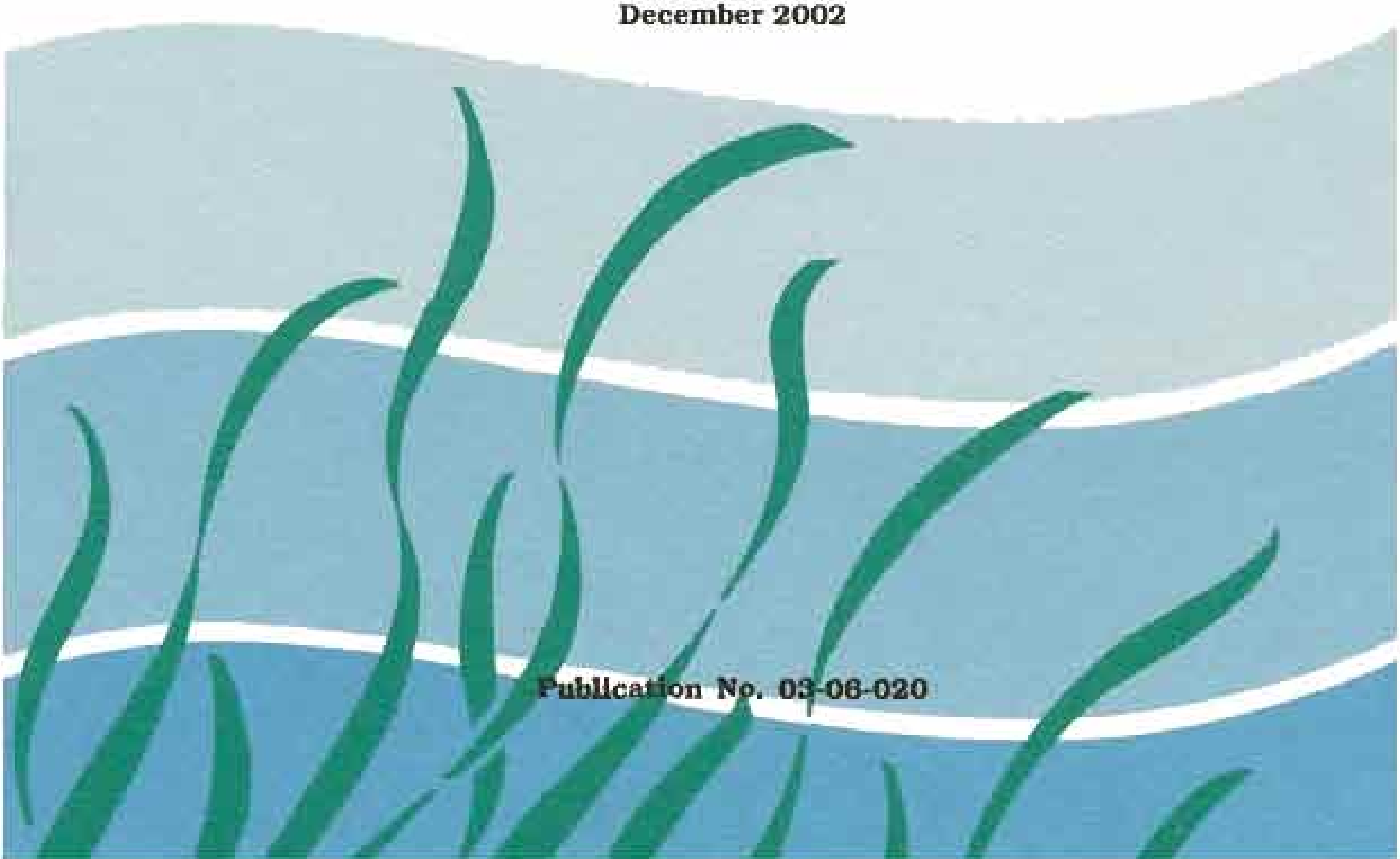
Padilla Bay
National Estuarine Research Reserve

Technical Report No. 26

A Methodology for Mapping Current and Historical Coverage of Estuarine Vegetation with Aerial Photography and ArcView

Suzanne Shull
and
Douglas A. Bulthuis

December 2002



Publication No. 03-06-020

The Padilla Bay National Estuarine Research Reserve is one of the reserves in the National Estuarine Research Reserve System. One of the purposes of the Reserve is to facilitate research and monitoring at Padilla Bay to provide information for the conservation and management of the nation's estuaries, in particular greater Puget Sound and other estuaries in the Pacific Northwest. The Padilla Bay National Estuarine Research Reserve assists the dissemination of this information from research and monitoring by publishing a Reprint Series and a Technical Report Series.

The **Reprint Series** includes research grant reports, out of print agency reports and student reports dealing with the Padilla Bay estuary. Reports are reprinted without revision or editing. Final reports for research grants and Masters Theses should be treated as unpublished data and should not be cited without permission of the author(s).

The **Technical Report Series** includes articles, reports of research projects, data reports, bibliographies and reviews dealing with the Padilla Bay estuary.

Communications concerning receipt or exchange of Technical Reports or Reprints or submission of manuscripts should be directed to the Research Coordinator at Padilla Bay National Estuarine Research Reserve. Communications concerning the content of reports and reprints should be directed to the author(s).

Padilla Bay National Estuarine Research Reserve
10441 Bayview-Edison Road
Mount Vernon WA 98273-9668
(360)428-1558

Padilla Bay National Estuarine Research Reserve is managed by the Shorelands and Environmental Assistance Program, Washington State Department of Ecology, in cooperation with the Estuarine Reserves Division, National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Commerce. The preparation of this document was financially aided through a grant to the Washington State Department of Ecology with funds obtained from NOAA/Office of Ocean and Coastal Resource Management, and appropriated for Section 306 or 315 of the Coastal Zone Management Act of 1972, as amended.

Technical Report No. 26

A Methodology for Mapping Current and Historical Coverage of Estuarine Vegetation with Aerial Photography and ArcView

Suzanne Shull
and
Douglas A. Bulthuis

December 2002

Publication No. 03-06-020

Padilla Bay National Estuarine Research Reserve
Technical Report No. 26

A Methodology for Mapping Current and Historical Coverage of Estuarine Vegetation with Aerial Photography and ArcView

Suzanne Shull
and
Douglas A. Bulthuis

December 2002

A report partially funded by the Washington State Department of Ecology (Publication No. 03-06-0202), Padilla Bay National Estuarine Research Reserve, National Oceanic and Atmospheric Administration grant #NA17OR1258 and Cooperative Institute for Coastal and Estuarine Environmental Technology award #00-367.

Padilla Bay National Estuarine Research Reserve
Shorelands and Environmental Assistance Program
Washington State Department of Ecology

10441 Bay View-Edison Road
Mount Vernon, WA 98273-9668

Note:
The preparation of this Technical Report was financially aided with grants from The Cooperative Institute for Coastal and Estuarine Environmental Technology (CICEET) and from the NOAA Office of Ocean and Coastal Resource Management, and appropriated for Section 315 of the Coastal Zone Management Act of 1972, as amended.

Bibliographic citation:
Shull, S. and D.A. Bulthuis. 2002. *A methodology for mapping current and historical coverage of estuarine vegetation with aerial photography and ArcView*. Washington State Department of Ecology (Publication No. 03-06-020), Padilla Bay National Estuarine Research Reserve: Mount Vernon, Washington. Padilla Bay National Estuarine Research Reserve Technical Report No. 26. 52 pp.

TABLE OF CONTENTS

TABLE OF CONTENTS .... **iii**

ABSTRACT .... **v**

INTRODUCTION **1**

METHODS **2**

- IMAGE ACQUISITION 2
- GROUND TRUTHING 4
  - *Datum Conversion* *5*
  - *GPS to GIS Conversion* *6*
- IMAGE PROCESSING 6
  - *Scanning Resolution* *7*
  - *Ground Control and Reference* *8*
  - *Orthorectification* *9*
  - *Image Warp* *10*
  - *RMS (Root Mean Square)* *11*
  - *Quality Assurance on Rectification* *12*
  - *Image Analyst* *13*
  - *Resampling* *13*
  - *Mosaics* *14*
- DELINEATION 15
- CLASSIFICATION SCHEME 17
- SHORELINE 17
- DATA VALIDATION 18
- HARDWARE, SOFTWARE, AND TIME REQUIREMENTS 19

EXAMPLES OF CHANGE DETECTION IN PADILLA BAY **20**

- MARCH POINT, PADILLA BAY 20
- NORTHEAST PADILLA BAY 20
- SULLIVAN-MINOR MARSH, PADILLA BAY 21

ACKNOWLEDGEMENTS **22**

LITERATURE CITED **23**

FIGURES **26**

TABLES **49**

ABSTRACT

Shull, S. and D.A. Bulthuis. 2002. *A methodology for mapping current and historical coverage of estuarine vegetation with aerial photography and ArcView*. Washington State Department of Ecology (Publication No. 03-06-020), Padilla Bay National Estuarine Research Reserve: Mount Vernon, Washington. Padilla Bay National Estuarine Research Reserve Technical Report No. 26. 52 pp.

Estuarine and coastal vegetation, such as emergent salt marshes and submerged seagrasses, are critical and important components of estuarine and coastal ecosystems. Coastal resource managers and their staff increasingly are being called on to protect and enhance these communities and in the process expected to map the location and/or areal extent of those vegetative communities. However, coastal planning staff and staff in other agencies, local government, and coastal resource offices are sometimes located in small coastal locations and counties where they do not have budget or access to new remote sensing technologies nor to complex image analysis and GIS software. However, these staff often do have access to desktop computers, ArcView (ESRI) software, and current or historical aerial photographs. This report describes an accessible methodology for mapping and monitoring estuarine vegetation cover with aerial photography, desktop computers, and ArcView 3.2a software. The methodology was developed, tested, and demonstrated with eelgrasses in the Padilla Bay National Estuarine Research Reserve, Washington in the year 2000 and with historical aerial photos of selected areas of Padilla Bay. The methodology includes procurement of aerial photographs, ground truth sampling, obtaining rectified reference photographs, scanning the aerial photos, georectifying of the aerial photos, mosaicking, photointerpretation, and on-screen digitizing of vegetative cover. The methodology can be used to map and monitor current distribution of submerged and emergent estuarine vegetation with technology accessible at many coastal resource offices: aerial photography, desktop computers, and ArcView 3.2a.

INTRODUCTION

Mapping and monitoring changes in aerial distribution of submerged and emergent coastal vegetation has become more important for staff in local government, agencies, and other coastal resource offices as both the recognition of the importance of coastal vegetation and population and development pressures near the coasts have increased. Coastal vegetation is being mapped and monitored with a variety of new and sophisticated remote sensing platforms and data interpretation and classification systems (Woodruff et al. 2002, Shull 2000, WADNR 1999). These are being developed in universities, private firms, and government agencies and offices. However, coastal planning staff and other staff in local government, agencies, and coastal resource offices are sometimes located in small coastal locations and counties where they do not have budget for, or access to, new remote sensing technologies nor complex image analysis and Geographic Information Systems (GIS) software. This report outlines a methodology that was developed at Padilla Bay National Estuarine Research Reserve, with funding from the Cooperative Institute for Coastal and Estuarine Environmental Technology (CICEET), to address this need. The methodology for mapping and monitoring of coastal vegetation described in this report utilizes widely available desktop computers, ESRI ArcView 3.2a software, its extensions, and aerial photography.

Steps in the Padilla Bay methodology include acquisition of true color aerial photographs, conversion of the contact print photography to digital images, rectification of the images to a common coordinate system, delineation of the vegetative units on screen, and assignment of a vegetative cover class category. The methods are then applied to historical aerial photography of the bay to identify changes in vegetated cover over an 11 year period.

