The Ecology of Padilla Bay, Washington:
An Estuarine Profile of a
National Estuarine Research Reserve

By Douglas A. Bulthuis

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PREFACE

The purpose of this document is to provide an overview of the existing state of knowledge about the ecology of Padilla Bay through a review of the literature including peer-reviewed articles, published and un-published reports and unpublished data on Padilla Bay. Padilla Bay has been the focus of many studies and investigations. Some of these studies covered a broad geographical area with one or two sampling sites in Padilla Bay; others focused specifically on Padilla Bay. These studies were carried out by students, Padilla Bay staff, and visiting scientists. This document is not a comprehensive review of those studies, but it does seek to introduce the reader to what is known about Padilla Bay and summarize the principle findings relevant to the bay from these studies. Research and monitoring in Padilla Bay continues and the state of our knowledge and understanding of the bay is dynamic. This document is an overview of studies completed through the late 2000's and is, thus, an indication of the state of knowledge about Padilla Bay at that time.

This document begins with an introduction to Padilla Bay in its institutional setting as a National Estuarine Research Reserve and its setting within Puget Sound and estuarine science. Chapter 2 describes the environmental setting of Padilla Bay including the geology, geomorphology and climate of the area and current landuse in the watershed. Chapter 3 includes the hydrology and water quality in the watershed, tides and currents in Padilla Bay, and water quality and contaminants in the bay. In Chapter 4 the literature is grouped by the various ecological communities in Padilla Bay. The predominant community in Padilla Bay is the eelgrass community and this community, or its constituent populations, has been the focus of the majority of studies in the bay. In addition to the communities, there are some plants and animals that are particularly important or of special interest in Padilla Bay. Studies on these biota are reviewed in Chapter 5. Chapter 6 is a brief outline of the research and monitoring programs at Padilla Bay National Estuarine Research Reserve and a compilation of the research and monitoring gaps that have been identified in the course of this review. The literature cited serves as a bibliography of the publications, reports, and theses about Padilla Bay up to the late 2000's.

It is hoped that this review of the state of the knowledge of Padilla Bay in the late 2000's may improve conservation, management, restoration, and a greater understanding of Padilla Bay, Puget Sound, and estuaries in the Pacific Northwest, and that it may stimulate further research to these ends.

This review has introduced the author to the work of many highly talented scientists and students who have studied various aspects of Padilla Bay. This review would not exist except for their insightful work. This profile is dedicated to them: the scientists and students who have studied and worked in Padilla Bay to gain a better understanding of the bay, its components, and how it functions.

ACKNOWLEDGEMENTS

Sincere thanks are due to many colleagues who have conducted the studies that are reviewed in this document and to many Padilla Bay staff who helped conduct studies in the bay and who provided support in many forms over the course of the writing of this review.

Thanks to many Padilla Bay staff who helped carried out investigations in Padilla Bay or conducted studies themselves in Padilla Bay and watershed. Some of their unpublished data are presented in this document. The NERRS System-wide Monitoring Program has been carried out at Padilla Bay since 1995 and thanks are due to the staff who implemented this program that provided the bulk of the information on the hydrochemistry of Padilla Bay: Sharon Riggs, Robin Cottrell, Paula Margerum, Nicole Burnett, and Heath Bohlmann. Many AmeriCorps and Padilla Bay staff and interns assisted in the System-wide Monitoring Program and with studies reported here including: Mark Olson, Britt Pfaff, Leslie Hill, Mary Anderson, David Weinman, Adam Morris-Cohen, Andrew Windham, Elizabeth Leavens, and Amy Campbell. Sacha Maxwell analyzed and summarized large files of water quality data.

Thanks are also due to colleagues who reviewed the literature in specific areas of research in Padilla Bay: Paul Dinnel, Jim Johannessen, Bert Rubash, Jim Lovvorn, Melora Haas, and Sharon Riggs. Several of these reviews have been published as Site Profile Contributions in the Padilla Bay National Estuarine Research Reserve Technical Report series (Dinnel 2000, 2001, Johannessen and Rubash 2001, and Lovvorn 2001).

Thanks are also due to staff who helped in the preparation of the manuscript and the figures and tables. Suzanne Shull produced or provided many of the maps of vegetation, other maps, and satellite photos. Amy Campbell produced many graphs from Padilla Bay data and reconstructed graphs from reports by others.

The manuscript has been improved by reviews and comments from Marie Bundy and colleagues in the National Oceanic and Atmospheric Administration, Estuarine Reserves Division.

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CHAPTER 1

INTRODUCTION TO PADILLA BAY, WASHINGTON

Padilla Bay is a biologically productive, predominately intertidal bay set in the Georgia Basin/Puget Sound estuarine system in Washington State, USA. Its perceived biological and ecological importance led to its nomination and designation as a National Estuarine Research Reserve (NERR) in the early 1980's (Washington State Department of Ecology 1984). Both before, and particularly after, its designation as a NERR, a variety of scientists and students carried out research in Padilla Bay. This estuarine profile of the ecology of Padilla Bay is a brief review of the publications, reports, and theses on Padilla Bay and summarizes what is known at this time about the Padilla Bay estuarine system.

BIOLOGICAL AND ECOLOGICAL IMPORTANCE OF PADILLA BAY

The extensive eelgrass beds are the basis for the biological and ecological significance and importance of Padilla Bay. With more than 3000 hectares (7400 acres) of both subtidal and intertidal eelgrasses, Padilla Bay contains one of the largest contiguous beds of seagrass along the west coast of North America (Bulthuis 1995). Monitoring of seagrasses in the U.S. portions of Puget Sound, Georgia Strait, and Strait of Juan de Fuca, has produced estimates that 1/5 to 1/4 of the total eelgrass in this area is within Padilla Bay (Dowty et al. 2005). These eelgrass communities in Padilla Bay, including the eelgrasses, the epiphytes of the eelgrasses, and the associated macroalgae, have a high primary productivity (Thom 1990). Some of this organic material is retained within the bay and enters the food chain directly via herbivory or as detritus, while other organic material is exported from the bay and supports secondary production in adjoining channels, straits, and bays.

A wide range of marine animals live in the eelgrass habitat or utilize it for certain life stages or times of the year. Harpacticoid copepods, nematodes, polychaetes, amphipods, and isopods are abundant in Padilla Bay and important in the food web for larger organisms (Simenstad et al. 1988, 1995, Shaw 1994, Shaw 1995). Dungeness crab use the eelgrass habitat during early stages of their life cycle (Dinnel et al. 1986, McMillan et al. 1995, Dinnel 2001). Juvenile salmon, surf smelt, Pacific herring, sculpins, shiner perch and other fish feed in the intertidal eelgrasses during high tide (Fresh 1979, Simenstad et al. 1995, Dinnel et al. 1990, Shaw 1995, Beamer et al. 2007). Brant geese graze the eelgrass directly and use Padilla Bay both in their autumn and spring migrations and as a wintering area (Reed, A. et al. 1998, Lovvorn 2001). Widgeon, pintail, mallard, teal, and other dabbling waterfowl are seasonally abundant in Padilla Bay, utilizing the eelgrasses and other habitats (Jeffrey 1976). Scoters and other waterfowl winter in the Georgia Basin/Puget Sound area and feed on various fauna and flora that are abundant in and around the eelgrass community (Lovvorn 2001, Anderson 2006). Channels with subtidal bottoms that distribute and drain tidal water to and from the intertidal flats provide important alternative habitat for animals that use the intertidal eelgrass community during high tide as well as provide the predominate habitat for some species (such as English sole and buffalo sculpin) and for certain life stages (such as adult Dungeness crabs and rock crabs). Many of the animals higher in the food chain either move freely among habitats in Padilla Bay or utilize different habitats in the bay during different life stages, times of the year, or times of the day. The mosaic of habitats combined with the extensive eelgrass community make Padilla Bay biologically and ecologically important within the Puget Sound/Georgia Basin system and, for some species, a significant habitat along the west coast of North America.

