errors are possible when creating a gridded dataset so optimization of interpolation parameters is critical. Also, datum transformations are to be avoided where possible since these introduce substantial error into the data (section B.3.2, p. 53).

This task will require substantial effort, but there will be applications beyond eelgrass management issues. The DNR Aquatic Resources Division and Regions may have important applications associated with locating ownership boundaries. It may be possible to pool resources to accomplish this task and generate multiple datasets with different tidal datums (e.g. MLW, MHW) as part of the same effort.

Recommendation 6: Generate a new bathymetric dataset based primarily on NOAA soundings that maintains the native MLLW datum of the soundings.

- Other data sources (e.g. sonar) should be incorporated where available.
- Terrestrial elevations must be incorporated where necessary to ensure data coverage in shallow depths not covered by soundings. These terrestrial data must be transformed to a MLLW datum.
- Substantial effort will be needed to optimize the interpolation parameters used in order to minimize error, particularly in places with rapidly changes slope.

6 References

Amante, C. and B. W. Eakins. 2009. ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. NOAA Technical Memorandum NESDIS NGDC-24, 19 pp. (http://www.ngdc.noaa.gov/mgg/global/global.html).

Bevington, P.R. 1969. *Data Reduction and Error Analysis for the Physical Sciences*. McGraw-Hill, New York.

Butler, R.W. 1995. The patient predator: Foraging and population ecology of the great blue heron, *Ardea herodias*, in British Columbia. *Occasional Papers for Canadian Wildlife Service* No. 86.

Costanza, R., R. d'Arge, R. de Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Naeem, R.V. O'Neill, J. Paruelo, R.G. Raskin, P. Sutton, and M. van den Belt. 1997. The value of the world's ecosystem services and natural capital. *Nature* 387:253-260.

Dowty, P., H. Berry and J. Gaeckle. 2010. *Developing Indicators and Targets for Eelgrass in Puget Sound: A Science Assessment*. Nearshore Habitat Program, Washington State Department of Natural Resources, Olympia.

Dowty, P. 2005. *A Study of Sampling and Analysis Methods: Submerged Vegetation Monitoring Project at Year 4*. Nearshore Habitat Program, Washington State Department of Natural Resources, Olympia.

Dowty, P., C. Donoghue, S. Wyllie-Echeverria and H. Berry. 2005. *Ability to Predict Zostera marina Presence Using Regional Datasets in Puget Sound, Washington*. Poster presentation at Georgia Basin Puget Sound Research Conference, March 29-31, Seattle, WA.

Finlayson, D.P. 2005. *Combined bathymetry and topography of the Puget Lowland, Washington State*. University of Washington. http://www.ocean.washington.edu/data/pugetsound

Finlayson, D.P., R.A. Hagerud, H. Greenberg and M.G. Logsdon. 2000. *Puget Sound Digital Elevation Model*. University of Washington. http://www.ocean.washington.edu/data/pugetsound

Gaeckle, J., P. Dowty, H. Berry, and L. Ferrier. 2009. *Puget Sound Submerged Vegetation Monitoring Project: 2008 Monitoring Report*. Nearshore Habitat Program, Washington State Department of Natural Resources, Olympia.

Gaeckle, J., P. Dowty, H. Berry, and L. Ferrier. 2011. *Puget Sound Submerged Vegetation Monitoring Project: 2009 Monitoring Report*. Nearshore Habitat Program, Washington State Department of Natural Resources, Olympia.

Goldmark, P. 2010. Letter from the Commissioner of Public Lands to the Executive Director of the Puget Sound Partnership, dated August 24, 2010. http://www.dnr.wa.gov/Publications/aqr_commissioner_letter_pps.pdf

Green, E.P., and F.T. Short. 2003. *World atlas of seagrasses*. Prepared by the UNEP World Conservation Monitoring Centre. University of California Press, Berkeley, USA. 298 pp.

Larkum, A.W.D., R.J. Orth, and C.M. Duarte (eds). 2006. *Seagrasses: biology, ecology and conservation*. Springer, Dordrecht, The Netherlands. 691 pp.

McLellan, W.L. 1954. *An area and volume study of Puget Sound, Washington*. University of Washington Department of Oceanography Technical Report No. 21. University of Washington, Seattle, WA.

Mote P.W., A. Petersen, S. Reeder, H. Shipman, L. Whitely Binder. 2008. *Sea level rise in the coastal water of Washington State*. Report prepared by the Climate Impacts Group, Center for Science in the Earth System, Joint Institute for the Study of the Atmosphere and Oceans, University of Washington, Seattle, WA and the Washington Department of Ecology, Lacey, WA.

NOAA. 2010. *Vertical Datum Transformation: Integrating America's Elevation Data*. Web page. Accessed 10/7/10. vdatum.noaa.gov.

NOAA National Geophysical Data Center. 2010. *U.S. Coastal Relief Model*. Accessed 10/7/10. www.ngdc.noaa.gov/mgg/coastal/crm.html.

NOAA National Ocean Service. 2010. *National Ocean Service Hydrographic Survey Data*. Web page providing interface to the NOS Hydrographic Database. Accessed 11/3/10. http://www.ngdc.noaa.gov/mgg/bathymetry/hydro.html

NOAA National Ocean Service. 2008. *Estuarine Bathymetric Digital Elevation Models (30 meter resolution) Derived from Source Hydrographic Survey Soundings Collected by NOAA*. National Ocean Service Special Projects. Retrieved 7/30/2010: http://estuarinebathymetry.noaa.gov/

Nysewander, D.R., J.R. Evenson, B.L. Murphie and T.A. Cyra. 2005. *Report of Marine Bird and Marine Mammal Component, Puget Sound Ambient Monitoring Program, For July 1992 to December 1999 Period*. Wildlife Management Program. Washington State Department of Fish and Wildlife. (p.142). Section 4.2 Creation of Improved Digital Bathymetric Database for Puget Sound.

http://fortress.wa.gov/dfw/gispublic/apps/psampdensity/speciespages/bird_decadal.pdf

Parker, B., K.W. Hess, D.G. Milbert and S. Gill. 2003. A national vertical datum transformation tool. *Sea Technology*, 44(9):10-15.