The methodology is not a recipe for mapping, but it is a description of the series of steps or methods used at the Padilla Bay Research Reserve to monitor coastal vegetation. National standardized method recommendations for mapping benthic habitats are documented in the National Oceanic and Atmospheric Administration (NOAA) Coastal Services Center (CSC) Guidance for Benthic Habitat Mapping: An Aerial Photographic

Approach (US NOAA CSC 2001) and are referenced in each section of this report. The Benthic Habitat Mapping guide is an updated report on the original coastal habitat-mapping document NOAA Coastal Change Analysis Program (C-CAP): Guidance for Regional Implementation (Dobson et al. 1995). It is recommended that anyone interested in mapping intertidal habitats first review the NOAA recommendations in the C-CAP and Benthic Habitat Mapping documents (www.csc.noaa.gov/crs).

The methodology described in the present report may be used in its entirety. However, its greatest use may be in selected steps or parts from the methodology or as a resource for ideas and information to be adapted to local environments and circumstances.

METHODS

Image Acquisition

Aerial photography has been the preferred method for acquiring images for mapping of submerged vegetation in the United States (Simons 1987, Costa 1988, Orth et al. 1990, Bulthuis 1991, 1995), Australia (Bulthuis 1981, 1982, Larkum & West 1990), and Europe (Meulstee et al. 1986, Gilfillan et al. 1995). The NOAA Coast Watch Change Analysis Project conducted workshops around the United States soliciting input from regional scientists on the most appropriate methods for mapping of submerged vegetation. The recommendations developed from those workshops, included aerial photography as the recommended method for mapping submerged aquatic vegetation (Dobson et al. 1992, 1995), along with protocols on how such imagery should be acquired, on ground truth investigations, and on geographic control points. The updated Guidance for Benthic Habitat Mapping: An Aerial Photographic Approach (US NOAA CSC 2001) is an extremely useful document for descriptions of the advantages of: vertical photography, use of calibrated metric cameras, use of diapositives versus contact prints; and mission specifications of film type, flight line orientation, appropriate scale, and environmental considerations (plant phenology, water turbidity, tidal stage, wind and surface waves, and sun angle).

Satellite systems are one alternative to aerial photography and have been used to map emergent vegetation (Dobson et al. 1995) and for submerged vegetation (Belsher et al. 1988, Webber et al. 1987, Morton 1988, Luczkovich et al. 1993). However, because of large minimum pixel size and the need for particular local conditions (wind and sea state, no cloud cover) satellite imagery usually has not been favored for submerged vegetation surveys (Ferguson and Wood 1990, Dobson et al. 1995). Modern airborne and pointable satellite sensors such as QuickBird2 (www.eurimage.com/products/quickbird.html) launched in 2001 with 60 cm panchromatic band and 2.5 m color bands, Ikonos (www.spaceimaging.com) with 1m pan and 4m color bands launched in 1999, and the new SPOT5 (www.spot.com) sensor launched in 2002 with 5 m pan and 10 m color bands may provide useful data. However, specialized image processing technologies are usually required for processing these images and file sizes are close to 10 times as large as aerial photos requiring higher-end computers. Our method is affordable, repeatable, and within the resolution and accuracy standards needed by local coastal managers.

In the Padilla Bay project true color vertical aerial photographs were taken on July 30, 2000 at scales of 1:12,000 and 1:42,000 during a one-hour period around a predicted low tide of –0.85m below Mean Lower Low Water (MLLW). A single flight line of five images with 60% overlap at 1:42,000 included all of Padilla Bay. More than 60 images in four flight lines with 60% overlap and 30% sidelap were needed to cover the 62 sq. km study area in Padilla Bay at 1:12,000. Contact prints (nine inches by nine inches) of all photos were developed and provided by the contractor.

For determination of historical coverage of vegetation, Padilla Bay National Estuarine Research Reserve has an archive of aerial photos of the bay taken under appropriate conditions for detecting intertidal vegetation. The images used for this study were collected on clear days, summer low tides (<-0.3 m) below MLLW in 1989, 1992, 1996, and 2000. Two scales of true color photography were acquired each year, one at 1:12000, four flight lines with 30% sidelap and 60% overlap and the other at 1:42000, one flight line, with 60% overlap. The imagery is collected within a half-hour window of the low tide.

Archives of historical aerial photography of shoreline areas collected by various agencies such as the Department of Agriculture and the Army Corps. Of Engineers (ACOE) are available for many coastal areas. For information check with the local university map librarian.

Ground Truthing

In order to identify what is on the ground at the time of imaging it is necessary to do "ground truthing." "Ground truthing" is the collection of information on the landcover type and its location. The NOAA Benthic Habitat Mapping Guide provides recommendations on ground truth planning for weather windows, tides, low turbidity, and phenology. It also provides a list of needed equipment.

Ground truth sites in Padilla Bay were selected based on accessibility and visual change in the habitat types. Percent cover of vegetation and areas of transition between types of vegetative cover were described by walking to sites during low water. The location of each ground control site was determined with a Garmin 12 or Garmin 12XL Global Positioning System receiver. Because selective availability had been turned off by the Department of Defense in 2000, the precision of these inexpensive ($100-$200 per unit) GPS units had improved to less than 5m with on-site averaging without differential correction. Today manufacturers claim users can gain better than 3 m accuracy 95% of the time in the field using Wide Area Augmentation System (WAAS) (www.garmin.com/aboutGPS/waas.html), but this technology was not available to us during the summer of 2000.

More than 250 ground truth sites throughout Padilla Bay were visited during July and August 2000. Ground truth investigations were conducted on July 18, 19, 26, 27, 28, 31, and Aug 1, 2, 10, 14, 15, 16, 29, 2000 (Figure 1). At each site the vegetative cover was identified, the percent cover class noted, and the location calculated with a Global Positioning System (GPS). The data collected at each ground truth site were entered in a spreadsheet and the GPS location was transformed and displayed in a standard projection in ArcView.

The Garmin GPS unit was set to average the data it collected at a 1-second interval on location for approximately 1-2 minutes. On the display one can watch the estimated accuracy for that position increase as the estimated accuracy of the position display decreases from over 10 m to below 3 m. Because the GPS units collect data using the World Geodetic System, 1984 (WGS84) datum, the raw GPS data were downloaded as decimal degree WGS84 data.

Datum Conversion

An important concept for any GIS user to understand is that of datum. A datum is a set of parameters, and a set of control whose geometric relationships are known, either through measurement or calculation (ESRI 1994). The datum defines part of a geographic coordinate system that is the basis for a planar coordinate system such as Washington State Plane Coordinate System. The standard datum used for map projections and coordinates by the state of Washington is North American Datum for 1927 (NAD27). The raw GPS data is collected in datum WGS84, therefore, it was necessary for us to transform the GPS data from WGS84 to NAD27. We tried using transformation algorithms from within the Garmin unit and the AVGarmin extension (http://arcscripts.esri.com/details.asp?dbid=11515) but the results were incorrect with a consistent offset.

The NAD83 datum is considered equivalent to WGS84 for mapping and charting purposes, so we described the WGS84 GPS shapefile data as NAD83 in order to use the NADCON transformation in the ArcView Projection Utility to transform the data to NAD27. For details on how to use the projection utility to do datum transformations see the spring 2001 issue of ArcUser "The Dilemma at the Border" (www.esri.com/news/arcuser/0401/apjn2001.html; Price 2001).

GPS to GIS Conversion

Two methods were used to download the Garmins and then to build projected GIS files. The first method utilized the free shareware software Waypoint+ (Copyright © 1996, 1997 by Brent Hildebrand www.tapr.org/~kh2z/Waypoint/OverviewInfo.htm) to download the unit to a text file using a $30 serial port cable. The space delimited text file was then opened in Excel, each data value imported into its respective field, the fields formatted as text (ID, Time, Date) or numeric (X, Y) with 6 decimal places then saved out to a Dbase4 (*.dbf) database file. This dbf file was then added as a table to the ArcView tables and then selected as the input to build an event theme in the view. Once displayed in the view the file was saved to a shapefile. Then the data needed to be projected. In order to retain as much accuracy as possible, the shapefile was imported into the Trimble Pathfinder software to transform the datum and to project the data.

To streamline the GPS to GIS data conversion process we later used the Minnesota DNR extension in ArcView which connects directly to the Garmin using Waypoint +, allows the user to select only the points on the unit that one wants to download then builds the shapefile(www.dnr.state.mn.us/mis/gis/tools/arcview/extensions/DNRGarmin/DNRGarmin.html). Although the DNR Garmin extension permits the user to select the projection information for the shapefile we were able to get better results by setting the projection information to that of the Garmin (geographic and WGS84) and using ArcView Projection Utility to transform the datum to NAD27 and projecting the data to Washington State Plane Coordinate System North Zone. We purchased the ArcView 3.3 upgrade for our software to be sure to have the latest updates to the projection utility.

Image Processing

Processing aerial photography into a digital and georeferenced image involves conversion of the contact print into a digital image file and rectification of that imagery to align with a real-world map coordinate system. The NOAA Benthic Habitat Mapping document provides a description of three image processing methods and their advantages and disadvantages. The methods include analytical photogrammetry, soft-copy photogrammetry, and analog interpretation. Analytical photogrammetry is expensive and requires specialized training and equipment to stereoplot, delineate and simultaneously rectify and digitize habitat polygons (US NOAA CSC 2001). Soft-copy photogrammetry utilizes "computer workstations and image processing software (e.g. ERDAS OrthoBase, Socet Set, Softplotter, and Intergraph)" with less, yet still substantial skill and hardware requirements (US NOAA CSC 2001). Analog interpretation is the traditional method used to generate data from aerial photography. It involves delineation of habitat polygons on transparent or semi-transparent overlays attached to the photos and use of a stereoscope for interpretation with images that have overlap and sidelap (US NOAA CSC 2001). The guide suggests "an alternative approach to zoom transfer and table digitization is the screen digitization approach. In this method the aerial photo, with interpreted overlay attached, will be scanned and rectified using control derived from Ground Control Points (GCP) or other rectified images" (US NOAA CSC 2001). The Padilla Bay project utilized several techniques based on the traditional analog interpretation method. However, the delineations were done on-screen after the images were made digital and georeferenced, not before. The images were scanned, then georeferenced using a rubbersheeting method, as described in the following paragraphs.

Scanning Resolution

To convert the contact print aerial photographs to a digital format the user must scan the prints using a large-format (minimum of 9"x9" scan area) scanner. To determine the optimal scanning resolution for a given project, there are several variables to consider. First the user must identify the scale at which the imagery was taken. If the scale of the original photography is not known, the most straightforward technique would be to measure a distance on the ground, then measure the same 2 points on the image, to determine the ratio of the distance between the 2 points on the ground versus that in the photo. The next variable to consider in the determination of scan resolution is the size the of the smallest feature to be mapped given the resolution of the imagery. Finally, the user must consider the size of the file resulting from the selection of a given scan resolution. Tables of information for help in converting scanned aerial photo parameters such as ground coverage, dots per inch (DPI) or pixels per inch (PPI), micron units to pixel size and file size (black and white vs. color) are provided in a worksheet on the Benthic Habitat Mapping CD document (US NOAA CSC 2001) as well as in the ESRI Image Analyst Help Pages.

For the Padilla Bay project the aerial photos were scanned at a resolution of 200 dpi for the 1:12000 (1.5-meter pixel resolution) and 600 dpi for the1:42000. The scanning was done on a large format Epson 836XL scanner. For the year 2000 images there were 61 photos at the 1:12000 scale to cover the bay and at 200 dpi each scan saved at Tiff image format resulted in about 10.5MB for a total of more than 600MB.