PADILLA BAY ESTUARY WITHIN PUGET SOUND

Padilla Bay, with its biologically productive flats is set within the Puget sound/Strait of Georgia inland sea, sometimes called the Salish Sea. As a National Estuarine Research Reserve, Padilla Bay is within the Columbian/Puget Sound bioregion. The other estuaries in the Columbian region are river dominated estuaries (Emmett et al 2000) whereas Puget Sound/Strait of Georgia is a fjord-type estuary with deep channels (to 420 m deep) and shallow sills (40-60 m) at the mouth. Within this system large shallow areas, including Padilla Bay, are mostly created by river deltas. Many large river deltas within the Puget Sound/Strait of Georgia system have been developed as port cities such as the Duamish (Seattle), Snohomish (Everett), Puyallup (Tacoma), and Fraser (Vancouver). Thus, Padilla Bay is one of a few large shallow and productive bays that have not been developed within this deep fjord-type estuarine system.

Puget Sound proper is the body of water south of Admiralty Inlet. The Strait of Georgia extends north of Padilla Bay and the San Juan Islands (Fig. 1). However, in popular and jurisdictional use, the Washington State portions of the inland waters of the Strait of Georgia and the Strait of Juan de Fuca are often called “Puget Sound”. Thus, the “Puget Sound Partnership” which is the EPA recognized management authority for the Puget Sound Estuary Program, includes all of the water within the U.S. in Puget Sound, the Strait of Georgia, and the Strait of Juan de Fuca, including Padilla Bay. In some contexts the area north of Admiralty Inlet is called “North Puget Sound”.

The lowland watershed of Puget Sound (south of Admiralty Inlet) is heavily urbanized with the cities of Seattle, Everett, Tacoma, Olympia, and Bremerton contributing to urban sprawl that extends throughout the Puget Lowlands of Puget Sound. The watersheds of North Puget Sound are less developed with more agriculture in the Puget Lowlands, particularly in the floodplains of the Skagit, Stilliguamish, and Nooksack Rivers. Padilla Bay is located in the delta of the Skagit River, but isolated from the Skagit since the main river flows moved south to Skagit Bay. The remnant watershed of Padilla Bay is small (9300 hectares) with agriculture as the main land use within the watershed.

Padilla Bay qualifies as an estuary in the sense that it is a semi enclosed body of water where marine and freshwater are mixed. However, Padilla Bay is better understood and defined as a bay in a larger estuary or estuarine system including the Strait of Georgia and Puget Sound, sometimes called collectively the Salish Sea (Fig. 1). Within that estuarine system, Padilla Bay is somewhat anomalous because of its shallow depth and because of the low volume of direct freshwater flow into the bay.

The Georgia Basin/Puget Sound estuarine system is a fjord-type estuary that was shaped and carved by the North American continental glaciers. Many rivers and streams flow into this estuarine system of which the two largest are the Fraser River 100 kilometers north of Padilla Bay and the Skagit River 15 kilometers south of Padilla Bay. Like other fjord type estuaries, Georgia Basin/Puget Sound is deep (maximum depths of 420 m and 280 m) with shallower sills (40 m and 65 m) at the mouth(s) (Thompson 1994). Thus Padilla Bay is an embayment within a fjord-type estuary. However, Padilla Bay itself is not a fjord-like estuary because it is composed predominately of intertidal flats dissected with tidal channels.

Padilla Bay also lacks a major source of freshwater entering the bay from the land or "upstream" side of the bay. In the past, Padilla Bay was probably one of the distributary mouths of the Skagit and Samish Rivers. As recently as 150 years ago various channels connected Skagit, Padilla, and Samish Bays and, during times of high river flow, part of the Skagit River may have flowed into Padilla Bay. However, the channels of the lower Skagit and Samish Rivers were diked in the last century and the Skagit River flows into Skagit Bay and the Samish River into Samish Bay (Fig. 2). Padilla Bay, thus, has been termed an "orphaned" estuary, since it has been cut off from the rivers that once flowed into it. Small sloughs and drainage ditches continue to drain the floodplain and raised marine terraces of the Padilla Bay watershed bringing some freshwater directly to the bay.

Semidiurnal tides with a mean range of 1.6 m (5.2 ft) and a spring range of 2.6 m (8.5 ft) regularly flush the water in Padilla Bay with the estuarine water of north Puget Sound. Thus, most of the freshwater that "measurably mixes with the seawater" in Padilla Bay enters Padilla Bay on the "marine" side of the bay and is derived from the Fraser, Skagit, Nooksack, Samish, and other rivers that flow into the Strait of Georgia and north Puget Sound. Salinity is generally vertically homogenous with no (or very weak) horizontal salinity gradients because of the tidal range, shallow depth, and low volume of direct freshwater flow to the bay. Padilla Bay is polyhaline (25-30 PSU [Practical Salinity Units]) reflecting the salinity of the surrounding straits and water bodies.