Phillips, R.C. 1972. *Ecological Life history of Zostera marina L. (Eelgrass) in Puget Sound, Washington*. PhD Dissertation, University of Washington, Seattle, WA.

Phillips, R.C. 1974. Temperate Grass Flats. In: Odum, H.T., B.J. Copeland and E.A. McMahan (eds.). *Coastal Ecological Systems of the United States*, Volume II. The Conservation Foundation, Washington, DC, pp. 244-299.

Phillips, R.C. 1984. *The ecology of eelgrass meadows in the Pacific Northwest: a community profile*, U.S. Fish and Wildlife Service, FWS/OBS 84/24.

Phillips, S.J., R.P. Anderson and R.E. Schapire. 2006. Maximum entropy modeling of species geographic distributions. *Ecological Modelling*, 190:231-259.

Selleck, J.R., H.D. Berry and P. Dowty. 2005. *Depth Profiles of Zostera marina Throughout the Greater Puget Sound: Results from 2002-2004 Monitoring Data*. Nearshore Habitat Program, Washington State Department of Natural Resources, Olympia.

Short, F.T., R.C. Davis, B.S. Kopp, C.A. Short, and D.M. Burdick. 2002. Site-selection model for optimal transplantation of eelgrass Zostera marina in the northeastern US. *Marine Ecology Progress Series* 227:253-267.

Simenstad, C.A. 1994. Faunal associations and ecological interactions in seagrass communities of the Pacific Northwest coast., Pages 11-17 in Wyllie-Echeverria, S., Olson, A.M., Hershman, M.J. (eds) *Seagrass Science and Policy in the Pacific Northwest: Proceedings of a Seminar Series*. U.S. Environmental Protection Agency, Seattle, WA. (SMA 94-1). EPA 910/R-94 004. 63 pp.

Simenstad, C., M. Ramirez, J. Burke, M. Logsdon, H. Shipman, C. Tanner, C. Davis, J. Fung, P. Bloch, K. Fresh, S. Campbell, D. Myers, E. Iverson, A. Bailey, P. Schlenger, C. Kiblinger, P. Myre, W.I. Gertsel and A. MacLennan. 2010. *Historic Change and Impairment of Puget Sound Shorelines: Atlas and Interpretation of Puget Sound Nearshore Ecosystem Restoration Projeect Change Analysis*. October 2009 Draft. Puget Sound Nearshore Ecosystem Restoration Project. Accessed on 9/8/10 at ftp://ftp.usace.army.mil/pub/nws/PSNERP_CA/.

Thayer, G.W. and R.C. Phillips. 1977. Eelgrass in Puget Sound. *Marine Fisheries Review* 39(11):18-22.

Thom, R.M. and L. Hallum. 1990. *Long-Term changes in the Areal Extent of Tidal Marshes, Eelgrass Meadows and Kelp Forests of Puget Sound*. Final Report to EPA, EPA 910/9-91-005, Fisheries Research Institute, University of Washington, Seattle, WA.

Wilson, U.W., and J.B. Atkinson. 1995. Black brant winter and spring-stages use at two Washington coastal areas in relation to eelgrass abundance. *The Condor* 97:91-98.

Youngmann, C. (Ed.). 1978, 1979, 1980. *Coastal Zone Atlas of Washington*. 12 Volumes published between 1978-1980, DOE 77-21-1 through 12. Washington State Department of Ecology, Olympia, Washington.

Appendix A Vertical Datums

This study utilized multiple bathymetric datasets that are based on different vertical datums. A Mean Lower Low Water (MLLW) datum is best for characterizing eelgrass depth because the elevation of MLLW is an important ecological constraint on eelgrass growth and survival. Above this elevation, there is periodic emersion at very low tides and it is a rough indication of upper limit of eelgrass growth. The depths of the shallow edge of eelgrass beds relative to Mean Sea Level (MSL) will vary widely across sites with different tidal ranges, thereby limiting the value of cross-site comparisons. In contrast, these depths would be relatively invariant when given relative to MLLW, thereby facilitating meaningful cross-site comparisons. Bathymetric data is typically based on a tidal datum (e.g. MLLW, MSL, or Mean High Water, MHW) or an orthometric datum[1].

A.1 Orthometric Datums

Since 1929, only two orthometric datums have been widely used in the U.S. – the National Geodetic Vertical Datum of 1929 (NGVD29) and the North American Vertical Datum of 1988 (NAVD88). In concept, orthometric datums are based on geopotential, or equipotential, surfaces. Every point on a geopotential surface has the same potential energy with respect to gravity. Plumb is always locally perpendicular to a geopotential surface and a spirit level is parallel. There are an infinite number of geopotential surfaces but only one, known as the geoid, coincides with the hypothetical surface of the global oceans at equilibrium (i.e. no earth rotation, no currents, no meteorological forcing). The geoid can only be determined through extensive gravitational measurements and modeling as it reflects the non-homogeneous distribution of the earth’s mass. In general, the surface of the geoid over tidal waters will not correspond with the actual local MSL due to local prevailing winds, river inputs and ocean currents (USACE 2010, p.2-5, 2-7). In other words, while the geoid represents the equipotential surface that is equilibrium sea-level and this may be used as a proxy for MSL, it is an inexact representation because local MSL elevations across locations will not lie on the same equipotential surface.

The NGVD29 datum, created by the US Coast & Geodetic Survey in 1929, was based on an equipotential surface and then warped to coincide with MSL as measured at 26 tide stations in the US and Canada. This was initially considered to be a “mean sea-level” datum, but the datum did not necessarily match local MSL outside the 26 control points. Also, due to the warping, the resulting datum no longer represented a true equipotential surface and was no longer truly ‘orthometric’.