Ground Control and Reference

In order to tie the images to the correct geographic locations, a reference coordinate system or grid has to be established. The State Plane Coordinate System, the Universal Transverse Mercator Grid System, and other local grids are most commonly used for GIS databases in the United States (Montgomery and Schuch 1993). The images are linked to these real-world coordinate-systems using Ground Control Points (GCP) that have known coordinates as reference. The NOAA Guide to Benthic Mapping provides a good source for information on sources of control, GCP selection, GCP distribution, GCP measurement and documentation (US NOAA CSC 2001).

The best available data for use as reference data for the Padilla Bay area at the time of this study was a 1:24000 scale 1998 Washington State Department of Natural Resources (WDNR) black and white orthophoto with 1 m pixel resolution and a stated accuracy of $\pm$13.3 m. Road intersections and other cultural features make the best ground control features. In order to avoid distortions due to elevation changes the selection of locations for control points in the Padilla Bay Project were kept on the lowland near the shoreline.

Because the reference imagery was in black and white and not acquired on an extreme low tide there were no features in the open bay area to use as control points. Therefore, it was necessary to create our own control features located in the intertidal area of the bay that would be visible in the true color aerial photos. Based on preliminary trials conducted in 1999 (testing the visibility of various shapes in aerial photos in the intertidal areas of Padilla Bay) ground control markers were constructed with two 55-gallon plastic drums joined with PVC piping and deployed as in-bay markers before the time of flyover (Figure 2). Marker designs that were tested, but subsequently rejected were an 8' plywood sheet painted white and two 12'x 8" beams crossed to form an X. The barrel markers were more easily detected in the 1:42000 scale imagery because of their 3-dimensional shape. Twelve of the barrel markers were constructed and deployed on June 27 and 28, 2000 on high tide throughout Padilla Bay in areas where shoreline and land-marks would not be visible on the low altitude aerial photos (Figure 3).

True color aerial photos were taken on July 30, 2000. The locations of the ground control markers were located with GPS a second time, as soon as possible after the aerial photographs were taken to correct for any drift. All ground control markers were recovered with the exception of one that apparently broke loose from its moorings and drifted.

Orthorectification

To obtain the best possible rectification results, the first method that we tested involved a free shareware extension called "Orthorec." "Orthorec" is an orthorectification process of correcting for elevation and lens distortions in the scanned imagery. This process uses calibration information about the camera lens and the focal plane on which the image is captured. The distance between the lens and the focal plane is termed focal length. Marks on the corners of each image are termed fiducial marks and the intersection of an imaginary axis through these fiducial marks crossing at the center of the photo is the photocoordinate origin(http://umbc7.umbc.edu/~tbenja1/santabar/vol1/lec6/6lecture.htm). The Orthorec extension was developed by Mr. Todd Jackson available for the ArcView 3.X software from the ESRI Arcscripts web site (http://arcscripts.esri.com/). It uses a digital elevation model (DEM) in combination with the fiducial marks on the corners of the contact print to correct for distortions in the lens and changes in elevation. A camera calibration can usually be obtained from the image vendor and the USGS has produced and made publicly available 30-meter grid DEMs for most areas in the United States. The correction for camera and elevation distortions makes this the most accurate method for rectifying imagery. However we found several hurdles in attempting to use this method.

The fact that there are only zero elevation values in the DEM for the bay itself (the area we are interested in mapping) contributed to problems in processing the imagery. This problem may be worked around by assigning a small value to all cells throughout the Bay, however in addition to the lack of elevation we found the processing time much too demanding. Processing time for one image took more than one hour. This combined with the need for the images to be in a bil, bsq, or bip format which is not easily obtained using our basic software packages and the fact that we are not truly interested in the upland (elevated) areas for this project we opted not to do ortho corrections, but instead to use a rubbersheeting technique.

Image Warp

Due to the flat terrain of the intertidal habitats and the good quality of the aerial photography we were able to utilize a simple rubber sheeting method to rectify the images. We started with Image Warp, another free shareware extension available from the ESRI Arcscripts web site, written by Kenneth McVay. In this method there are two factors over which the user has control, the number of ground control points selected and the order of the polynomial least squares fit to transform the image. The user selects the ground control points to be used from the image and the corresponding location on a real-world coordinate reference dataset.

Three 1:42,000 scale year 2000 aerial photos were georectified with a second order polynomial transformation and a nearest neighbor resampling method using 1998 orthophotographs as reference data (a USGS version of these photos is available on the web at http://duff.geology.washington.edu/data/raster/doqs/) and keeping root mean square RMS values below 2 pixels (see section on RMS).

About sixty aerial photographs at a scale of 1:12,000 for the year 2000 were georectified using second order polynomials and referenced to point locations on the mosaicked 1:42,000 photos and the ground control marker locations (see section on Ground Control). Selected portions of each 1:12,000 aerial photograph were used to create a mosaic of the photos covering Padilla Bay using Mike DeLaune's Xtools and Philip Hooge's Spatial Tools shareware extensions for ArcView (http://arcscripts.esri.com/).

RMS (Root Mean Square)

During the control point selection for the Imagewarp process a root mean square (RMS) error is calculated that gives the distance between the location on the scanned imagery to the rectified location after applying the current transformation. It is commonly accepted that the value of the root mean square (RMS) error be kept as low as possible. In practice one will find that the more control points one selects the higher the polynomial order one is permitted to use to transform the imagery. A higher order transformation will reduce the RMS. A problem with this approach is that there is greater distortion in the areas where you do not have control points and a bubble effect ensues. Another problem is that the RMS will be high if there is a lot of distortion in the imagery. For example, if you select 5 ground control points and the RMS is less than 5 feet you have a good rectification. But if the RMS is 10 feet either the selection of control points is poor, or you have some distortion in the imagery. That distortion requires a greater stretch to get all points from the page coordinates of the contact print to the real world coordinates of the reference image. For our purposes we used the RMS value to help guide in the selection of Ground Control Points. However, we were not so concerned with the value of the total RMS for an image. If the RMS is very high but the image still aligned well then we accepted it or moved individual Ground Control Points closer into the center of the image to avoid an area that appeared stretched or distorted. In the Padilla Bay study RMS values were kept below two pixels (3.3 m). However, the best estimate of actual accuracy of the final product is collected from field measurements.

Quality Assurance on Rectification

Quality assurance of the image rectification included comparison of the shoreline with the Washington Department of Natural Resources 1998 orthorectified aerial photos of the Padilla Bay area and comparison of the intertidal flats with the NOAA point bathymetry for the Padilla Bay area. Digitizing features on the reference image helps to create some control for subsequent photos by checking alignment with these features. When selecting control features avoid those that may change and create different size shadow effects in each year's image (i.e. tree shadows along the shoreline).

The effect of the 2nd order warp and the shift resulting from each time an image was added to the mosaic created a noticeable shift along the shoreline. These inaccuracies became apparent after initial comparisons were made for between year differences in salt marsh vegetation. So the 1:12,000 images were rewarped using a 1st order rectification keeping the RMS under 2 pixels and then the images were displayed individually using a script (viewsetimaeextent.avx from ESRI Arcscripts web site) to set the image extent to crop off unwanted edges of the images.

To document and visualize what happens to an aerial photo during the process of georectification, a square grid shapefile was converted to an image then rectified to the page coordinates of a 1:42,000 aerial photo. The ground control points concentrated along the shoreline in combination with ground control markers in the bay used to georectify the aerial photo were applied to the grid using the 2nd order polynomial warp. (Seventeen ground control points were applied to the grid with a resulting RMS of 6.5 feet in the X and 8.9 feet in the Y.) The grid shows considerable bending of the image in the areas most distant from the ground control points (Fig. 4). Therefore, at Padilla Bay, we chose to use 1st order rectification.

Image Analyst

Processing time was decreased dramatically by switching from Imagewarp to the purchased extension ESRI Image Analyst to process the 1992, 1996, and 1989 imagery. This extension permits the user to rectify the imagery without having to convert the image to a grid and then back to an image, thereby reducing distortion and loss of original color, texture, and hue. The software also permits the user to select 4 Ground Control Points and then obtain an RMS for each Ground Control Point as well as a total RMS. Thus, the user is able to both refine the selection of Ground Control Points interactively (as the Imagewarp software did) and also see how Image Analyst performs the warp on the fly. The images were rectified to the 1:42,000 image unless there were sufficient land features, in which case, points were selected from the 1998 ortho photo. The RMS values for the rectification were all below 2 pixels.

Resampling

When transforming the pixels of an image from scanned page coordinates to a real-world coordinate system pixel positions are shifted and the brightness value for each of the transformed pixels must be resampled to a new value. There are typically three resampling methods available: nearest neighbor, bilinear interpolation, and cubic convolution. Nearest neighbor preserves spectral integrity and is the simplest to perform, but it may break up linear features, drop data values, and may be less appealing due to jagged edges. Bilinear interpolations is the most spatially accurate method, but causes some smoothing of edges and loss of some extreme data values. Cubic convolution produces a smooth image for mosaicking, tends to reduce noise in the data, and is visually appealing due to the smooth edges, but it is computationally intensive and can alter the spectral values (US NOAA CSC 2002). For the Padilla Bay project we used the Nearest Neighbor resampling method.

Mosaics

To display all of the individual georeferenced images as one file they must be mosaicked. There are two methods most commonly used to mosaic images, mosaic and merge. The mosaic process smoothes the transition between images by using a weighted average of the values for the overlap pixels, whereas the merge process assigns the first input value from the series of grid themes (ArcView Help topic Mosaic).

Two softwares were used for mosaicking images in the Padilla Bay project. The free shareware extension Spatial Tools was used in conjunction with the Spatial Analyst to convert the image to a grid, clip the grid (using Spatial Analyst Properties and Spatial Tools extensions), then merge several grids together into one grid for each band. After the merge is complete the grid is transformed back to an image. This method is slow and requires the user to convert the image into a grid and thereby poses the possibility of some loss of image brightness. After completing the mosaic, unwanted files are deleted to clean up space on the hard drive.

The Image Analyst software permits the user to set the analysis properties mask to a shapefile that, when selected, will clip an image to the area of that shapefile when one saves the image. To mosaic the images, make all clipped images to be mosaic displayed, remove all masks from the Image Analyst Properties, and then select from the Image analysis menu "mosaic." This will create a temporary file that should then be saved to a permanent filename and directory.

The Image Analyst extension permits the user to display the mosaicked images as Image Analysis Data sources that can be easily manipulated with enhancements such as standard deviation stretches so that the features are emphasized and the overall image is not a dark blurred featureless display. The problem with mosaic in Image Analyst is that there is no option to simply merge the images if there is any overlap between them. If you have an overlap area where more than 2 images overlay you will see that all the pixel values are averaged into the mosaic for that area. This results in strange coloration for the overlapped areas of the final mosaicked image.

Image Analyst permits the user to perform a stretch before mosaicking the images and then the final output does not need the stretch applied. This permits the user to apply different enhancements to each image. In the Padilla Bay project no enhancements were made before the photos were mosaicked.

When performing mosaic operations it is best to select all images to be mosaicked to be processed at one time. Each time a mosaic operation is performed there is a slight shift in the pixel position due to the lack of perfect alignment of individual pixels from image to image.

Delineation

The standard procedures for photointerpretation and image analysis recommended by the CSC in the benthic habitat mapping guide include stereoscope interpretation onto Mylar overlay using the tone, color, contrast, texture, and shadow as cues to features within 1:24000 scale imagery to delineate at a 1 meter minimum mapping unit (MMU).

In the Padilla Bay application several different approaches (plus variations of each method) were considered or investigated for delineation of nearshore habitats: on-screen digitizing, automated delineation on red, green, and blue color bands, and delineation by hand on acetate sheets covering aerial photos followed by scanning of the acetate sheet and transformation of the lines to polygons.