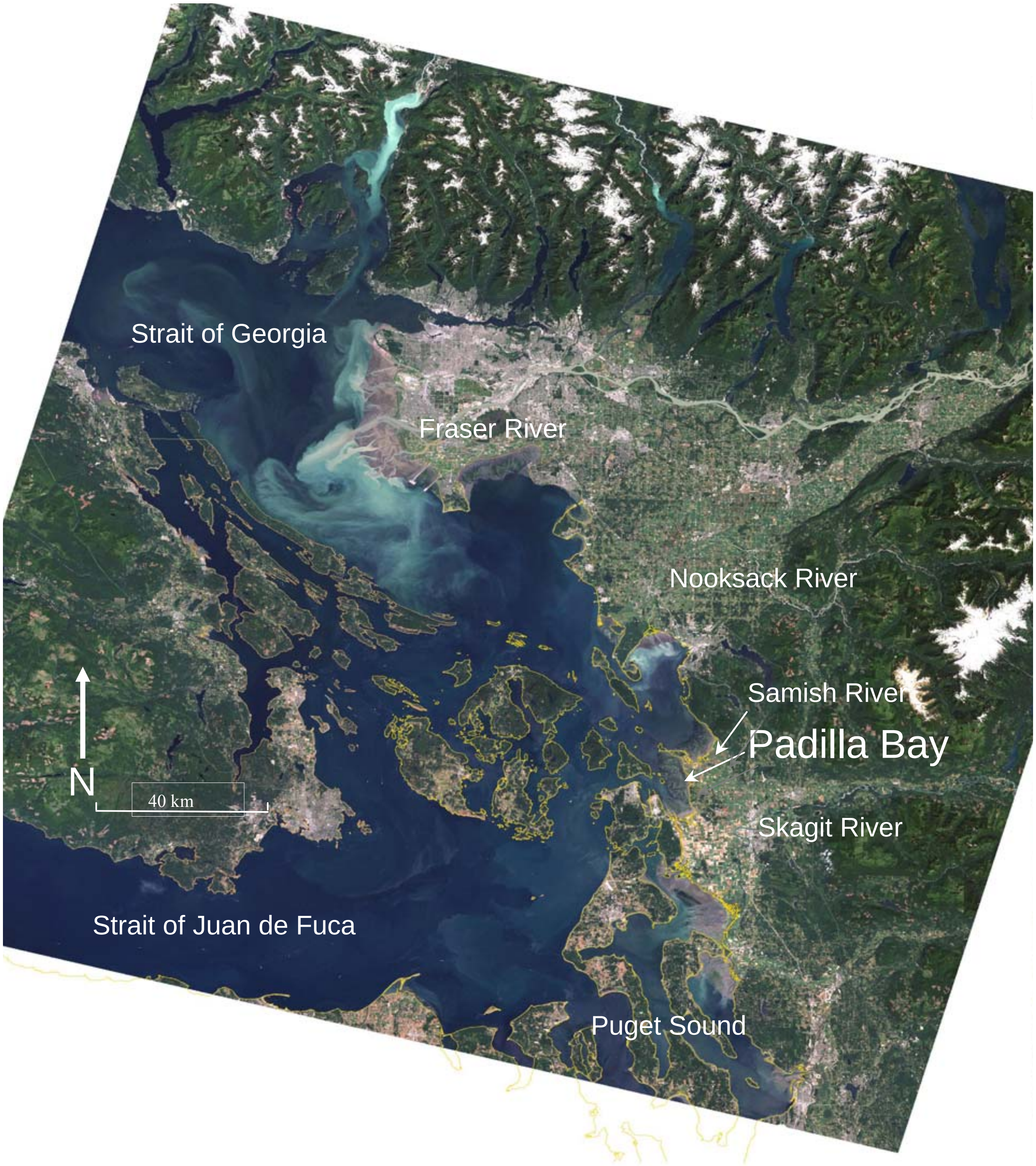


Figure 1. Location of Padilla Bay in the Salish Sea, south of the Strait of Georgia, north of Puget Sound and east of the Strait of Juan de Fuca , and the rivers flowing into the Salish Sea in the region of Padilla Bay. Landsat image taken June 16, 2000, modified by Shull.

Figure 2. Skagit River delta Landsat image taken June 16, 2000, modified by Shull.

ECOLOGICAL COMMUNITIES

Eelgrass communities of *Zostera marina* and *Z. japonica* are the predominate community type in Padilla Bay covering more than 3800 hectares of intertidal flats and subtidal slopes (Fig. 3). Intertidal sand and mud flats without macrophytes, and flats with green macroalgae also cover extensive areas of Padilla Bay. Other important communities that add to the diversity of habitats in the bay include salt marshes, rocky intertidal and subtidal habitats, and estuarine tidal channels.

This mosaic of habitats may be classified with a variety of classification systems. In the Cowardin classification Padilla Bay is in the estuarine system with "aquatic bed" and "unconsolidated bottoms" the main classes in both the "intertidal" and "subtidal" subsystems. In the Washington State marine and estuarine classification system (Dethier 1990) Padilla Bay would be classified as “Estuarine,” “semi-protected”. In the Coastal Habitat Classification Scheme (Ray 1994) the habitats in Padilla Bay would be classified as "Polyhaline" with mainly "Intertidal" of "Unconsolidated Bottom" of "Sand" and of "Mud" and "Aquatic Bed" of "Rooted Vascular" and "Algal." The main "Subtidal" habitats would be "Unconsolidated Bottom: Sand" and "Aquatic Bed: Rooted Vascular."

These various classification systems set Padilla Bay in the context of other aquatic habitats or estuarine and marine systems by comparing salinity, frequency of inundation, bottom type, and presence and type of macrophytes. These characteristics have been used in this report to divide the studies on the biota of Padilla Bay into seven different ecological communities: eelgrass communities, intertidal algae, intertidal sand and mudflats, salt marshes, rocky habitats, estuarine channels, and the plankton communities. Studies on most biota in Padilla Bay have been conducted within one of these communities and will be discussed in the review of our knowledge of that community. However, most fauna move among these various community types on a tidal, diurnal, seasonal, or annual frequency or at various life history stages. The presence of a mosaic of these habitats in Padilla Bay contributes to the importance of Padilla Bay as a whole for these biota.

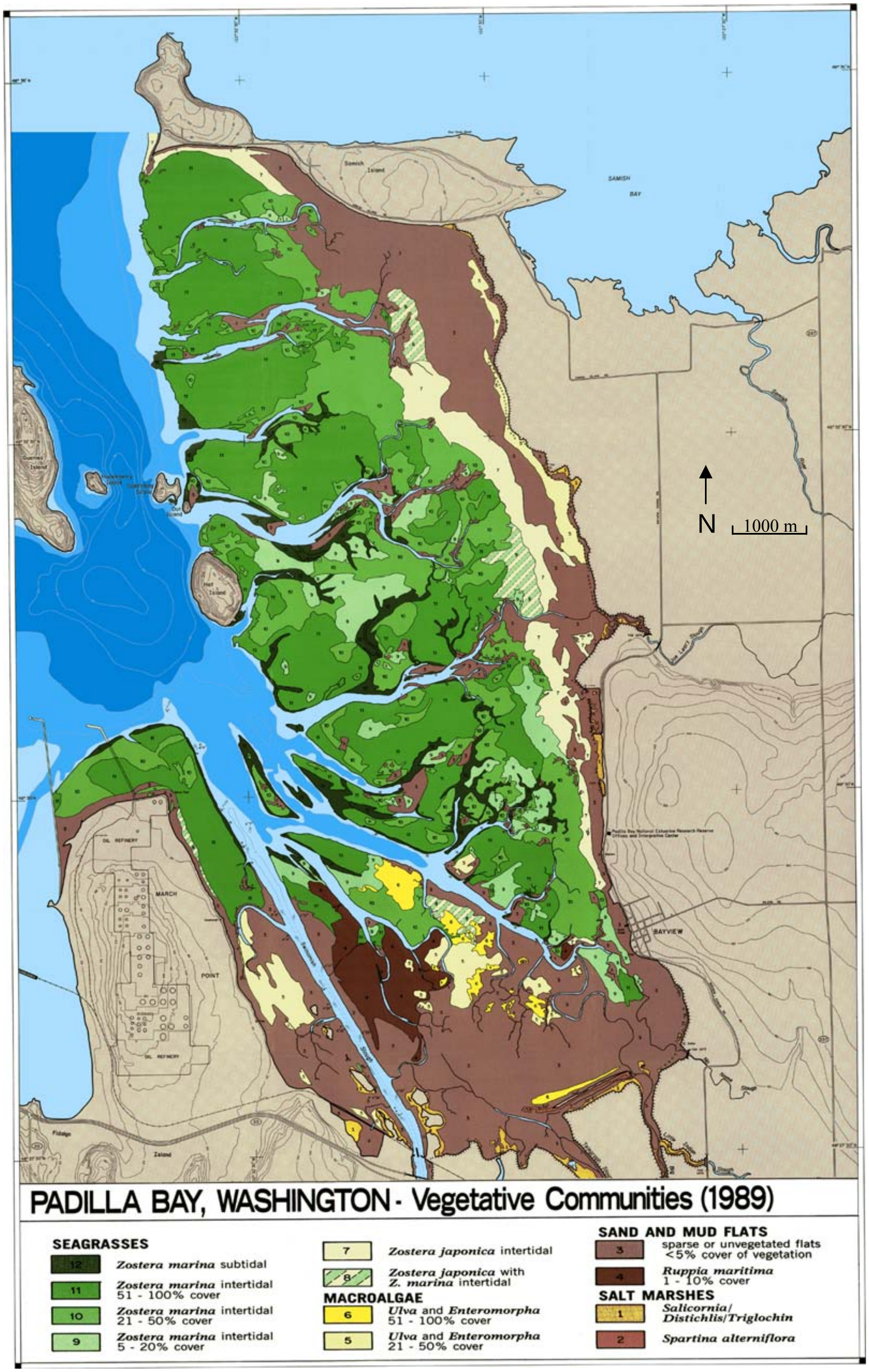


Figure 3. Vegetative communities in Padilla Bay in 1989. (From Bulthuis 1991)