The NAVD88 datum, created by the National Geodetic Survey of NOAA in 1988, is a true equipotential surface (White et al. 2009; USACE 2010). The specific equipotential surface was selected to coincide with local MSL at one location – a tidal

[1] Orthometric datums are also referred to as geodetic datums (USACE 2010, p.2-1).

bench mark at Father Point at the mouth of the Lower St. Lawrence River in Quebec (USACE 2010, p.2-5). The NAVD88 datum is loosely thought of as a MSL datum, but it is an equipotential surface and a height of zero will not necessarily coincide with local MSL except at the control tide gage at Father Point in Quebec.

A.2 Tidal Datums

Tidal datums are determined from local tide gages and represent average tidal stages, e.g. MSL, MHW, MLLW. Formally, a 19-year tide gage record that covers a tidal epoch must be used to derive tidal datums for legal purposes (Gill and Schultz 2001). NOAA's National Ocean Service (NOS) establishes National Tidal Datum Epochs (NTDE) for this purpose. The epoch in current use is 1983-2001, which superseded the previous epoch of 1960-1978[2].

The period of the tidal epoch is related to the 18.6 year tidal cycle that is caused by the precession of the lunar nodes (i.e. rotation of the plane of the moon's orbit relative to the plane of the earth's orbit around the sun) (Schureman 1958). This cycle of the lunar nodes has been associated with atmospheric (Currie 1996) and oceanic (Loder and Garrett 1978) climatic cycles. It has also been associated with cycles in marine nearshore organisms in the intertidal zone caused by resultant cycles in emersion times (Denny and Paine 1998; Mislan et al. 2009).

The height difference between MLLW and MSL varies significantly across locations in greater Puget Sound. This is caused by variation in the overall tidal range. For example, the tidal range is 1.9 m in the eastern Strait of Juan de Fuca (Victoria) and 4.4 m at Olympia (Mofjeld and Larsen 1984). The tidal range at Neah Bay is 2.2 m (Mofjeld and Larsen 1984). The associated difference between MSL and MLLW in Puget Sound proper alone ranges from 1.40 m at the northern entrance to Admiralty Inlet, to 2.52 m at the head of Oakland Bay near Shelton (Figure A-1). Consequently, it is necessary to pay particular attention to the datum of bathymetric data for regional analyses and hence the need for transformations between datums. Differences between MSL and MLLW as represented by VDatum are shown in Figure 3-4 (p. 18).

A.3 NOAA's VDatum

NOAA's VDatum software tool[3] has been characterized as paramount among many initiatives to provide transformations between the orthometric and tidal datums, as well as ellipsoidal datums (mathematical datums utilized by GPS systems)(USACE 2010, p.2-6). It is a free Java program that is supplied with region-specific transformation grids (Parker et al. 2003). Two transformation grids were required to cover the greater Puget Sound study area.

Currently (version 2.3.3, released 10/26/2010), VDatum only accepts ASCII *x*,*y*,*z* triplets in input files and the *x*,*y* values must be lat-long degrees or UTM coordinates.

[2] The years of these tidal epochs are noted on the NOAA CO-OPS web site: tidesandcurrents.noaa.gov/index.shtml
[3] The VDatum software, transformation grids and documentation are available at vdatum.noaa.gov.

Consequently, substantial pre- and post-processing may be necessary to convert digital raster data for use with VDatum.

Analysis for this project began when version 2.3.2 was the current version of VDatum. Transformation of the Finlayson 2005 dataset was completed with this version on a UNIX system (Sun Solaris). However, analysis of the Finlayson et al. 2000 dataset could not be completed on UNIX because of a bug in the NAD27 and NGVD29 transformations. Analysis of this version was completed on a Windows XP system that was not affected by the bug. This problem was reported to VDatum technical support and a new version (2.3.3) was subsequently released that fixed the bug.

A.4 References

Currie, R.G. 1996. Variance Contribution of Luni-Solar (M_n) and Solar Cycle (S_c) Signals to Climate Data. *International Journal of Climatology*. 16:1343-1364.

Denny, M.W. and R.T. Paine. 1998. Celestial Mechanics, Sea-Level Changes, and Intertidal Ecology. *Biological Bulletin*. 194;108-115.

Gill, S.K. and J.R. Schultz (Eds.). 2001. *Tidal Datums and their Applications*. NOAA Special Publication NOS CO-OPS 1. NOAA, Silver Spring, MD.

Loder and Garrett. 1978. The 18.6-Year Cycle of Sea Surface Temperature in Shallow Seas Due to Variations in Tidal Mixing. *Journal of Geophysical Research*, 83(C4):1967-1970.

Mislan, K.A.S., D.S. Wethey and B. Helmuth. 2009. When to worry about the weather: role of tidal cycle in determining patterns of risk in intertidal ecosystems. *Global Change Biology*, 15:3056-3065.

Mofjeld, H.O. and L.H. Larsen. 1984. *Tides and Tidal Currents of the Inland Waters of Western Washington*. NOAA Technical Memorandum ERL PMEL-56. Pacific Marine Environmental Laboratory, Seattle WA.

Mofjeld, H.O., A.J. Venturato, V.V. Titov, F.I. González and J.C. Newman. 2002. *Tidal Datum Distributions in Puget Sound, Washington, Based on a Tidal Model*. NOAA Technical Memordandum OAR PMEL-122. Pacific Marine Environmental Laboratory, Seattle WA.

Parker, B., K.W. Hess, D.G. Milbert and S. Gill. 2003. A national vertical datum transformation tool. *Sea Technology*, 44(9):10-15.

Schureman, P. 1958. *Manual of Harmonic Analysis and Prediction of Tides*. 1958 reprint with corrections. Special Publication No. 98, Coast and Geodetic Survey, Washington DC. Accessed 10/7/10 at http://www.archive.org/details/manualofharmonic00schu

USACE. 2010. *Standards and Procedures for Referencing Project Elevation Grades to Nationwide Vertical Datums*. Engineer Manual EM 1110-2-6056, 30 September

2010 Draft. US Army Corps of Engineers, Washington D.C. Accessed 10/6/10 at http://www.agc.army.mil/ndsp/downloads/EM%201110-2-6056%20(Final%20Draft).pdf

White, S., L. Graham and S. Riddell. 2009. Implementing Tidal Datums in GeoCue. *Photogrammetric Engineering & Remote Sensing*. 75(11):1246-1250.