Delineation by hand on acetate sheets was not considered practical in Padilla Bay where there are extensive areas of continuous eelgrass cover without land or good control features. In an early trial, selected areas near shore were delineated on acetate sheets, but mosaicking of these sheets was formidable; therefore this approach was not used.

Grids of the imagery were used to explore the use of automated delineation of large homogeneous features such as subtidal bare areas and 51-100 % cover eelgrass. The problems encountered included extreme pixelation along the polygon edges and differences in reflectance between photos which required the delineation to be applied on a per image basis. This limits the efficiency of an automated process.

Given the inherent problems with the other two methods, the Padilla Bay application utilized the Habitat Digitizer, a free extension, for on-screen delineation and attributing of polygons (http://biogeo.nos.noaa.gov/products/apps/digitizer/). Some advantages of using this method include: saves the loss of resolution and time used to print the mosaic because the user delineates on-screen, the scale and minimum mapping unit (MMU) can be constrained to standardize the delineation process, and polygons are attributed immediately. Even when the polygon attribute is not known immediately, a placeholder is created in the table. The Habitat Digitizer extension comes with documentation and sample schemes for learning to use the tool.

Digitizing on-screen worked well. Problems encountered included polygons snapping closed before the user has completed the delineation or not snapping at all. This kind of problem has a lot to do with the user's technique. Another problem that apparently is common to many ArcView users is that the table will not accept edits made and the cell value reverts to the original entry after moving onto a new cell. Some solutions to this are to close the table and save edits then reopen the table to edit, refresh the table before doing edits, or just save edits even if no edits have been made then proceed with editing.

Another problem encountered was the loss of some texture to the photos from scanning and display. This problem was addressed by referring to the contact prints kept beside the computer screen while digitizing.

A suggested improvement to the Habitat Digitizer is to incorporate a streaming digitizer option. Stream digitizing permits the user to log XY coordinates along a polygon or line without actually having to click the mouse or on the LCD screen (if the user has a touch screen display). There is an extension available from the Minnesota Department of Natural Resources (MN DNR) to do StreamMode Digitizing (www.dnr.state.mn.us/mis/gis/tools/arcview/extensions/streammode/streammode.html).

Classification Scheme

The CSC recommends interpretation decision rules for standardized processing in attributing the habitat polygons. Environment Canada has published a manual of "Field Methods for Mapping and Monitoring Eelgrass Habitat in British Columbia" and in it they recommend standardized mapping methodologies to identify, classify, and quantify eelgrass habitat in British Columbia (http://www.shim.bc.ca/eelgrass/main.htm). In the Padilla Bay scheme, standardized classification rules were based on a previous habitat map of Padilla Bay (Bulthuis 1995). In addition to subtidal eelgrass, the Padilla Bay classification scheme includes two categories of percent cover (11-50% and 51-100%) for Zostera marina, Zostera japonica, and green macroalgae, one category for native saltmarsh vegetation, unvegetated intertidal, and unvegetated subtidal.

Shoreline

Following completion of the year 2000 and 1992 georectified photomozaics, comparisons of the shoreline, vegetative units near the shoreline, and the state agency statewide shoreline indicated that interannual comparisons would be precluded or ambiguous until an accurate georeferenced shoreline was available for the southern part of Padilla Bay at a scale of less than1:12000. As a result we invested time in developing a more accurate shoreline for Padilla Bay than what was available from state and local agencies.

Corrections to the existing shoreline data were completed using a Padilla Bay NERR reference image, a Padilla Bay NERR file of 6 inch bathymetric contours for southern Padilla Bay, and the use of a survey grade GPS unit (Trimble Pro XR). (The survey grade GPS unit was loaned to us by one of the organizations that was a recipient of our advice and consultation on methods of georectification developed in this project.) The WDNR shoreline and the corrected shoreline are both overlaid on a 1998 orthophotograph and the year 2000 georectified photomosaic in Figures 5 and 6. These figures illustrate why the best available shoreline from state and local agencies may not be applicable at the appropriate scale or accuracy for your project. The two figures also show that ground truthing with high grade GPS can demonstrate or test the accuracy of the georectification. In this case, the true color aerial photo aligns well with the GPS shoreline (Figure 5).

Data Validation

After habitat polygons were drawn on-screen and attributed for the entire study area the table was opened and a new field was added and filled using the calculator command “rec” to add a sequential record number id for each record in the table. The table was then sorted according to the unique id assigned for each habitat category to check for 0 values. The 0 value polygons were either reattributed or deleted. Using the Xtools extension, area fields for square feet, acres, and hectares were added. The table was then sorted by size in hectares and the 0 value for size polygons were investigated to verify that they were real or deleted as sliver polygons. Be aware that once these additional fields are added the habitat digitizer extension will not work using the original classification scheme due to the mismatched number of fields. Spatial accuracy was checked during change detection analysis. Major channels and stationery fixtures were checked for alignment by overlaying the vector data on the imagery. The final products meet or exceed national map accuracy standards of +-13.3 meters at a scale of 1:12000 (http://www.state.nj.us/dep/gis/mapcritd.html).

Hardware, Software, And Time Requirements

The initial processing for this project was performed on a Pentium II with 384 MB RAM, 32-MB video RAM, Windows 98 operating system with a single 16 GB IDE Hard Drive running ArcView 3.2a. A second 5 GB hard drive was added later.

Georectification of the aerial photos was a very time consuming process. Processor time on the computer using Image Warp took up to 30 minutes to process one trial on one photo. Each photo required many trials with various combinations of ground control points. In December of 2000 a new Pentium IV PC was purchased by Padilla Bay NERR in order to speed up this process. The increased processing speed is due in part to the use of a SCSI hard drive and almost all of the final georectification of the aerial photos was accomplished after purchase of the new computer.

The data processing was performed on a Pentium IV 1.4 GHz (512K RAM PC800) computer with a SCSI (18 GB) hard drive running Windows 98 2nd Edition operating system and ArcView 3.2a with the Environmental Systems Research Institute (ESRI) Spatial Analyst and Image Analyst extensions. Four months before the end of the contract a 2nd 25 GB SCSI hard drive was added. For the purposes of this project there was a significant improvement in processing speed between the SCSI drives and the traditional IDE harddrives. Some time allotment estimates include: rectification of 50 images ~ 2 months full time and delineation of entire bay ~1 month full time, mosaic of target areas and backup to CD ~1 day per area.

The estimated cost of professional ortho products is $10,000 for the area of Padilla Bay. The Image Analyst extension also enhanced the processing speed by permitting the user to see the warp being applied to the image as soon as 4 GCP were added and simultaneously having the reference image displayed as a background. The Image Analyst extension is capable of converting the images to a rectified image without first converting the image to a grid format and back again.

EXAMPLES OF CHANGE DETECTION IN PADILLA BAY

The methodology described in this report was used to map the distribution of eelgrasses, macroalgae, and salt marshes throughout Padilla Bay in 2000 and preliminary results are presented in Figures 7 and 8 (Bulthuis and Shull 2002). The total area covered by seagrasses in Padilla Bay in 2000 was 3867 hectares with Z. marina accounting for 3029 hectares and Z. japonica 838 hectares, (Table 1). The methodology was also used on historical aerial photos of Padilla Bay in selected areas. The following three examples illustrate how the methodology described in this report can be used to document changes in cover of vegetation.

March Point, Padilla Bay

Near March Point, the distribution of eelgrasses (mainly Z. marina) declined from 1992 to 2000 (Figures 9-12). This decline was visible first as openings in the once relatively continuous eelgrass bed, to patches of eelgrass, to a decline in the area covered by patches (Figures 11 and 12). This set of aerial photos illustrates how the methodology can be used for retrospective historical analysis. The total area covered by eelgrasses in the March Point designated project area (see outline in Figures 9-12) declined from 121 hectares in 1992 to 112 hectares in 2000 (Table 2).

Northeast Padilla Bay

In the northeast corner of Padilla Bay eelgrasses covered only a small portion of the intertidal flats in 1989 (Figure 13). Mapping the distribution of eelgrasses in 1992, 1996, and 2000 indicated fluctuations in the area covered (Figures 14, 15, and 16). In the historical aerial photographs, two general types of eelgrass coverage could be identified: continuous cover and sparse cover. In the four years (1989, 1992, 1996, 2000) for which eelgrass cover was mapped, there were wide fluctuations in the area of sparse cover, as little as 8 hectares in 1989 and as much as 61 hectares in 2000 (Table 3). Continuous and total eelgrass cover also fluctuated during these years (Table 3).

Sullivan-Minor Marsh, Padilla Bay

A linear native salt marsh area along the eastern shore of Padilla Bay, called Sullivan-Minor marsh has had its seaward edge eroded shoreward from 1989 to 2000 (Figures 17-21). The marsh width decreased 11m from 108 m to 97 m near the area of maximum erosion. An estimated 1410 m^2 of Sullivan-Minor marsh was lost in the eleven years from 1989 to 2000, although there was also some gain in areas as Salicornia viriginica and Distichlis spicatum became established in areas that had been predominately log cover (Figures 17-20).

ACKNOWLEDGEMENTS

Sincere thanks to the Cooperative Institute for Coastal and Estuarine Environmental Technologies for their financial support of the project in which this methodology was developed. This study was also financially aided through a grant to the Washington State Department of Ecology with funds obtained from NOAA Office of Ocean and Coastal Resource Management, and appropriated for Section 315 of the Coastal Zone Management Act of 1972, as amended.

LITERATURE CITED

Belsher, T., A. Meinesz, J.R. Lefevre and C.F. Boudouresque. 1988. Simulation of SPOT satellite imagery for charting shallow-water benthic communities in the Mediterranean. *Marine Ecology (Pubblicazioni della Stazione Zoologica di Napoli I)*. 9: 157-165.

Bulthuis, D.A. 1981. Distribution and summer standing crop of seagrasses and macroalgae in Western Port, Victoria. *Proceedings of the Royal Society of Victoria*. 92: 107-112.

Bulthuis, D.A. 1982. *Distribution of seagrasses in Port Phillip, Victoria*. 18 pp. Victorian Dept Conservation, Forests & Lands: Queenscliff, Victoria, Australia. Mar. Sci. Lab., Queenscliff Tech. Rep. No. 5.

Bulthuis, D.A. 1991. *Distribution of habitats and summer standing crop of seagrasses and macroalgae in Padilla Bay, Washington, 1989*. 35 pp. Washington State Dept Ecology: Mount Vernon, Washington. Padilla Bay National Estuarine Research Reserve Technical Report No. 2.

Bulthuis, D.A. 1995. *Distribution of seagrasses in a North Puget Sound Estuary: Padilla Bay, Washington, U.S.A. Aquatic Botany*. 50:99-105.

Bulthuis, D.A. and S. Shull. 2002. *Accessible methodology for monitoring estuarine and coastal vegetation cover*. [Final report to Cooperative Institute for Coastal and Estuarine Environmental Technology]. Washington State Department of Ecology, Padilla Bay National Estuarine Research Reserve: Mount Vernon, Washington.

Costa, J.E. 1988. *Eelgrass in Buzzards Bay: distribution, production and historical changes in abundance*. 204 pp. United States Environmental Protection Agency: Boston. EPA 503/4-88-002.

Cracknell, A.P. 1999. Remote sensing techniques in estuaries and coastal zones—an update. *International Journal of Remote Sensing*. 19: 485-496.

Dobson, J.E., R.L. Ferguson, D.W. Field, L.L. Wood, K.D. Haddad, H. Iredale III, V.V. Klemas, R.J. Orth and J.P. Thomas. December, 1992. *NOAA Coastwatch Change Analysis Project guidance for regional implementation*. 128 pp. Coastwatch Change Analysis Project, Coastal Ocean Program, NOAA, U.S. Dept Commerce.