PADILLA BAY AS A NATIONAL ESTUARINE RESEARCH RESERVE

Early reconnaissance of the habitats and marine communities in the Puget Sound/Georgia Basin area indicated the biological importance of Padilla Bay. This recognition led to early efforts to preserve Padilla Bay as part of the estuarine ecosystem and prevent conversion to agricultural, industrial, or residential uses. Edna Breazeale, who had been raised on the shores of Padilla Bay, taught in Seattle for many years and retired to Padilla Bay, was particularly effective in raising awareness of the need to protect Padilla Bay in the 1960's and 70's. The National Estuarine Research Reserve System (NERRS) was established by Congress in 1971, as part of the Coastal Zone Management Act. In the late 1970's (then called National Estuarine Sanctuaries) Washington State surveyed various possible sites before nominating Padilla Bay. Padilla Bay was selected for several reasons, including the extensive waterfowl numbers in Padilla Bay, particularly during winter; the numbers of juvenile fish and crabs in the bay; and the extensive eelgrass beds that were important to a wide variety of juvenile and adult marine and estuarine animals. Padilla Bay’s extensive eelgrass meadows were ecologically important in the Skagit/Padilla/Samish/Fidalgo complex of bays that supported much of the biological richness of North Puget Sound. In addition, there were real threats to Padilla Bay with most of its tidelands privately owned and a variety of proposals to “develop” the bay for industrial land with deep water access, agricultural land, and Venice style housing estates. In this context public pressure, political will, and conservation goals converged to agree to set aside Padilla Bay as a sanctuary (reserve) for research and education with the understanding that then current uses such as hunting, fishing, and public recreational uses would continue. Padilla Bay was designated as a National Estuarine Sanctuary in 1980 (Washington State Department of Ecology 1984). Following designation, Padilla Bay National Estuarine Research Reserve has been managed by the Washington State Department of Ecology.

The National Estuarine Research Reserve System is a network of protected areas established to promote informed management of the Nation’s estuaries and coastal habitats. Reserves are established and protected to provide opportunities for research, monitoring, education, and interpretation. The Estuarine Reserves Division of NOAA (National Oceanic and Atmospheric Administration) provides overall coordination of the NERRS. Organizations within each state (usually state agencies) manage the reserves and implement site based programs. System wide programs include estuarine education programs for students, coastal training programs for coastal planners and other coastal professionals, and a monitoring program of physical water quality, nutrients, and weather.

Following designation of Padilla Bay as National Estuarine Research Reserve, an interpretive center with estuarine displays was built on the site of a farm donated by Edna Breazeale and her brothers; most of the tidelands of Padilla Bay have been purchased from willing sellers; education and public information programs have been developed for all ages and education levels, of which the middle school program has been particularly popular, with more than 10,000 students per year visiting Padilla Bay; stewardship programs have been developed to address various threats, particularly non-native species introductions such as *Spartina alterniflora* and *S. anglica*; and research and monitoring programs have been developed both to assist scientists, agencies, and students to conduct research on estuarine science and coastal zone management in Padilla Bay, and to conduct such research and monitoring with Padilla Bay NERR staff. (See Chapter 6 for further information about research and monitoring in Padilla Bay and about the NERRS System-wide Monitoring Program.)

HISTORY OF RESEARCH AND MONITORING IN PADILLA BAY

The earliest published record of biological research in Padilla Bay was by Shelford et al. (1935) who identified "*Zostera* Faciations" in Padilla Bay in a general reconnaissance of the San Juan Islands and adjacent marine bottom communities. Later the lack of success of an oyster industry in Padilla Bay prompted investigations of pollution sources (Neale 1952; Orlob et al. 1950; Saxton and Young 1948; and Wagner et al. 1957). Washington State agencies such as the Department of Fisheries and of Wildlife have conducted various surveys that include Padilla Bay: subtidal hard-shell clams (Goodwin 1973); winter herring spawn (Pentilla 1982, 1983, 1984, and 1985; Trumble et al. 1977); and waterfowl (Jeffrey 1976). The possibility of oil pipelines and shipment of oil to and through northern Puget Sound prompted numerous surveys of the area in the 1970's and many studies included one or more sampling sites in Padilla Bay (e.g. Gardner 1978; Calambokidis et al. 1979; Simenstad et al. 1979; Fresh 1979; Smith and Webber 1978; Wahl et al. 1981; Westlake and Cook 1980).

Following designation of Padilla Bay as a National Estuarine Research Reserve, various research activities and research projects were conducted at the Reserve. For example, numerous student projects and theses focused on Padilla Bay; the Washington State Department of Ecology sponsored research in the bay; NOAA Sanctuaries and Reserves Division sponsored research in Padilla Bay; Padilla Bay Research Assistantships were awarded to graduate students (46 assistantships awarded from 1991 through 2007); NOAA Estuarine Reserves Division awarded Graduate Research Fellowships (10 fellowships awarded for work in Padilla Bay from 1997 through 2007); and Padilla Bay staff conducted studies on the bay. Some of these studies addressed management issues and threats. The possibility of oil spills highlighted the need for baseline biological data. The presence of non-native species such as *Spartina alterniflora*, *S. anglica*, *Zostera japonica*, and *Battilaria attramentaria* prompted research on the role of these non-natives in Padilla Bay and methods for control of unwanted species. Research was conducted on light and eelgrass growth because of the potential to water clarity from dredging or flood water discharges to the bay.

The eelgrass communities in Padilla Bay are extensive and much of the research in the bay has focused on the eelgrasses and the communities that they support. This research is particularly relevant to the Puget Sound/Georgia Basin region, but also has relevance to eelgrasses throughout the world. Because of the location of Padilla Bay and the strong flow of water into and out of the bay each day, Padilla Bay communities and water quality are closely linked with the surrounding channels, bays, and straits. Thus, research in Padilla Bay is particularly important in the North Puget Sound area. Partnerships have been developed with a variety of institutions in the region to promote research in Padilla Bay and to link research in Padilla Bay to area science and management needs. Joint projects have been developed with scientists in NOAA Fisheries, Washington State Department of Fish and Wildlife, Skagit Systems Cooperative (tribal), Washington State Department of Natural Resources, many departments in Western Washington University (WWU) and with the WWU Shannon Point Marine Laboratory, University of Washington, Washington State University, particularly in developing research on the Padilla Demonstration Farm, Washington Sea Grant, Battelle Pacific Northwest National Laboratory, and the local Skagit Conservation District.

These studies and others conducted in Padilla Bay (see Padilla Bay bibliographies: Bulthuis 1989, 1993a; Bulthuis and Shull 1998) provide an indication that Padilla Bay is a biologically productive and important estuarine system. But a perusal of these studies also indicates gaps in our knowledge of Padilla Bay and its role in the Puget Sound/Georgia Basin estuarine system. This estuarine profile of the ecology of Padilla Bay provides a brief review of the publications, reports, and theses on Padilla Bay and seeks to summarize what is known at this time about the Padilla Bay estuarine system.