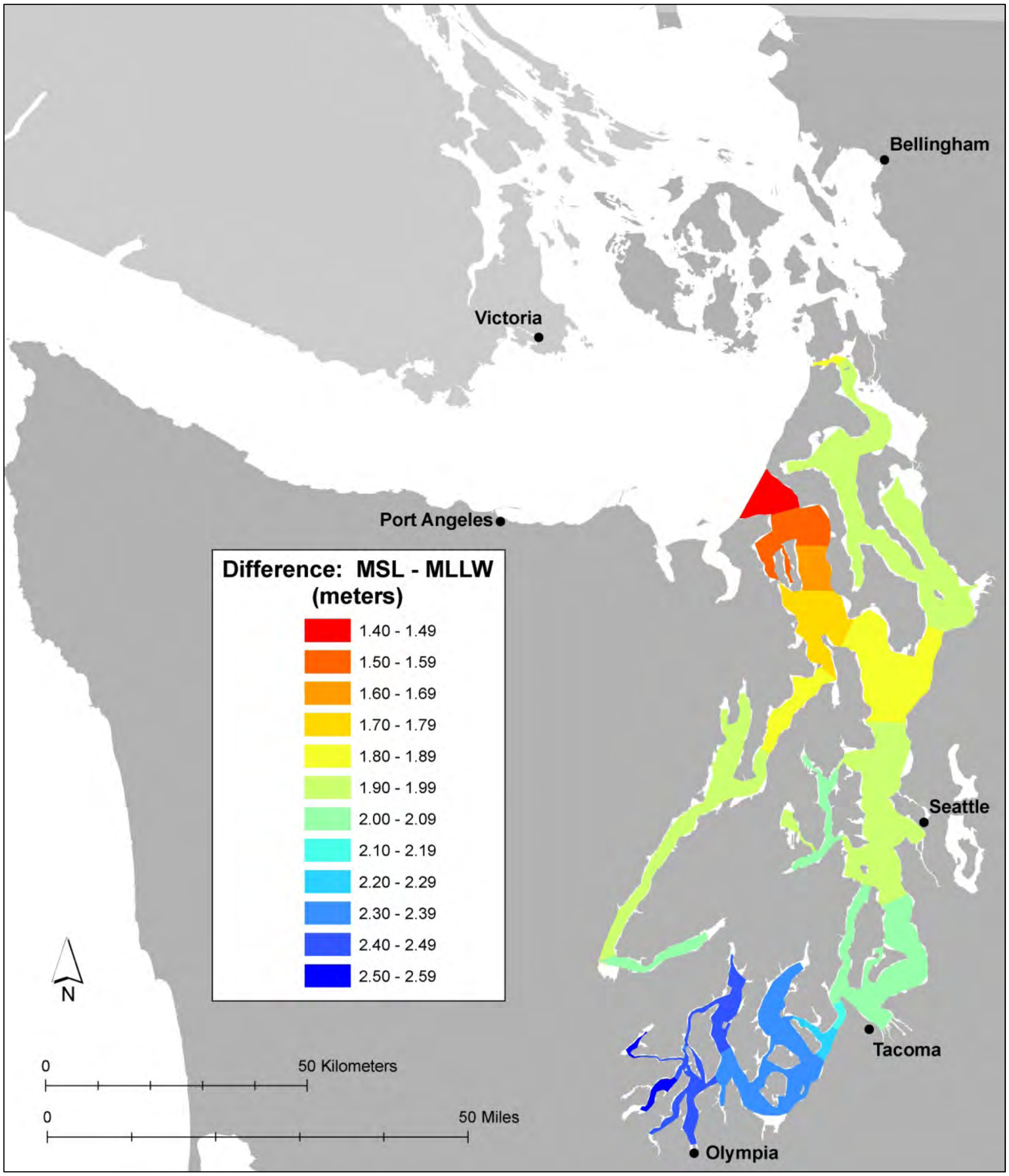


Figure A-1. Elevation difference between Mean Sea Level (MSL) and Mean Lower Low Water (MLLW) datums for Puget Sound. Data from Mofjeld et al. (2002).

Appendix B Use of NOAA Soundings to Augment Finlayson et al. 2000

B.1 Methods

The area of missing data in the Finlayson et al. 2000 dataset was filled using NOAA hydrographic survey data. The data were downloaded from NOAA's National Ocean Service[4]. All surveys within the following geographic bounds were retrieved:

North: 48.686263 degrees latitude; *South*: 48.463541 degrees latitude
West: -122.834151 degrees longitude; *East*: -122.487888 degrees longitude

This produced 359,661 soundings from 25 different surveys going back to 1887. For each survey, the survey year and datums used were extracted from the HYD93 header information[5] available online with the survey data. Of the 25 surveys retrieved, six of the most recent surveys (1998 and later) were selected that covered most of the area of missing data. Selected soundings from two older 1955 surveys were added to expand the data coverage (Table B-1, Figure B-1).

Table B-1. Eight NOAA hydrographic surveys used to augment the Finlayson et al. 2000 dataset. Attributes were extracted from the survey HYD93 headers.

	Survey	Survey End Year	Horizontal Datum	Original Horizontal Datum	Vertical Datum	Original Vertical Units
1	H11269	2004	NAD83	NAD83	MLLW	unknown
2	H11268	2003	NAD83	NAD83	MLLW	unknown
3	H10792	2000	NAD83	NAD83	MLLW	decimeters
4	H10887	1999	NAD83	NAD83	MLLW	decimeters
5	H10911	1999	NAD83	NAD83	MLLW	decimeters
6	H10766	1998	NAD83	NAD83	MLLW	decimeters
7	H08331	1955	NAD83	NAD27	MLLW	fathoms
8	H08333	1955	NAD83	NAD27	MLLW	fathoms

A total of 205,880 soundings with depths relative to a MLLW datum were selected. Supplementary points (n=33) were added from the surrounding Finlayson data (transformed to MLLW datum) to expand data coverage to the shallow margins of Fidalgo and Padilla Bays and the northern shore of Sinclair Island (Figure B-1).