Dobson, J.E., E.A. Bright, R.L. Ferguson, D.W. Field, L.L. Wood, K.D. Haddad, H. Iredale III, J.R. Jensen, V.V. Klemas, R.J. Orth and J.P. Thomas. 1995. *NOAA coastal change analysis program (C-CAP): guidance for regional implementation*. 92 pp. [Prepared for CoastWatch Change Analysis Project, Coastal Ocean Program, National Oceanic and Atmospheric Administration, U.S. Department of Commerce]. U.S. Department of Commerce, NOAA, National Marine Fisheries Service: NOAA Technical Report NMFS 123.

Environmental Systems Research Institute, Inc. 1994. *Map Projections: Georeferencing Spatial Data*, Redlands, California.

Ferguson, R.L. and L.L. Wood. 1990. Mapping submerged aquatic vegetation in North Carolina with conventional aerial photography. In: *Federal coastal wetland mapping programs*. S.J. Kiraly, F.A. Cross and J.D. Buffington) 125-133 pp. U.S. Dept. Interior, Fish & Wildlife Service: Washington, D.C. Biological Report 90. 18 pp.

Gilfillan, E.S., N.P. Maher, C.M. Krejsa, M.E. Lanphear, C.D. Ball, J.B. Meltzer and D.S. Page. 1995. Use of remote sensing to document changes in marsh vegetation following the Amoco Cadiz oil spill (Brittany, France, 1978). *Marine Pollution Bulletin*. 30: 780-787.

Larkum, A.W.D. and R.J. West. 1990. Long-term changes of seagrass meadows in Botany Bay, Australia. *Aquatic Botany*. 37: 55-70.

Luczkovich, J.J., T.W. Wagner, J.L. Michalek and R.W. Stoffle. 1993. Discrimination of coral reefs, seagrass meadows, and sand bottom types from space: a Dominican Republic case study. *Photogrammetric Engineering & Remote Sensing*. 59: 385-389.

Meulstee, C., P.H. Nienhuis and H.T.C. Van Stokkom. 1986. Biomass assessment of estuarine macrophytobenthos using aerial photography. *Marine Biology*. 91: 331-335.

Montgomery, G.E. and H.C. Schuch. 1993. *GIS data conversion handbook.* Fort Collins, Colorado. 320 pp.

Morton, M.D. 1988. *Mapping seagrass meadows using Landsat-5 TM imagery and a microcomputer*. M.S. Thesis, Western Washington University: Bellingham, Washington. 43 pp.

Orth, R.J. and K.A. Moore. 1983. Chesapeake Bay: an unprecedented decline in submerged aquatic vegetation. *Science*. 222: 51-53.

Orth, R.J., K.A. Moore and J.F. Nowak. 1990. Monitoring seagrass distribution and abundance patterns: a case study from the Chesapeake Bay. In: *Federal coastal wetland mapping programs*. (Editors "by" S.J. Kiraly, F.A. Cross and J.D. Buffington) 111-123 pp. U.S. Dept Interior, Fish & Wildlife Service: Washington, D.C. Biological Report 90. 18 pp.

Price, M. 2001. The Dilemma at the Border, Registering Vector Data Across Datums. *ArcUser.* April-June 2001: 32-35.

Shull, S. 2000. *Mapping seagrass meadows of Padilla Bay, Washington, using a 1996 Compact Airborne Spectrographic Imager (CASI) dataset*. M.S. Thesis, Western Washington University: Bellingham, Washington. Washington State Dept Ecology: Mount Vernon, Washington. Padilla Bay National Estuarine Research Reserve Technical Report No. 34. 76 pp.

Simons, J.D. 1987. Mapping submerged aquatic vegetation in the Maryland Chesapeake Bay with aerial photography: 1978-1985. In: *Wetland and Riparian Ecosystems of the American West, Eighth Annual Meeting of the Society of Wetland Scientists*, at Seattle, Washington, May 26-29, 1987. pp. 195-202.

U.S. NOAA Coastal Services Center. 2001. *Guidance for Benthic Habitat Mapping: An Aerial Photographic Approach* by Mark Finkbeiner [and by] Bill Stevenson and Renee Seaman, Technology Planning and Management Corporation, Charleston, SC. (NOAA/CSC/20117-PUB). Available on: U.S. National Oceanic and Atmospheric Administration. Coastal Services Center. Submerged Aquatic Vegetation: Data Development and Applied Uses. (CD-ROM). (NOAA/CSC/20116-CD). Charleston,SC. 2001. (http://www.csc.noaa.gov/crs/bhm).

U.S. NOAA Coastal Services Center. 2002. *Remote Sensing for Spatial Analysts.* U.S. National Oceanic and Atmospheric Administration. Coastal Services Center GeoSpatial Technology Courses for Coastal Resource Managers. Charleston, SC. (http://www.csc.noaa.gov/)

WADNR. 1999. Puget Sound Intertidal habitat Inventory, Puget Sound Intertidal Habitat Inventory 1996 for Skagit County and Northern Whidbey Island of Washington State. Washington Department of Natural Resources, Puget Sound Ambient Monitoring Program. CDROM.

Woodruff, D., A. Borde, G. Williams, J. Southard, R. Thom, C. Simenstad, R. Garono, R. Robinson, J. Norris. 2002. *Mapping of subtidal and intertidal habitat resources, Hood Canal floating bridge, Washington.* 36 pp. Washington State Transportation Commission Department of Transportation and in cooperation with U.S. Department of Transportation Federal Highway Administration Report Number WA-RD 523.1 (http://www.wsdot.wa.gov/ppsc/research/CompleteReports/WARD523_1HoodCanalFinal.pdf).

Webber, H.H., T.F. Mumford and J. Eby. 1987. *Remote sensing inventory of the seagrass meadow of the Padilla Bay National Estuarine Research Reserve. Areal extent and estimation of biomass*. 70 pp. [Final report to Marine & Estuarine Management Division, NOAA grant no. NA86AA-D-CZ027]. Western Washington University, Huxley College of Environmental Studies: Bellingham, WA. Padilla Bay National Estuarine Research Reserve Reprint Series No. 6, 1990.

FIGURES

Figure 1. Ground truth data sites (more than 250) in Padilla Bay, Washington overlaid on a mosaic of 1:42000 scale georeferenced aerial photos taken July 20, 2000.

Figure 2. Control markers built from plastic barrels and PVC pipe used to establish georeference control in Padilla Bay, Washington.

Figure 3. Control marker barrels overlaid on the 1998 black and white reference image from WADNR of Padilla Bay, Washington.

Figure 4. Grid rectified to reference image using 2nd order warp for illustrating effects of georectification on aerial photographs.

Figure 5. State agency shoreline and survey grade GPS shoreline displayed on 1998 orthophotograph. Note the lack of alignment between the state agency shoreline and the orthorectified reference image.

Figure 6. State agency shoreline and survey grade GPS shoreline displayed on a 2000 aerial photo that has been georectified. Note the positional accuracy of the georectified photograph, and the lack of alignment between the state agency shoreline and the GPS shoreline.

Figure 7. All cover classes of intertidal and subtidal vegetation delineated in Padilla Bay, Washington from 1:12,000 scale aerial photographs taken July 30, 2000.

Figure 8. Two classes of eelgrass, salt marsh, and macroalgae in Padilla Bay, Washington in 2000 with the delineated cover classes (see Figure 7) combined into four categories.

Figure 9. Continuous eelgrass cover (in solid fill) and sparse eelgrass cover (in stipple pattern) in March Point area of interest in Padilla Bay, Washington as delineated on true color aerial photographs taken on June 3, 1989.

Figure 10. Continuous eelgrass cover (in solid fill) and sparse eelgrass cover (in stipple pattern) in March Point area of interest in Padilla Bay, Washington as delineated on true color aerial photographs taken on July 28, 1992.

Figure 11. Continuous eelgrass cover (in solid fill) and sparse eelgrass cover (in stipple pattern) in March Point area of interest in Padilla Bay, Washington as delineated on true color aerial photographs taken on July 1, 1996.

Figure 12. Continuous eelgrass cover (in solid fill) and sparse eelgrass cover (in stipple pattern) in March Point area of interest in Padilla Bay, Washington as delineated on true color aerial photographs taken on July 30, 2000.

Figure 13. Continuous eelgrass cover (in solid fill) and sparse eelgrass cover (in stipple pattern) in Northeast area of interest in Padilla Bay, Washington as delineated on true color aerial photographs taken on June 3, 1989.

Figure 14. Continuous eelgrass cover (in solid fill) and sparse eelgrass cover (in stipple pattern) in Northeast area of interest in Padilla Bay, Washington as delineated on true color aerial photographs taken on July 28, 1992.

Figure 15. Continuous eelgrass cover (in solid fill) and sparse eelgrass cover (in stipple pattern) in Northeast area of interest in Padilla Bay, Washington as delineated on true color aerial photographs taken on July 1, 1996.

Figure 16. Continuous eelgrass cover (in solid fill) and sparse eelgrass cover (in stipple pattern) in Northeast area of interest in Padilla Bay, Washington as delineated on true color aerial photographs taken on July 30, 2000.

Figure 17. Native saltmarsh and log piles in Sullivan-Minor marsh, Padilla Bay, Washington as delineated on true color aerial photographs taken on July 30, 1989.

Figure 18. Native saltmarsh and log piles in Sullivan-Minor marsh, Padilla Bay, Washington as delineated on true color aerial photographs taken on July 30, 1992.

Figure 19. Native saltmarsh and log piles in Sullivan-Minor marsh, Padilla Bay, Washington as delineated on true color aerial photographs taken on July 30, 1996.

Figure 20. Native saltmarsh and log piles in Sullivan-Minor marsh, Padilla Bay, Washington as delineated on true color aerial photographs taken on July 30, 2000.

Figure 21. Area of salt marsh in Sullivan-Minor marsh, Padilla Bay, Washington that was lost between 1989 and 2000; displayed on an aerial photo taken on July 30, 2000.