CHAPTER 2

ENVIRONMENTAL SETTING

GEOLOGY

Plate tectonics, volcanic eruptions, glaciers, earthquakes, and sea-level changes have all shaped the Padilla Bay of today. Padilla Bay is located on the geologically active continental margin of the Pacific Northwest coast of North America. West of Padilla Bay, Washington, the "young" Juan de Fuca Oceanic Plate is forming and moving northeast toward and under the North American Plate at the rate of about 3.75 cm (1.5 inches) per year (Johannessen and Rubash 2001). Because of the stress of the collision between these two plates Padilla Bay is located in a geologically active area of earthquakes, mountain building, and volcanoes. The Olympic mountains and Vancouver Island mountains are to the west and the Cascade mountains to the east of Padilla Bay. Two subduction zone volcanoes, Glacier Peak and Mount Baker, form part of the headwaters of the Skagit River, which flowed into Padilla Bay in the past.

The tectonics and continental drift have brought several exotic terrains of bedrock to the area. Bedrock near the surface in Padilla Bay area includes igneous rocks of Hat Island that were formed about 175 million years ago and Darrington Phyllite (which is part of the Easton Terrane) on northwestern Samish Island. The bedrock geology of the north Cascades to San Juan Islands is very complex and is currently being studied and its origins debated (Lapen 2000, Dragovich et al. 2000, Brandon et al. 1988, Vance 1975).

VOLCANOES

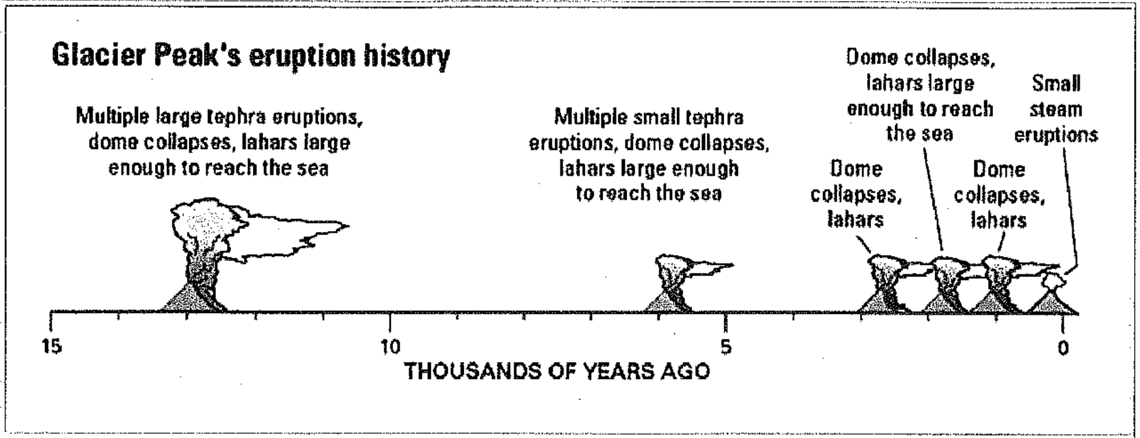
Two active volcanoes, Mount Baker and Glacier Peak are located 80 and 160 km east of Padilla Bay. These subduction zone volcanoes are evidence of the Juan de Fuca plate that is sliding under the North American Plate at the subduction zone. Past Mount Baker and Glacier Peak eruptions created pyroclastic flows (an avalanche of very hot gas, rock, and dust). These pyroclastic flows sometimes melted large quantities of ice and snow, and the resultant combination of rock, water, and dust then continued down the mountain and valleys as a thick slurry called a lahar. Lahars from Mount Baker and Glacier Peak have flowed down the Skagit River many times since the last glaciation, some of them large enough to reach Puget Sound, presumably including Padilla Bay (Washington Division of Geology and Earth Sciences 2000; Johannessen and Rubash 2001; Figure 4). The floodplain portion of the Padilla Bay watershed and the tide flat sediments may be a combination of these lahars and the fluvial deposits from the Skagit River.

GLACIERS

Glaciation was an important landscape forming process in the Puget Lowlands with at least six major advances during the Pleistocene Epoch (Easterbrook 1986). The most important for the Padilla Bay area was the most recent, the Vashon Stade of the Fraser Glaciation, which advanced over the area about 22,000 years ago and retreated about 13,000-10,000 years ago. Glacial ice reached its maximum thickness of approximately 5,000 feet over Padilla Bay (Easterbrook 1969). Glacial deposits of Vashon till and advance outwash, Vashon Stade are found on the surface in various parts of the Padilla Bay watershed, including Bay View Ridge, March Point, and Samish Island.

EARTHQUAKES

Earthquakes that occur as part of the tectonic plate movement have also shaped Padilla Bay and the Georgia Basin/Puget Sound estuary. Active faults have not been well located and few have been mapped at the surface in the Padilla Bay region and northward. One well mapped subsurface fault is the contact between the North American Plate and the subducting oceanic Juan de Fuca plate. This subsurface fault passes below Padilla Bay at a depth of about 50 km. Another known active fault is the Devils Mountain fault, which extends 125 km on the surface from the Cascade foothills to Vancouver Island and passes a few km south of Padilla Bay (Johnson et al. 2000). Groupings of earthquake epicenters within the North American Plate and in the oceanic plate are located near Friday Harbor, about 40 km west of Padilla, but earthquake epicenters beneath Padilla Bay are scattered indicating that local stress in the continental



Known eruptive episodes at Glacier Peak during the past 15,000 years. Each episode (depicted by a single icon) represents many individual eruptions. The ages of these episodes, in calendar years before present are corrected from dates based on a radiocarbon time scale. The uncorrected radiocarbon ages for these episodes, which appear in some publications, are 11,200, 5,100, 2,800, 1,800, 1,100, and 300 years before present.

Figure 4. Eruption history of Glacier Peak during the past 15,000 years. (From Johannessen and Rubash 2001)

crust below Padilla Bay is being relieved incrementally and therefore unlikely to produce major earthquakes (Johannessen and Rubash 2001). On a regional scale however, recent studies have indicated that very large earthquakes occurring since the last retreat of the glaciers have periodically altered shorelines, shaken loose slopes from hillsides and mountains and have sent giant waves (tsunamis) onto the shores of the Pacific Ocean. Drowned forests and drowned freshwater marshes have been found all along the coasts of Oregon, Washington, and Vancouver Island (Johannessen and Rubash 2001). Radiocarbon dating and tree ring analyses of some of these forests, and Native American legends and tsunami records in Japan, give evidence that one of these earthquakes occurred on January 26, 1700 extending from California to British Columbia. (Atwater et al. 1995; Atwater 2000). In Padilla Bay, Beale (1991) reported tree stumps in the tide flats near Bay View Ridge that may be remains of a forest that drowned when the land surface subsided during a large earthquake.

HISTORIC AND CURRENT SEA LEVEL TRENDS

Sea level rise (and fall) in the Puget Sound/Georgia Basin area are caused by tectonic (local change in land elevation due to plate movement), isostatic (changes in crustal mass e.g. rebound following retreat of glaciers) and eustatic (regional and global changes in the amount and volume of seawater). Isolating tectonic, isostatic, and eustatic factors of post-glacial sea-level change is difficult in a subduction zone setting (Thorsen 1989). Tectonic stress is an important factor in the Puget Sound/Georgia Basin region as seen by the falling sea level at Neah Bay 150 km west of Padilla Bay and the rising sea level at Friday Harbor 40 km west of Padilla Bay (Johannessen and Rubash 2001). Isostatic rebound from the last glaciation is presently very small relative to other current sea level changes in the region (Shipman 1990; Beale 1991). Eustatic sea-level change cannot be isolated by applying global rates of sea-level rise because sea-level does not change uniformly around the globe (Beale 1991; Fletcher 1988). Instead regional relative sea-level curves are recommended for which local variables have been identified (Fletcher 1988). The tectonic complexity of Puget Sound/Georgia Basin requires that data for many sites be determined before such a regional relative sea-level history can be determined as has been done e.g. for Delaware Bay (Fletcher et al. 1990; Beale 1991).