[4] Survey data retrieved from www.ngdc.noaa.gov/mgg/bathymetry/hydro.html
[5] HYD93 header documentation available here: www.ngdc.noaa.gov/mgg/dat/geodas/docs/hyd93.htm

The soundings were imported into ArcGIS as a point shapefile with geographic (lat/long) coordinates and assigned the original 1986 version of the NAD83 datum[6]. This data layer was transformed to the NAD27 datum using the NADCON method and re-projected to the UTM projection, Zone 10N to match the Finlayson et al. 2000 dataset. The HYD93 headers specify that sounding depths were integer values in units of tenths of meters.

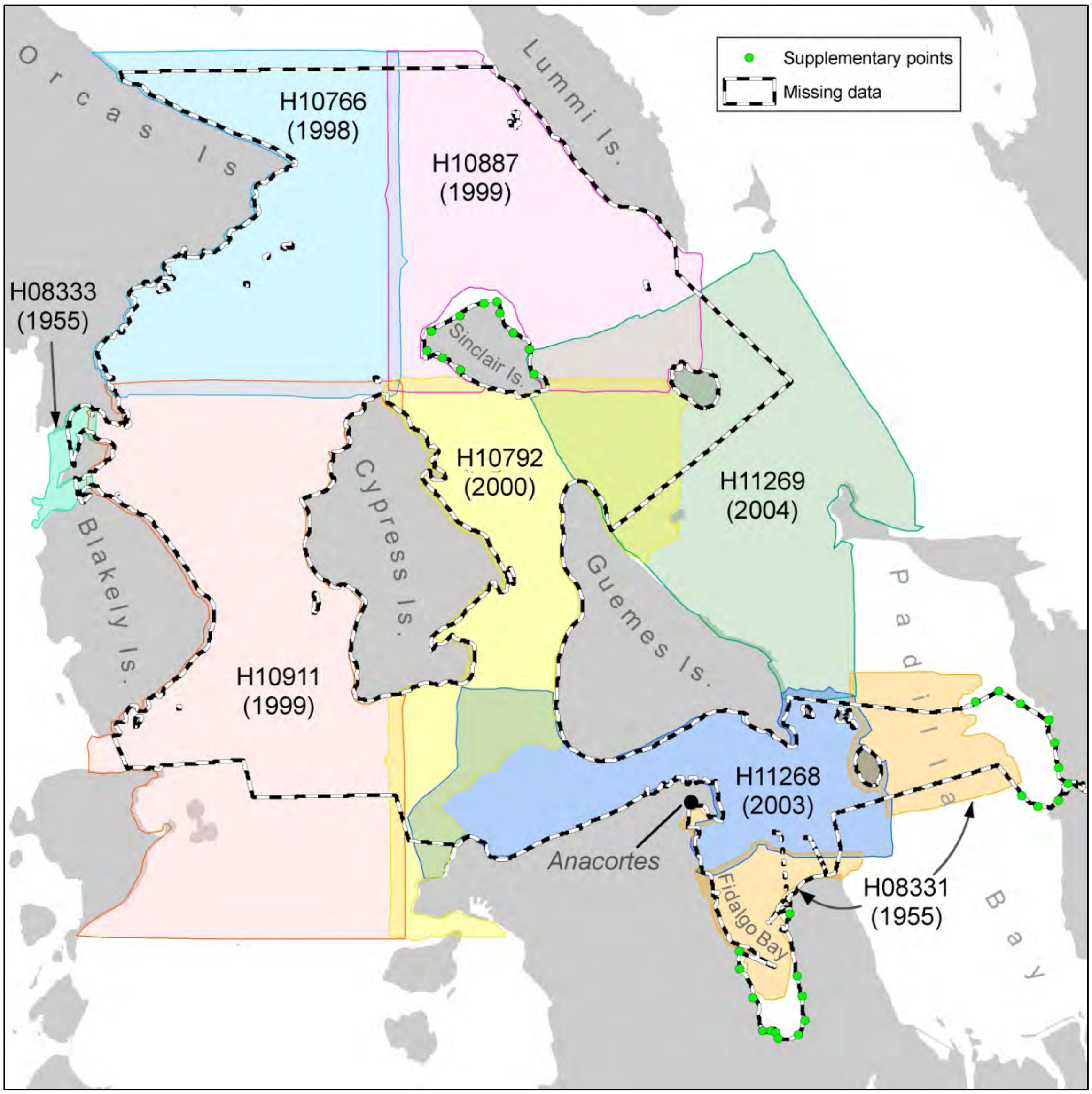


Figure B-1. Spatial bounds of the eight NOAA hydrographic survey areas used to fill the area of missing data in the Finlayson et al. 2000 dataset. The green points indicate the 33 supplementary points drawn from the surrounding Finlayson data (transformed to MLLW) to expand data coverage to the shallow areas of Fidalgo and Padilla Bays and the northern shore of Sinclair Island.

[6] The original 1986 version of the NAD83 datum is specified in the "North American Datum 1983.prj" projection file in ArcGIS. This is similar, but distinct, from the most recent U.S. re-adjustment "NAD 1983 (NSRS2007).prj", the HARN re-adjustment "North American 1983 HARN.prj", and the Canadian re-adjustment "North American 1983 (CSRS98).prj."

Ordinary kriging (ArcGIS Spatial Analyst 9.3) with 12-point interpolation was used to create a bathymetric surface with 30 m horizontal resolution based on the 205,880 point depths from NOAA soundings and the 33 supplementary points. The kriging parameters used were the ArcGIS defaults and were not optimized for this application. The resulting surface depicted depths relative to MLLW in integer centimeters. By maintaining an extra significant digit, the original precision in sounding depths will be maintained to a greater extent (see Bevington 1969, p.5).