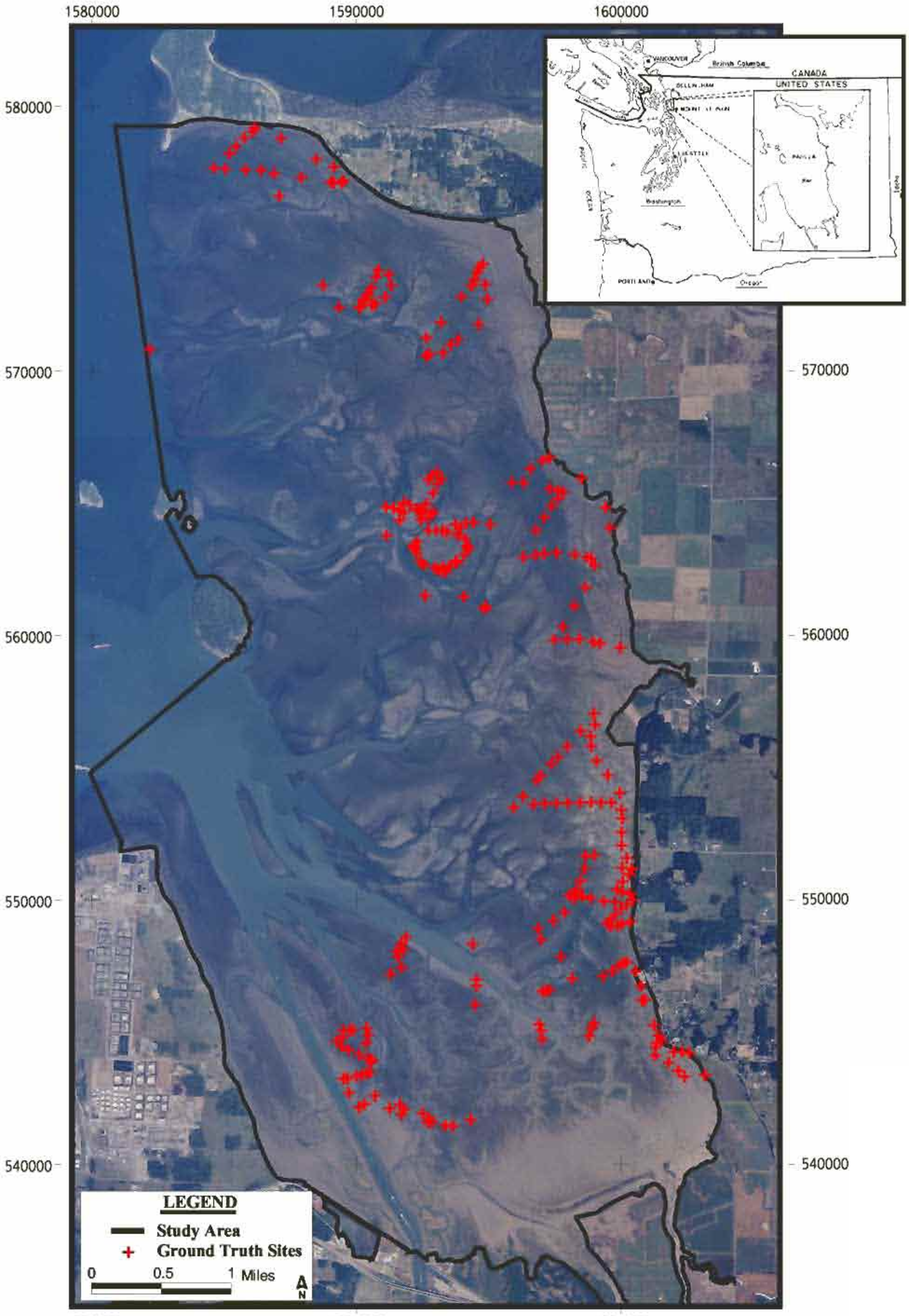


Figure 1. Ground truth data sites (more than 250) in Padilla Bay, Washington overlaid on a mosaic of 1:42000 scale georeferenced aerial photos taken July 20, 2000.

Figure 2. Control markers built from plastic barrels and PVC pipe used to establish georeference control in Padilla Bay, Washington.

Figure 3. Control marker barrels overlaid on the 1998 black and white reference image from WADNR of Padilla Bay, Washington.

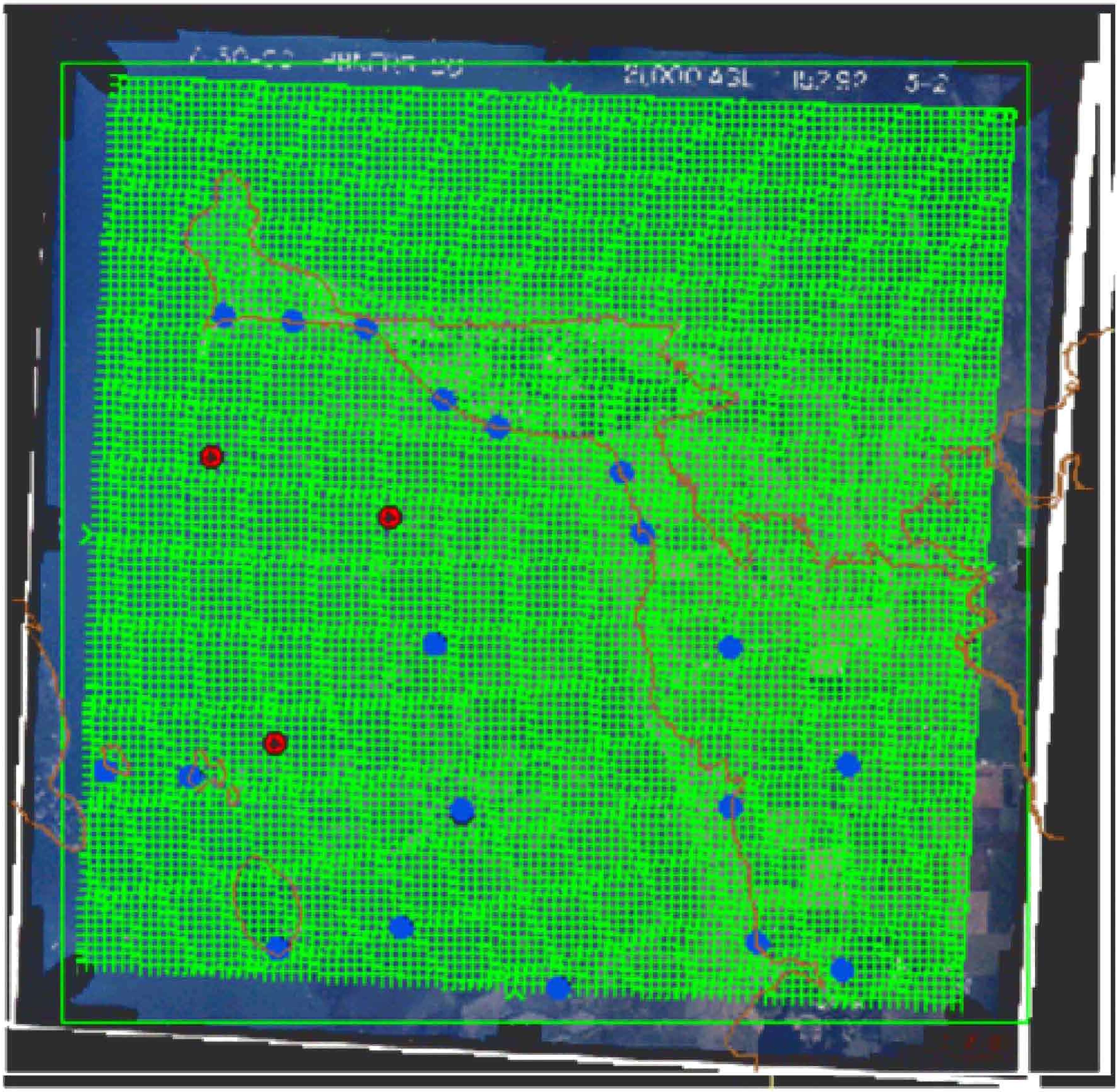


Figure 4. Grid rectified to reference image using 2nd order warp for illustrating effects of georectification on aerial photographs.

Figure 5. State agency shoreline and survey grade GPS shoreline displayed on 1998 orthophotograph. Note the lack of alignment between the state agency shoreline and the orthorectified reference image.

Figure 6. State agency shoreline and survey grade GPS shoreline displayed on a 2000 aerial photo that has been georectified. Note the positional accuracy of the georectified photograph, and the lack of alignment between the state agency shoreline and the GPS shoreline.

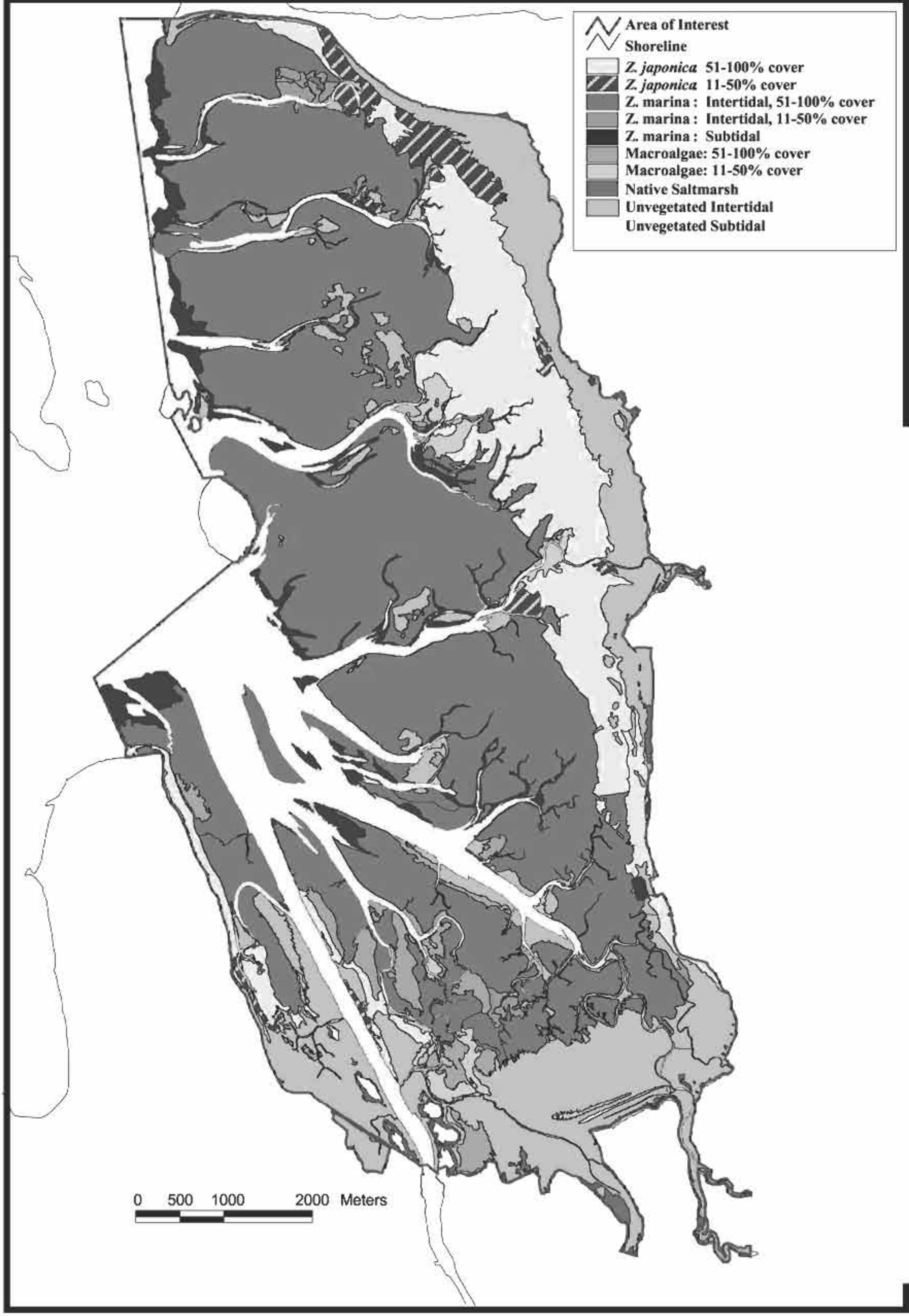


Figure 7. All cover classes of intertidal and subtidal vegetation delineated in Padilla Bay, Washington from 1:12,000 scale aerial photographs taken July 30, 2000.