Beale (1991) sampled six salt marshes in Puget Sound, San Juan Islands, and Padilla Bay and estimated a relative sea-level rise of approximately 2-3 m between 5,000 and 3,000 years ago, approximately 1 m between 3,000 and 1,000 years ago, and probably not more than 1 m in the past 1,000 years. At Padilla Bay, the maximum estimated average rate of sea-level rise over the last 4,000 years is about 0.8 mm/yr (Beale 1991).

Projected sea level rise in the future for Puget Sound differs across regions of Puget Sound and the Washington coast. Based on the fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), Mote et al. (2008) projected a "medium" estimate that sea level rise in Puget Sound would closely match global sea level rise. On the Olympic coast, they projected very little apparent sea level rise because of tectonic uplift. Thus, projected sea level rise over the next century for Puget Sound and Padilla Bay is between 18 and 38 cm (7-15 in) for the lowest emissions scenario and between 26 and 59 cm (10-23 in) for the highest emissions scenario of the IPPC. The highest likelihood for Puget Sound was 15 cm (6 in) apparent sea level rise by 2050 and 33 cm (13 in) by 2100 (Mote et al. 2008).

GEOMORPHOLOGY

Padilla Bay is located near the northwest edge of a flat delta formed by river, volcanic, and glacier borne sediments that fill the irregularities of the rocky land surface of western Skagit County. The shape of the delta is determined by the surrounding rock basin (mountains) and by the residues of glacial retreat. With the exception of Hat Island on the western edge of Padilla Bay, glacial and post-glacial deposits from the last glaciation cover the surface throughout Padilla Bay, the watershed, and the nearby land. Thus, Padilla Bay is set within the post-glacial Skagit River delta, with remnant high elevation features in the watershed and soils in the watershed and bay that have been formed or deposited in the last 10-12,000 years.

SKAGIT RIVER DELTA

The Skagit River delta is the single largest landform in the Padilla Bay area extending on the north from Blanchard at the base of the Chuckanut Mountains to Conway and Milltown in the south (Fig. 2). Prior to European settlement, the distributary channels of the Skagit River were not fixed features, but fluctuated over time; the Skagit River flowed into Samish Bay and Padilla Bay at various times since the last glaciation. Deposition of sediment from the Skagit River and lahar deposits caused the shoreline to prograde westward about 10 km (6 miles) during the last 5,000 years from approximately downtown Mount Vernon to the present shoreline (Johannessen and Rubash 2001). Thus, most of the floodplain portion of the Padilla Bay watershed was deposited in the last 5,000 years. The Skagit and Samish River deltas were diked in the 1880's, fixing the channels in their present position (Bortleson et al. 1980a, 1980b). At that time the shore of Padilla Bay from Joe Leary Slough to Samish Island was established with diking and the wetlands east of the dikes were drained for agriculture.

REMNANT HIGH ELEVATION FEATURES

Land areas that have elevations higher than the Skagit/Samish River delta wetlands were islands in the early Holocene, shortly after the last glaciation. In the Padilla Bay watershed, these include the raised marine terraces of Bay View Ridge, Samish Island and March Point made up primarily of Vashon fill and advance outwash of the Vashon Stade (Dragovitch et al. 2000, Johannessen and Rubash 2001). These terraces rise 160 to 200 feet above Padilla Bay and the Skagit/Samish floodplain.

SOILS OF THE WATERSHED

The soils of the watershed are sharply divided between the delta or floodplain soils that are agriculturally important and the glacial till soils of the raised marine terraces (Fig. 5). A detailed soil survey of Skagit County was conducted by the Soil Conservation Service and published in 1989 (USDA Soil Conservation Service 1989). Thirty-nine soil types were identified by the Soil Conservation Service in the Padilla Bay watershed. The soils can be grouped into three types: Skagit-Sumas-Field and Larush-Pilchuck that occur on the floodplain portion of the watershed and Bow-Cloveland-Swinomish that occurs on the raised marine terraces. The floodplain soils are very deep, poorly drained (or occasionally moderately well drained) soils with a slope of less than 3%, often with a high clay content, and with a seasonal high water table (Soil Conservation Service 1989; Padilla Bay/Bay View Watershed Management Committee and Skagit County Department of Planning and Community Development 1995). These are very important agricultural soils and are used for annual crops, fruit, berries, seed crops and pasture.

BATHYMETRY

Padilla Bay consists primarily of shallow intertidal flats with a system of dendritic channels that drain and distribute tidal waters to the intertidal flats (Fig. 3). These intertidal flats drop off to deep troughs, up to 90 m (300 ft) deep, between Padilla Bay and Guemes Island and Guemes Channel. The bathymetry of the intertidal flats has not been surveyed in detail because of the lack of commercial or recreational boating activity over the flats. But early hydrographic surveys did measure water depth in Padilla Bay and these have been used as a basis for producing a bathymetric map of the intertidal area and channels in Padilla Bay. However, small changes in elevation have important ecological implications for intertidal plants and animals and the lack of fine scale bathymetry on the intertidal flats precludes important information that may be controlling observed patterns and changes. For example, the central portion of some of the intertidal flats in the northern part of the bay appears to be raised slightly above the surrounding flats. This slight increase in elevation causes water to drain from the central area during ebbing tides faster than from the surrounding flats. In aerial photos taken each year, the eelgrasses fluctuate strongly in density from year to year in these central areas compared to the surrounding flats. This is apparently due to exposure during low tide because of the slight (unknown) rise in elevation.