B.2 Discrepancies between Datasets

A simple inspection of the results reveals noticeable discrepancies between the kriged data and the transformed Finalyson dataset where the two meet – perhaps most obviously in Padilla Bay (Figure 3-5, p.19). These discrepancies prompted further characterization of the differences between the datasets. Twenty points were selected along the boundary between the two datasets. The elevation of each dataset and the difference between them was recorded for each point (Figure B-2).

The differences were much larger in magnitude and more variable than expected. The kriged dataset ranges from being 2.0 meters higher than the transformed Finlayson dataset to being -30.8 meters lower (Figure B-2). These differences were considered large enough to warrant further consideration of error.

B.3 Error Assessment

An assessment of error was clearly needed in order to better understand the error associated with the kriged dataset and the transformed Finlayson datasets. Such an assessment may also provide insight into the sources of error and guide future work to produce the best datasets possible.

B.3.1 NOAA Soundings

The source data for both datasets are the NOAA soundings contained in the GEODAS database, although recent surveys were used for the kriged dataset that were not available when the Finlayson et al. 2000 dataset was produced. The vertical error is likely dominated by corrections to the depth measurement rather than error of the depth measurement itself. The measured depths must be adjusted to a MLLW depth using the closest tide station. The documentation for the more recent surveys specifies that the Friday Harbor station has been used for this purpose. This and other related errors have a maximum allowable error.

> *"The allowable contribution of the error for tides and water levels to the total survey error budget falls between 0.20 m and 0.45 m (at the 95% confidence level)." (NOAA 2010a, p. 11).*

In contrast, the error associated with the actual depth measurements is required to have

> *"…sufficient precision to support Total Propagated Uncertainty (TPU) estimates for depth values at centimeter precision." (NOAA 2010a, p. 76)*.

The maximum allowable overall error, or Total Vertical Uncertainty (TVU) in NOAA's terms, is depth dependent and is less than 65 cm for depths of 30 m or less (NOAA 2010, p. 77).

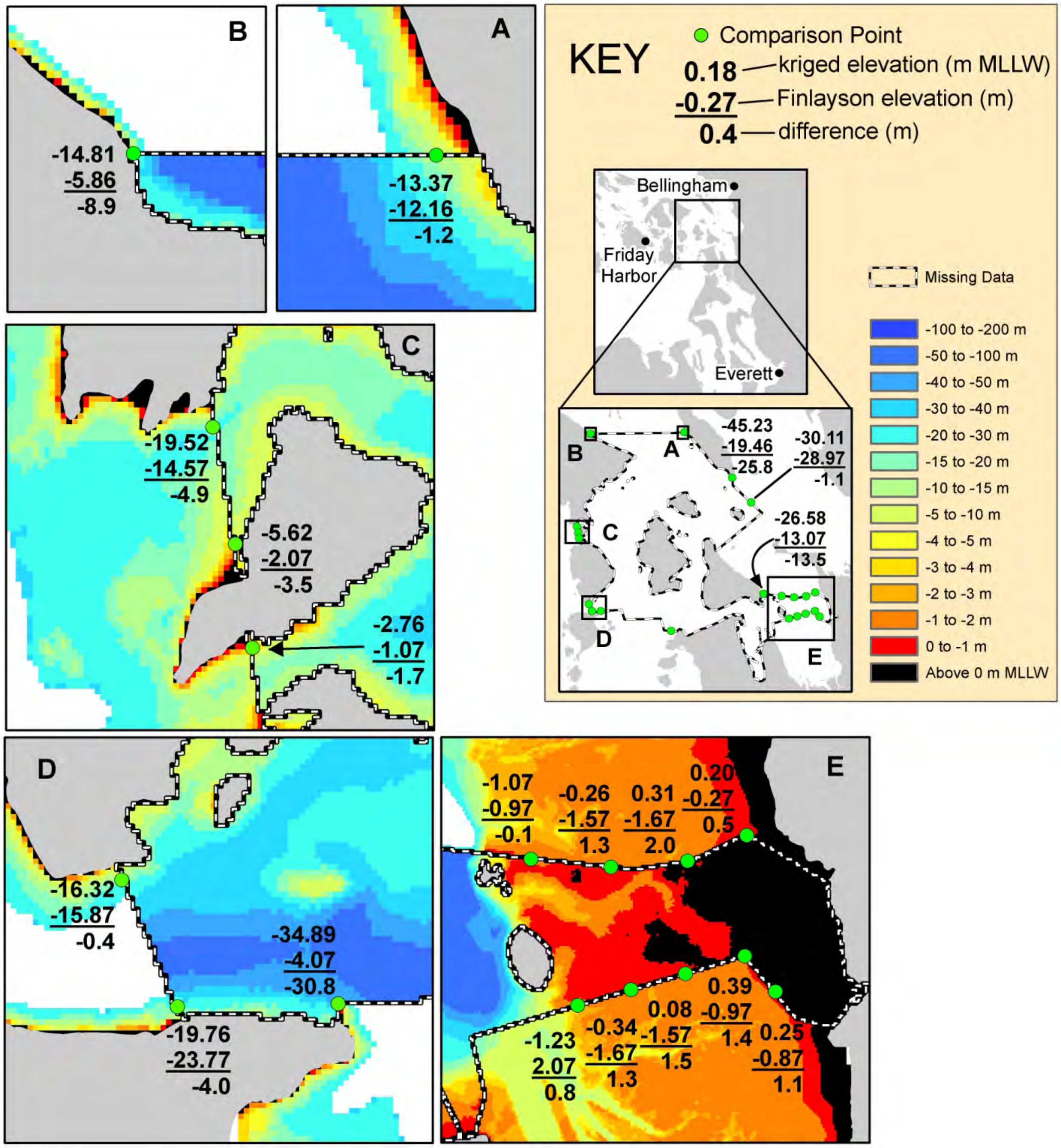


Figure B-2. Comparison of elevations from Finlayson et al. 2000 (transformed to a MLLW datum) to those from the kriged data along the boundary between the two datasets – i.e. the boundary of the missing data in Finlayson et al. 2000. Elevations from each dataset and the difference are shown for each of 20 comparison points. The differences at these 20 points range from the kriged dataset being 2.0 m above the Finalyson et al data (inset map E) to 30.8 m below (inset map D).