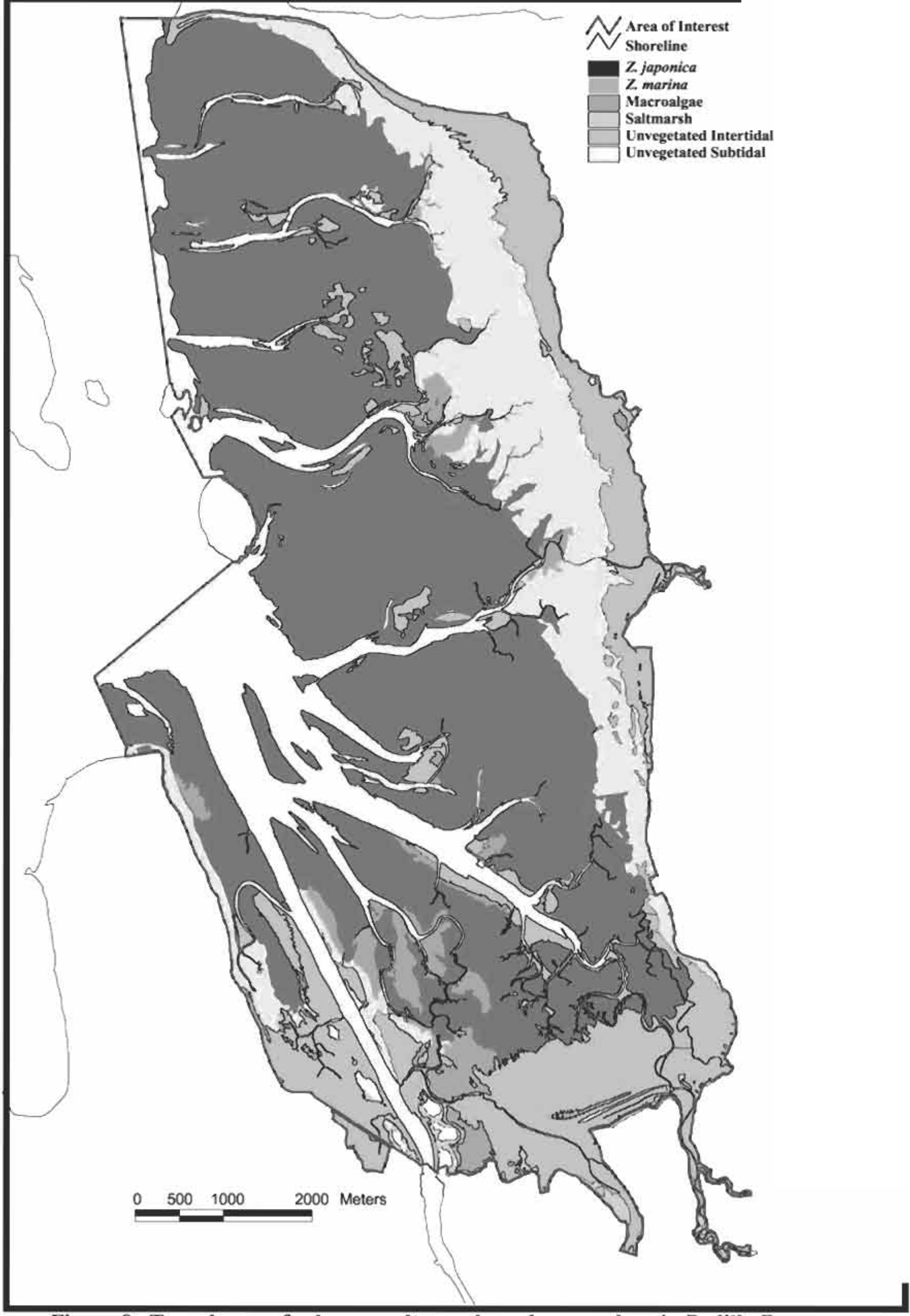


Figure 8. Two classes of eelgrass, salt marsh, and macroalgae in Padilla Bay, Washington in 2000 with the delineated cover classes (see Figure 7) combined into four categories.

Figure 9. Continuous eelgrass cover (in solid fill) and sparse eelgrass cover (in stipple pattern) in March Point area of interest in Padilla Bay, Washington as delineated on true color aerial photographs taken on June 3, 1989.

Figure 10. Continuous eelgrass cover (in solid fill) and sparse eelgrass cover (in stipple pattern) in March Point area of interest in Padilla Bay, Washington as delineated on true color aerial photographs taken on July 28, 1992.

Figure 11. TContinuous eelgrass cover (in solid fill) and sparse eelgrass cover (in stipple pattern) in March Point area of interest in Padilla Bay, Washington as delineated on true color aerial photographs taken on July 1, 1996.

Figure 12. Continuous eelgrass cover (in solid fill) and sparse eelgrass cover (in stipple pattern) in March Point area of interest in Padilla Bay, Washington as delineated on true color aerial photographs taken on July 30, 2000.

Figure 13. Continuous eelgrass cover (in solid fill) and sparse eelgrass cover (in stipple pattern) in Northeast area of interest in Padilla Bay, Washington as delineated on true color aerial photographs taken on June 3, 1989.

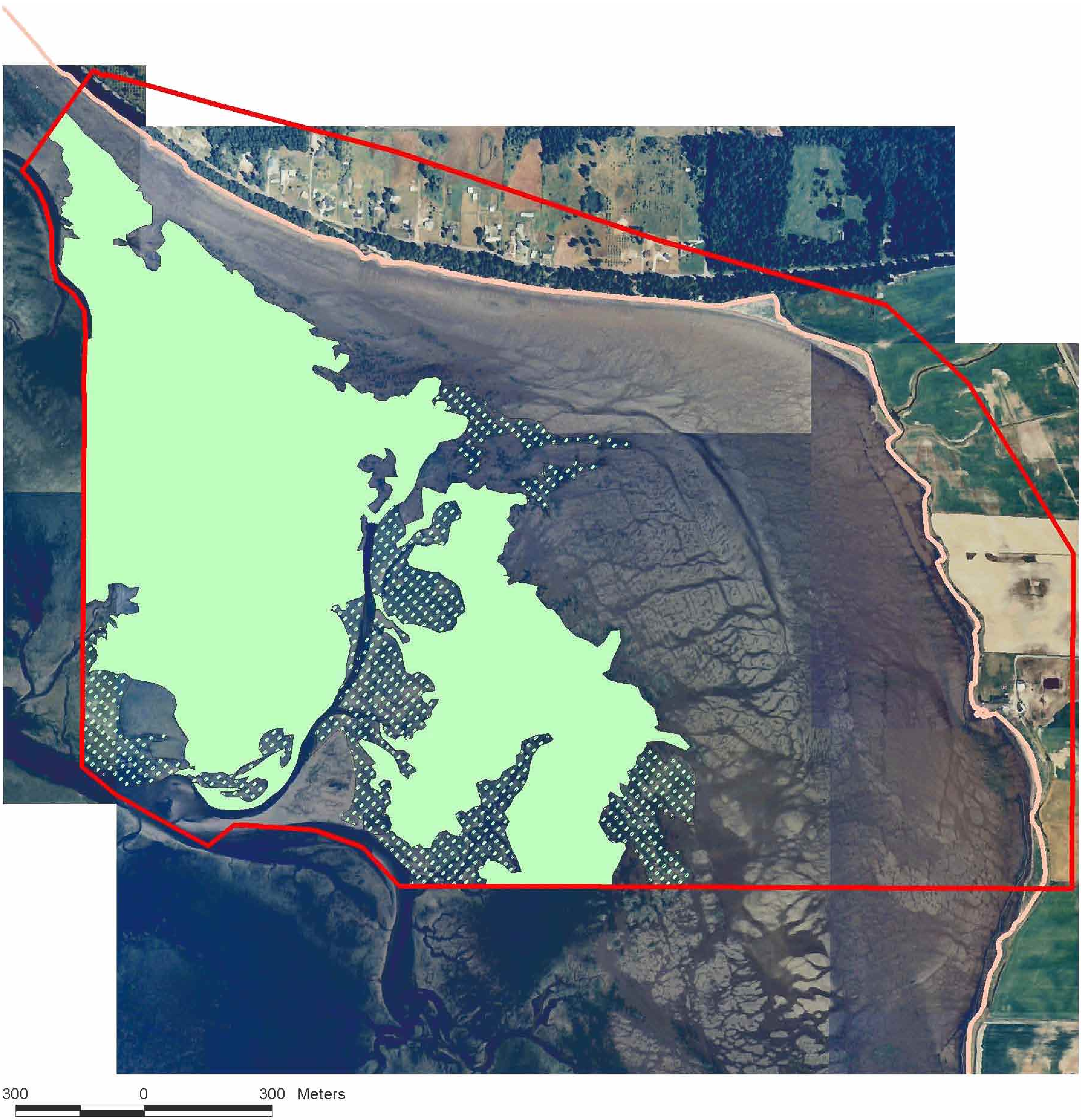


Figure 14. Continuous eelgrass cover (in solid fill) and sparse eelgrass cover (in stipple pattern) in Northeast area of interest in Padilla Bay, Washington as delineated on true color aerial photographs taken on July 28, 1992.

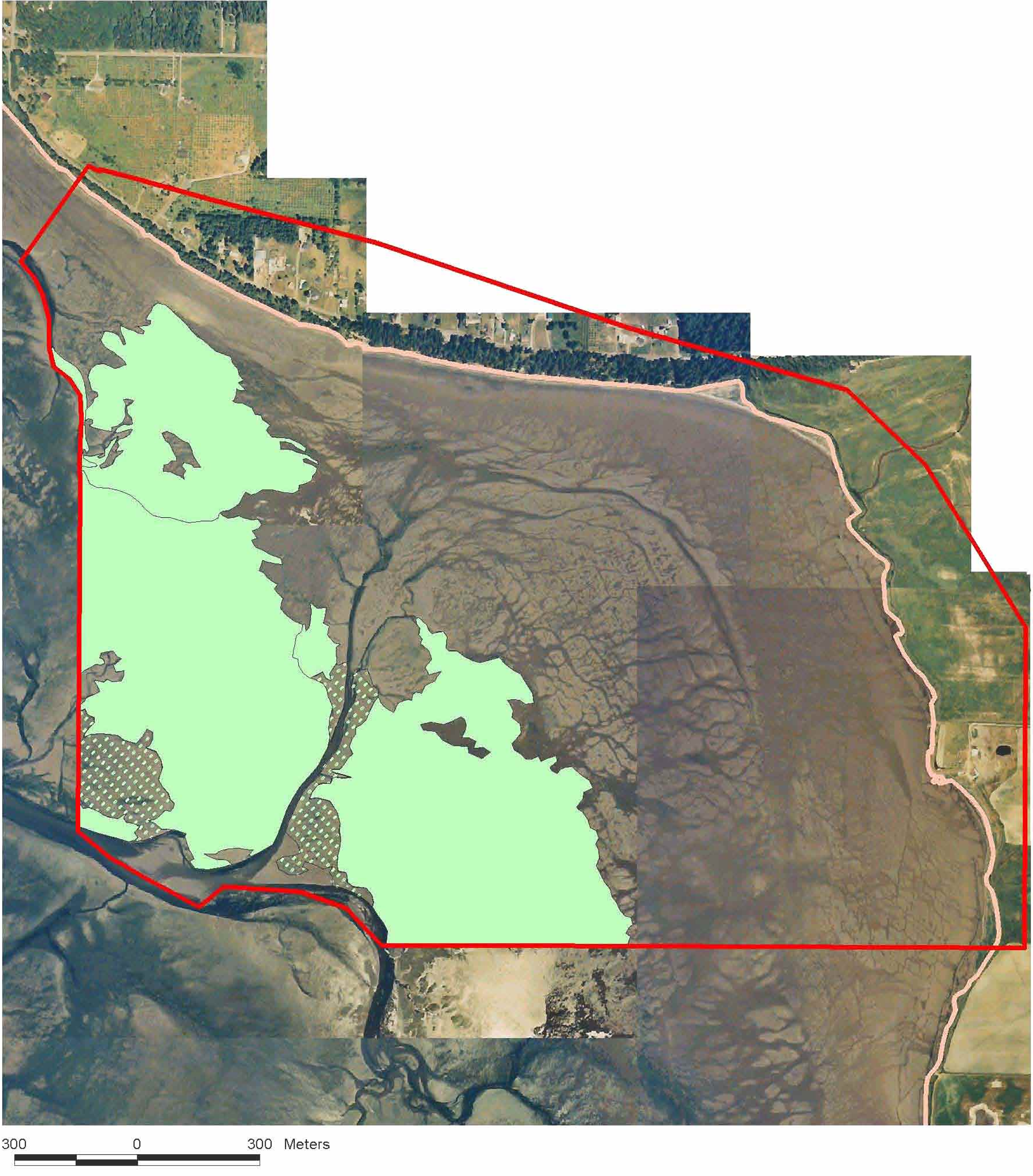


Figure 15. Continuous eelgrass cover (in solid fill) and sparse eelgrass cover (in stipple pattern) in Northeast area of interest in Padilla Bay, Washington as delineated on true color aerial photographs taken on July 1, 1996.