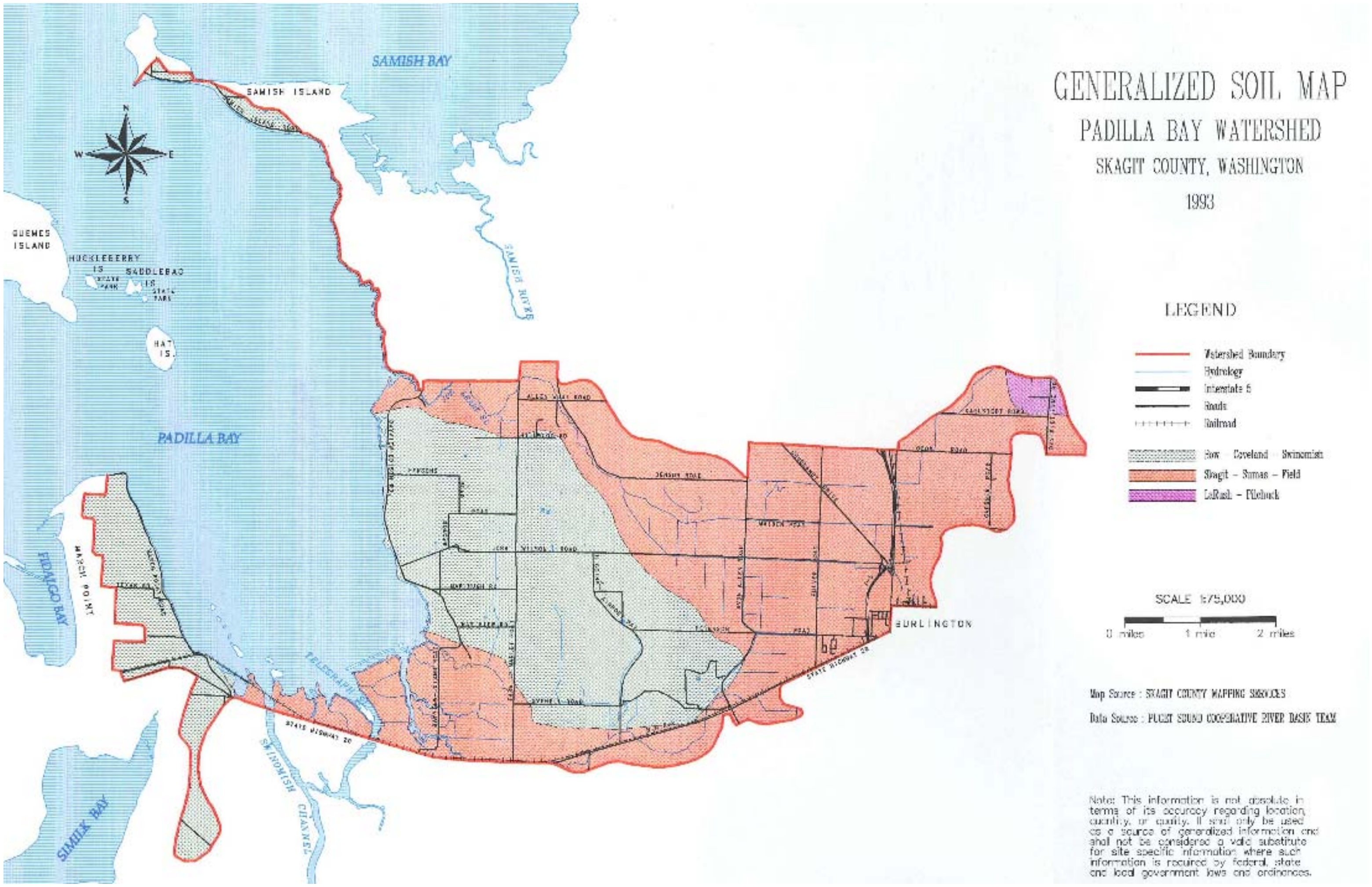


Figure 5. General soil types in watershed of Padilla Bay. (from Padilla Bay/Bay View Watershed Management Committee and Skagit County Department of Planning and Community Development 1995)

COASTAL DYNAMICS

Shore and nearshore processes in Padilla Bay are influenced by the predominate winds and wind-generated waves. Southerly and south-southwesterly winds were both the predominant and the prevailing winds in a study at March Point in 1990-91 (Johannessen 1993) and at Padilla Bay weather station (Fig. 6). The strongest winds came from the south-southwest during the middle and later stages of southerly wind frontal systems. A secondary wind direction from the northwest originates in the Strait of Georgia. Waves in the bay are shallow water, wind-generated waves of low to moderate energy levels because the shallow nearshore limits wave height. The eastern shore of Padilla Bay is exposed to waves coming from the northwest through southwest. The maximum fetch along the central east shore is about 12 km (7.2 miles) from the northwest and 4 km (2.4 miles) from the south-southwest (Johannessen and Rubash 2001). Wind waves from the southerly quadrant (which dominate the annual winds in the area) act at roughly 45º to the east shore, making them very effective waves for sediment transport. West-southwesterly and westerly winds of high velocity also occur in the area causing beach erosion. For example, when 8.1 m/s (18 mph) winds act on the unimpeded south-southwest fetch at the east shore of the bay significant wave heights of 0.8 m (2.6 ft.) are generated in less than two hours. However, because of the shallow nature of Padilla Bay, waves of these heights will only be generated during high water, since depth would limit wave height during mid- and low-water periods. Therefore, beach erosion occurs primarily when high wind events coincide with high tide periods (Johannessen and Rubash 2001).

The Puget Lowland in which Padilla Bay is situated is unusual because of the limited amount of sediment supplied to littoral cells from rivers and streams. The majority of river sediment in the Puget Lowland is deposited in marshes and deltas and river sediment that is initially deposited on beaches is too fine to remain on beaches under prevailing wave regimes (Downing 1983, Kueler 1988). In Padilla Bay today, there are no major rivers and the small coastal sloughs bring a very small sediment load. Therefore, a very high percentage of all beach and nearshore sediment is supplied by

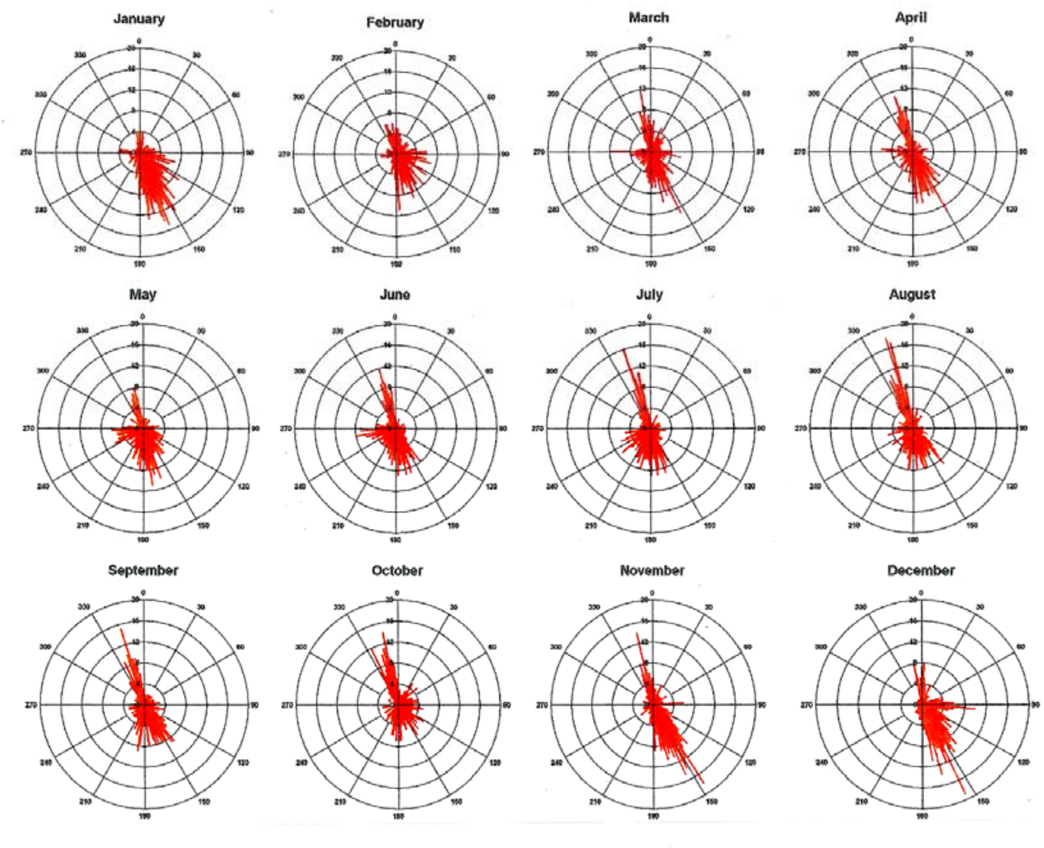


Figure 6. One hour average wind direction during 2002 with the number of hours during the month in each direction. The length of the vector is proportional to the number of hours in each direction. Wind direction data collected at Padilla Demonstration Farm. (From Cottrell and Bulthuis unpublished data)

erosion of unconsolidated (glacial drift) coastal bluffs (Johannessen and Rubash 2001). The exposed bluffs in Padilla Bay and surrounding area commonly experience long-term mean retreat rates on the order of 1-4 in/yr (Kueler 1988, Coastal Geological Services unpublished data) contributing sediment directly to the littoral system. The large majority of bluff sediment in the area is silt and clay. The beach-forming sediment supply is therefore quite limited in Padilla Bay.