Thus, while the raw depth measurements have error on the order of a centimeter, the final MLLW depth may have error on the order of a several decimeters (i.e., several tens of centimeters). Notes from surveys provide further characterization of vertical errors. For example, the descriptive report for survey H11269 found discrepancies of one fathom (1.8 m) or less and occasionally up to three fathoms in a comparison to an existing chart and concluded the two "agreed extremely well." In comparison to a different chart, discrepancies in deep water (> 6 fathoms, > 11 meters) within 1 fathom (1.8 m) and within half a fathom (0.9 m) in shallow water were also considered to have "agreed extremely well".

In summary, the error on contemporary NOAA sounding depths is on the order of a few decimeters, but when compared to older bathymetry data, differences of 1-2 meters is considered to be good agreement.

B.3.2 Vertical Datum Transformation

Two vertical datum transformations are involved in the datasets being compared. First, NOAA soundings (with MLLW datum) were transformed to NGVD29 by Finlayson et al. (2000) as part of their data processing. No documentation of this processing was available for this study, but the approach used to produce the later Finlayson (2005) dataset is instructive.

The metadata for Finlayson (2005) specifies that an early version of NOAA's VDatum tool (v1.06) was used to transform depths from MLLW to NAVD88 (Finlayson 2006, Appendix A). At that time, however, NOAA had not released a transformation grid for the Strait of Juan de Fuca which would cover the area of concern here (area of Figure B-1). Instead, these areas were transformed with a NAVD88 correction surface developed by Finlayson using tidal benchmarks (Finlayson 2006, p. 200). Finlayson (2006, p. 208) estimated that the error associated with this transformation to be 0.75 cm, but it is not clear if this is the error relative to VDatum output or the overall error.

This information indicates that production of the earlier dataset (Finlayson et al. 2000) certainly did not utilize VDatum for transformations in the area of the current comparison (the area of the kriged data), and may not have used VDatum at all.

The second transformation to be considered was the transformation conducted as part of this study (Section 2.1.2, p. 5) of the NGVD29 data of Finlayson et al. (2000) back to MLLW. This was done with VDatum version 2.3.2. Documentation for VDatum states that the standard deviation of expected error is 9.7 cm for the Puget Sound transformation grid and 14.0 cm for the Strait of Juan de Fuca transformation grid (NOAA 2010b). Larger errors of 18 cm can be assumed to be involved when source data has a NGVD29 datum, which may have been the case with at least some of the terrestrial data used by Finlayson et al. (2000) to create the dataset.

Since different methods were used to transform from MLLW to NGVD29 and then back to MLLW, the errors were not reversed but were instead compounded. Given that the error quoted for datum transformation by Finlayson (2006) (0.75 cm) is an order of magnitude less than that quoted by NOAA (2010b) for VDatum, the lower number presumably describes the incremental error only associated with the transformation developed by Finlayson – i.e., this error is in addition to the error associated with VDatum transformations.

An overall estimate of error for this transformation would be the sum of errors associated with VDatum and the additional error, 0.75 cm, given by Finlayson (2006). An estimate for the error of the second transformation (from NGVD29 back to MLLW) would not include the additive term 0.75 cm. The VDatum errors are given as standard deviations (NOAA 2010b), so they are doubled here to give rough 95% confidence intervals ($z_{0.05}$=1.96).

$$\textit{total transformation error} = \sqrt{\left[2\times\left(0.75+14.0\right)\right]^2+\left[2\times14.0\right]^2} = 41\text{cm}$$

B.3.3 Horizontal Positional Accuracy

The specifications for NOAA surveys indicate that the total horizontal uncertainty in the position of the soundings must not exceed 5 meters + 5% of the water depth (NOAA 2010a). There is a much greater potential uncertainty associated with the horizontal datum transformation and re-projection of these data when they are imported into ArcGIS. For example, the initial bathymetric surface generated in this effort had an obvious horizontal offset of several pixels that was due to an inappropriate transformation. This version was discarded and the obvious horizontal offset was eliminated with the use of the NADCON transformation.

It is difficult to translate uncertainty in horizontal position to an uncertainty in vertical elevation. This will depend on the particular beach profile at given location. Fortunately, if we assume that any horizontal offset is relatively constant over small spatial scales, it will have little to no effect on estimated areas within specific depth bands. Any effect of horizontal offsets is therefore ignored in this study.

B.3.4 Interpolation Error

There is error associated with the kriging of the NOAA soundings. This error is not assessed quantitatively here, but an inspection of the interpolated data in relation to the NOAA soundings suggests that this may be an important source of error (Figure B-3). In the space of a few pixels, the match between the interpolated cell values and the source point data ranges from good to poor. This indicates that the kriging algorithm used is not flexible enough to track rapidly changing bathymetry. To some extent, this may be a result of using default krige parameters, rather than optimizing the parameters for the spatial properties of the dataset.