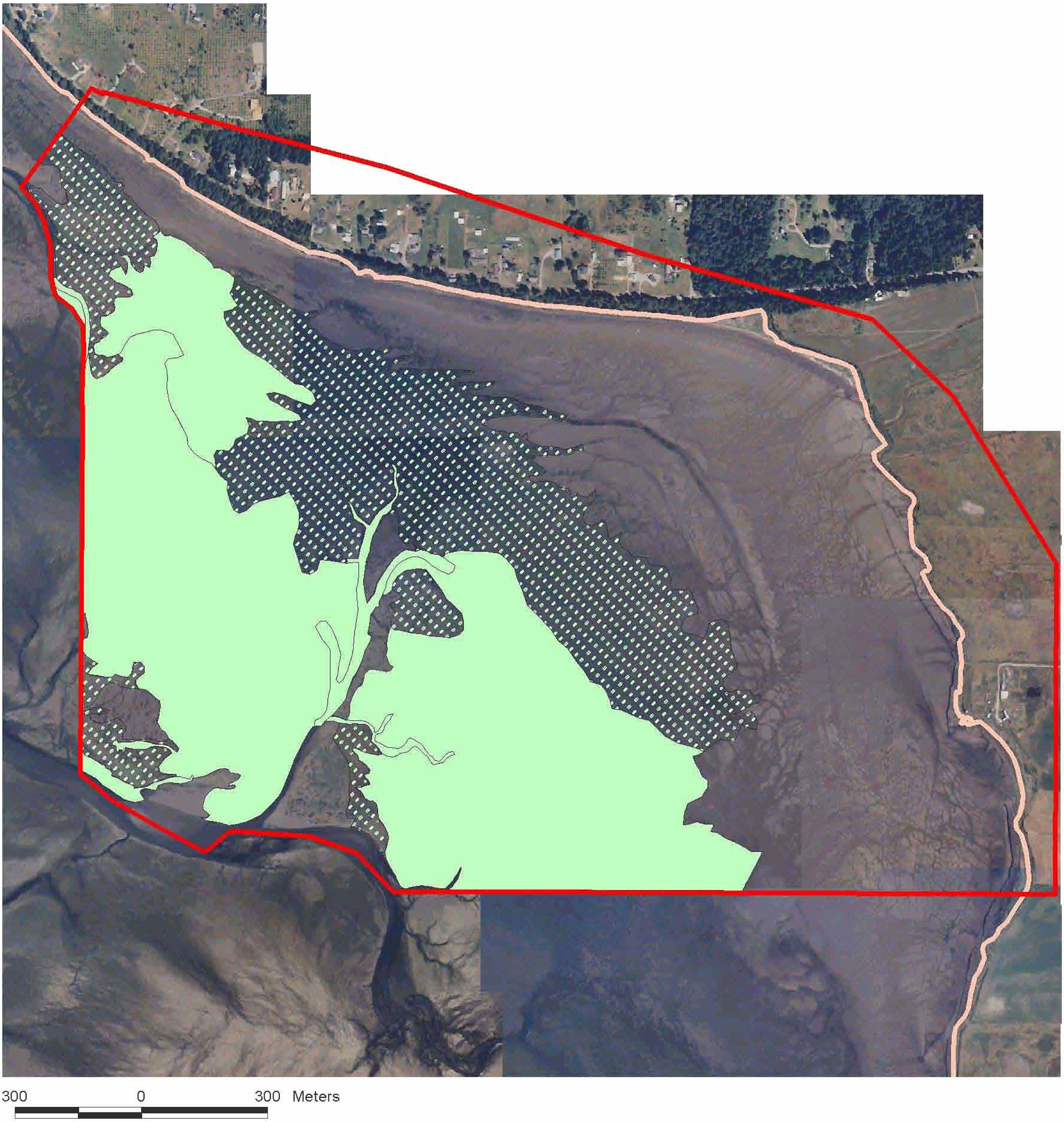


Figure 16. Continuous eelgrass cover (in solid fill) and sparse eelgrass cover (in stipple pattern) in Northeast area of interest in Padilla Bay, Washington as delineated on true color aerial photographs taken on July 30, 2000.

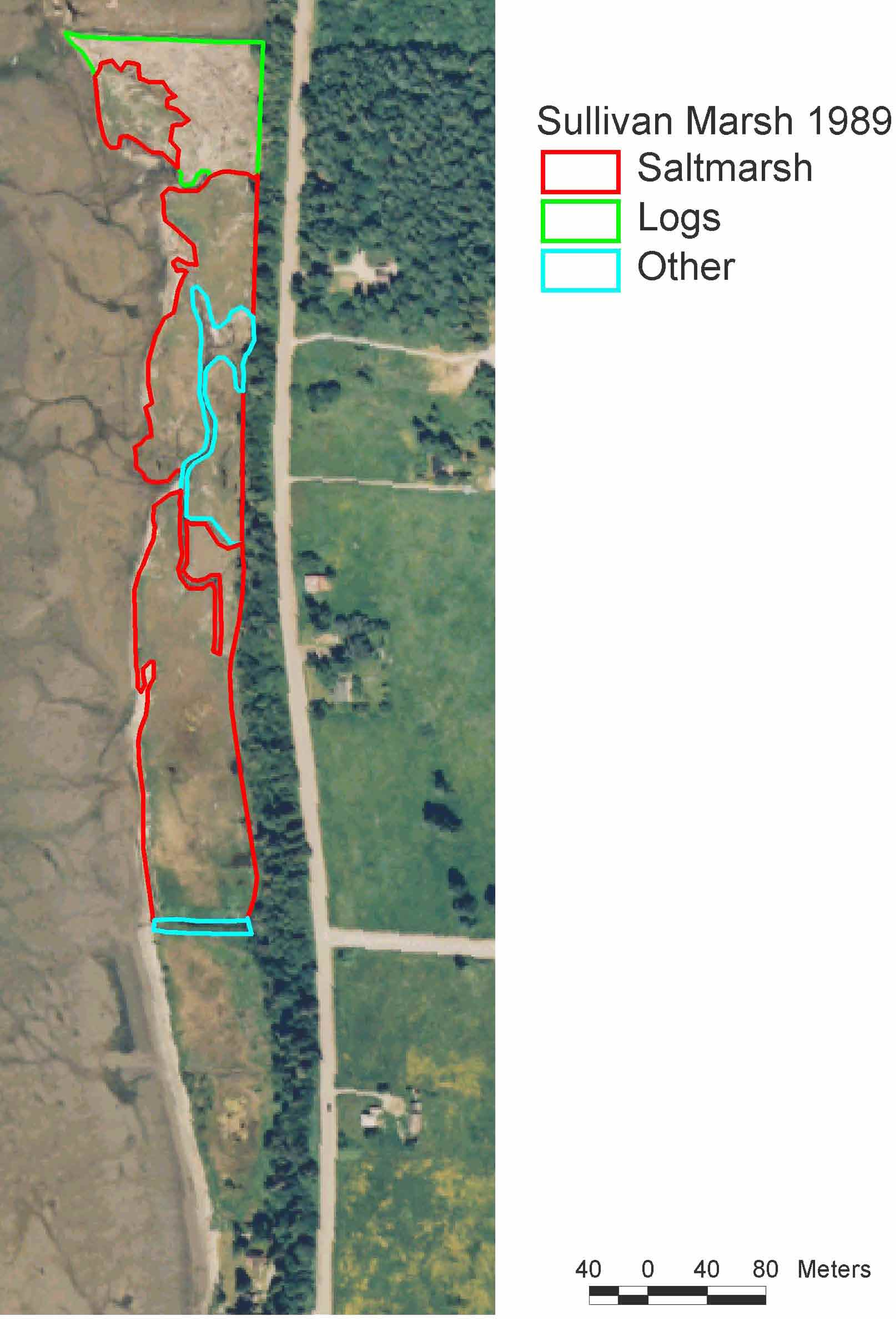


Figure 17. Native saltmarsh and log piles in Sullivan-Minor marsh, Padilla Bay, Washington as delineated on true color aerial photographs taken on July 30, 1989.

Figure 18. Native saltmarsh and log piles in Sullivan-Minor marsh, Padilla Bay, Washington as delineated on true color aerial photographs taken on July 30, 1992.

Figure 19. Native saltmarsh and log piles in Sullivan-Minor marsh, Padilla Bay, Washington as delineated on true color aerial photographs taken on July 30, 1996.

Figure 20. Native saltmarsh and log piles in Sullivan-Minor marsh, Padilla Bay, Washington as delineated on true color aerial photographs taken on July 30, 2000.

Figure 21. Area of salt marsh in Sullivan-Minor marsh, Padilla Bay, Washington that was lost between 1989 and 2000; displayed on an aerial photo taken on July 30, 2000.

TABLES

Table 1. Area (hectares) of estuarine vegetation in Padilla Bay, Washington and the area of intertidal flats and subtidal channels without macrophytes (cover less than 10%) in the Padilla Bay study area in July 2000. (See Figure 7 for distribution of these categories in Padilla Bay.)

Table 2. Area of eelgrasses (*Zostera sp*.) in the March Point study area in Padilla Bay, Washington in 1989, 1992, 1996, and 2000. The eelgrass covered areas were divided into those with an apparent continuous cover or those with a sparse cover.

Table 3. Area of eelgrasses (Zostera sp.) in the northeast study area in Padilla Bay, Washington in 1989, 1992, 1996, and 2000. The eelgrass covered areas were divided into those with an apparent continuous cover or those with a sparse cover.

Table 1. Area (hectares) of estuarine vegetation in Padilla Bay, Washington and the area of intertidal flats and subtidal channels without macrophytes (cover less than 10%) in the Padilla Bay study area in July 2000. (See Figure 7 for distribution of these categories in Padilla Bay.)

Submerged or emergent vegetation and percent cover category	**Area (hectares)**
Zostera marina intertidal 51-100%	2779
Zostera marina intertidal 10-50%	33
Zostera marina subtidal	217
Total Zostera marina	**3029**
Zostera japonica intertidal 51-100%	723
Zostera japonica intertidal 10-50%	114
Total *Zostera japonica*	**838**
Total *Zostera sp*.	**3867**
Macroalgae 51-100%	124
Macroalgae 10-50%	80
Total macroalgae	**204**
Saltmarsh	47
Total vegetation	**4117**
Intertidal bare	1144
Subtidal bare	944

Table 2. Area of eelgrasses (*Zostera sp*.) in the March Point study area in Padilla Bay, Washington in 1989, 1992, 1996, and 2000. The eelgrass covered areas were divided into those with an apparent continuous cover or those with a sparse cover.

Year	**Continuous eelgrass (hectares)**	**Sparse eelgrass cover (hectares)**	**Total eelgrass cover (hectares)**
1989	115.8	5.2	121.0
1992	118.9	3.6	122.5
1996	107.9	8.6	116.4
2000	92.3	19.6	111.9

Table 3. Area of eelgrasses (Zostera sp.) in the northeast study area in Padilla Bay, Washington in 1989, 1992, 1996, and 2000. The eelgrass covered areas were divided into those with an apparent continuous cover or those with a sparse cover.

Year	**Continuous eelgrass (hectares)**	**Sparse eelgrass cover (hectares)**	**Total eelgrass cover (hectares)**
1989	40.6	7.9	48.5
1992	107.3	27.4	134.6
1996	91.9	8.6	100.5
2000	107.3	61.1	168.3