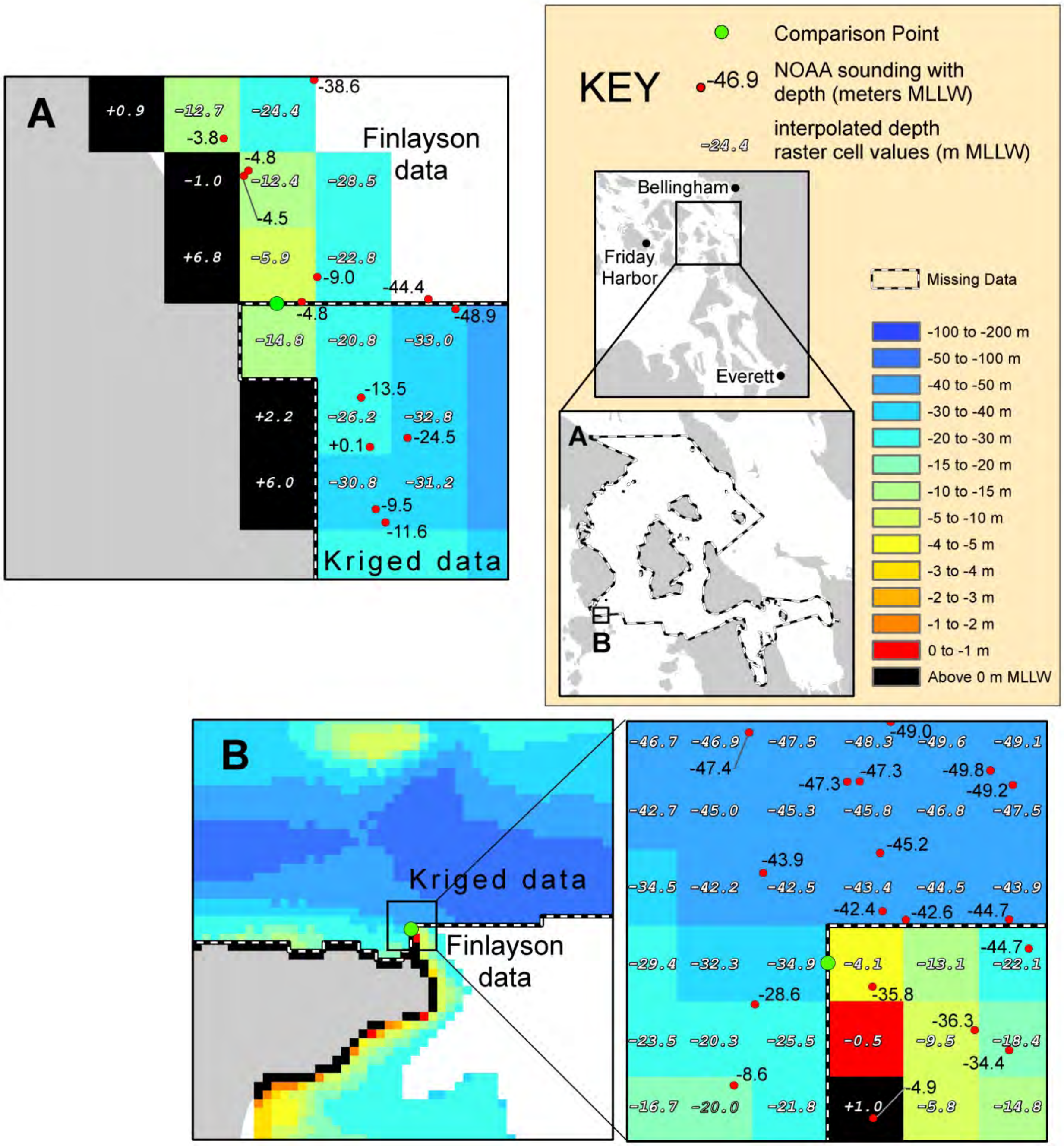


Figure B-3. Detailed comparison at two points of elevations from Finlayson et al. 2000 (transformed to a MLLW datum) to elevations in the kriged data. For each of the two comparison points, the depth values of the adjacent raster cells and the NOAA soundings are shown in meters MLLW. At the comparison point in (a), the depth in the kriged data was 8.9 meters below the adjacent cell in the Finlayson et al. 2005 data transformed to MLLW. This is an area with a steep beach profile so large differences between adjacent cells may be expected and any differences in horizontal errors between the datasets could cause large depth errors. Nevertheless, comparison of the raster cell depths of the kriged data to the soundings suggests that there is large error associated with the interpolation. In (b), there are large errors in the transformed Finalyson data that are unexplained but could possibly be related to interpolation error.

B.3.5 *Total Error*

The error associated with the NOAA soundings can be combined with the error associated with transformations. Taking the upper limit on estimate error for the soundings (0.45 m), the combined error is

$$\sqrt{(0.45m)^2 + (0.41\mathrm{m})^2} = 0.61\mathrm{m}$$

This estimate ignores contributions from errors in horizontal position and interpolation errors associated with the kriging and should therefore be considered a rough, lower limit on the true error associated with sounding depths. Finlayson (2006, pp. 200-201) discusses other error sources and concludes that "without an independent accuracy assessment it is difficult to estimate the vertical accuracy of these data", when referring to the Finalyson 2005 dataset. The fact that NOAA surveyors consider differences of 1-2 meters to be good agreement between surveys also indicates that there are additional errors. This is also useful as best professional judgment as to the overall uncertainty.

It is likely that there is important structure in the error that is not considered here. The relative error between adjacent cells of interpolated data is likely small when they are based on the same input survey data. However, there are likely to be larger errors between interpolated data based on difference surveys. It is also possible that error is related to the beach profile with greater error where there are sharp changes in slope. It would be difficult to build these considerations into a more sophisticated treatment of error and this was not attempted here.

B.4 References

Bevington, P.R. 1969. *Data Reduction and Error Analysis for the Physical Sciences.* McGraw-Hill, New York.

Finlayson, D.P. 2005. *Combined bathymetry and topography of the Puget Lowland, Washington State*. University of Washington. http://www.ocean.washington.edu/data/pugetsound

Finlayson, D.P. 2006. *The Geomorphology of Puget Sound Beaches*. PhD dissertation. School of Oceanography, University of Washington, Seattle WA.

Finlayson, D.P., R.A. Hagerud, H. Greenberg and M.G. Logsdon. 2000. *Puget Sound Digital Elevation Model*. University of Washington. http://www.ocean.washington.edu/data/pugetsound

NOAA. 2010a. *NOS Hydrographic Surveys Specifications and Deliverables,* April 2010. NOAA. Retrieved 12/14/10 from http://www.nauticalcharts.noaa.gov/hsd/specs/SPECS_2010.pdf

NOAA. 2010b. *Estimation of Vertical Uncertainties in VDatum*. Revised June 2010. Viewed 12/15/10 at http://vdatum.noaa.gov/docs/est_uncertainties.html#estTransform