Net shore-drift is the long-term, net effect of shore drift occurring over a period of time along a particular coastal sector. Because exposed bluffs are the primary source of beach-forming sediment in the Puget Sound area, the concept and mapping of net shore-drift cell has been used in coastal studies and shoreline management programs. A drift cell usually consists of three components: a site, such as an eroding bluff, that serves as a sediment source; a transport zone where wave energy moves drift material alongshore; and an area of deposition that is the terminus of the drift cell. Net shore-drift cells were mapped by Kueler (1979, 1988) in Padilla Bay and surrounding area. Net shore-drift is generally northerly in Padilla Bay except on the southern part of March Point and the western end of Samish Island (Fig. 7). Net shore-drift is northward along Bay View Ridge as far as Joe Leary Slough, which acts as a temporary barrier to northward net shore-drift. North of Joe Leary Slough, there is a limited volume of net shore-drift. The south shore of Samish Island has a westerly net shore-drift driven by southerly quadrant winds with a drift cell terminus in a cuspate spit at Point Kirby (Kueler 1988, Johannessen and Rubash 2001, Fig. 7). Generally, there is net shore drift north or west along the raised marine terraces of Bay View Ridge, and Samish Island, but little net shore drift along the diked shores of Padilla Bay.

Figure 7. Net shore drift in the Padilla Bay area. Arrows indicate the direction of net shore drift. (redrawn from Keuler 1979, 1988, and Johannessen and Rubash 2001)

CLIMATE

Mild, cloudy, wet winters and cool, relatively dry summers characterize the climate of Puget Sound and the Strait of Georgia. Three of the most important factors controlling the climate are the Pacific Ocean, the semi permanent high and low pressure regions over the north Pacific Ocean, and the coastal and Cascade mountain ranges. The Pacific Ocean is a source of moisture laden air and dampens seasonal fluctuations in temperature. During spring and summer the high pressure area spreads over most of the North Pacific Ocean while the low pressure center becomes weak and moves north of the Aleutian Islands. This brings prevailing westerly and northwesterly flow of dry, and cool air into the Pacific Northwest. In the fall and winter, the low pressure center intensifies and moves south while the high pressure center weakens and also moves south. Circulation around the pressure centers brings a prevailing southwesterly and westerly flow of moist air into the Pacific Northwest. Rain occurs as this air moves over the cooler land and rises along the slopes of the mountains. This results in a wet season from October through winter and into spring (Kruckeberg 1991, NOAA, Western Regional Climate Center 2003).

TEMPERATURE

The mild climate of the Padilla Bay area is illustrated by the average maximum and minimum temperatures each month from a fifty year record at the Mount Vernon weather station (Fig. 8, NOAA, Western Regional Climate Center 2003). The average daily maxima are 23º C (74º F) in August (the hottest month) and 8º C (46º F) in January (the coldest month); and the minima are 11º C (51º F) in August and 1º C (34º F) in January (NOAA, Western Regional Climate Center 2003).

RAINFALL

Rainfall in Western Washington can be highly variable over short distances because of the mountainous terrain. This is true for the small Padilla Bay watershed even though the highest point in the watershed is less than 125 m (400 feet). Anacortes, located just west of Padilla Bay has an annual average precipitation of 664 mm (26 inches) whereas, the average at Sedro Woolley, less than 65 km (40 miles) away and located just east of the Padilla Bay watershed, is 1172 mm (46 inches) (Figs. 9 and 10) (NOAA, Western Regional Climate Center 2003). Anacortes is located in the "rain shadow" that extends northeast of the Olympic Mountains whereas, Sedro Woolley is near the foothills of the Cascade Range. Rainfall data from the Padilla Demonstration Farm (SWMP data) were not used in this comparison because of the short time that it has been operating. However, rainfall at the Padilla Demonstration Farm is similar to the Mount Vernon weather station that has a continuous record since 1956 (Cottrell, unpublished data).

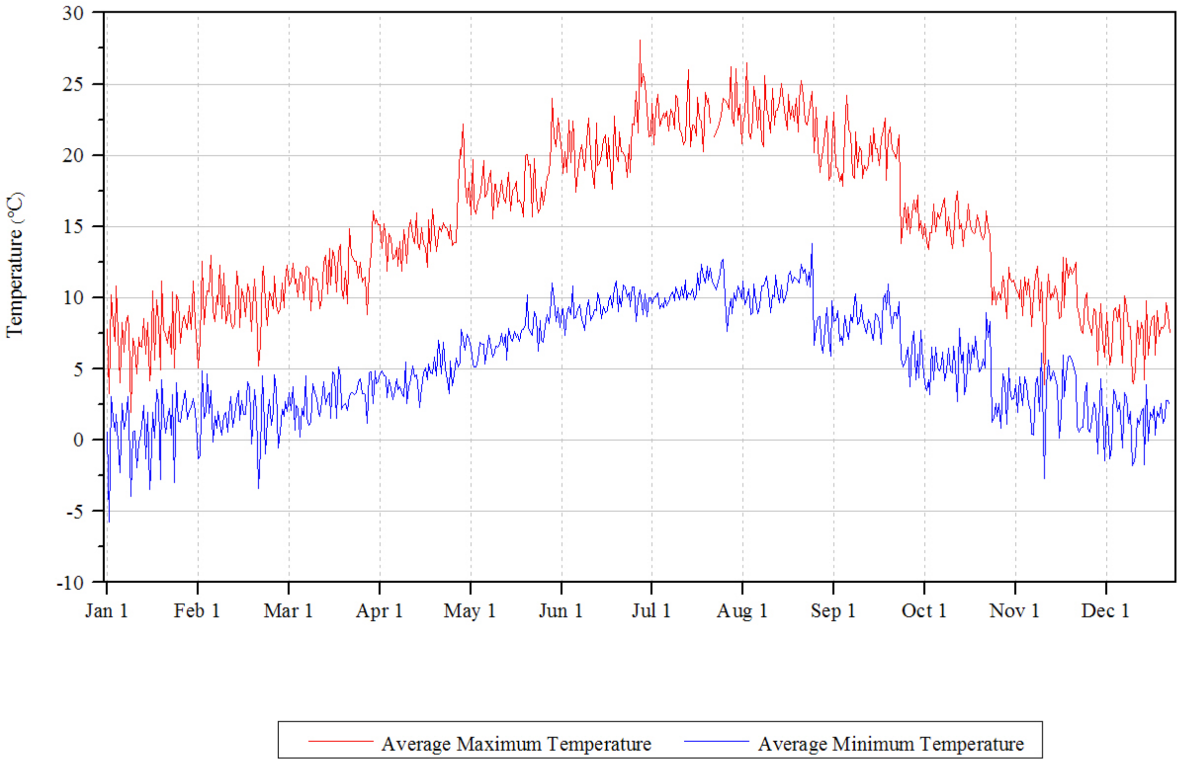


Figure 8. Average daily maximum and minimum temperatures recorded for each the day of the year from January 1, 1956 to December 31, 2005 at Mount Vernon Washington State University Experiment Station (Weather Service identification: Mount Vernon 3 WNW,Washington), located just south of the Padilla Bay watershed. Data from the NOAA, Western Regional Climate Center.

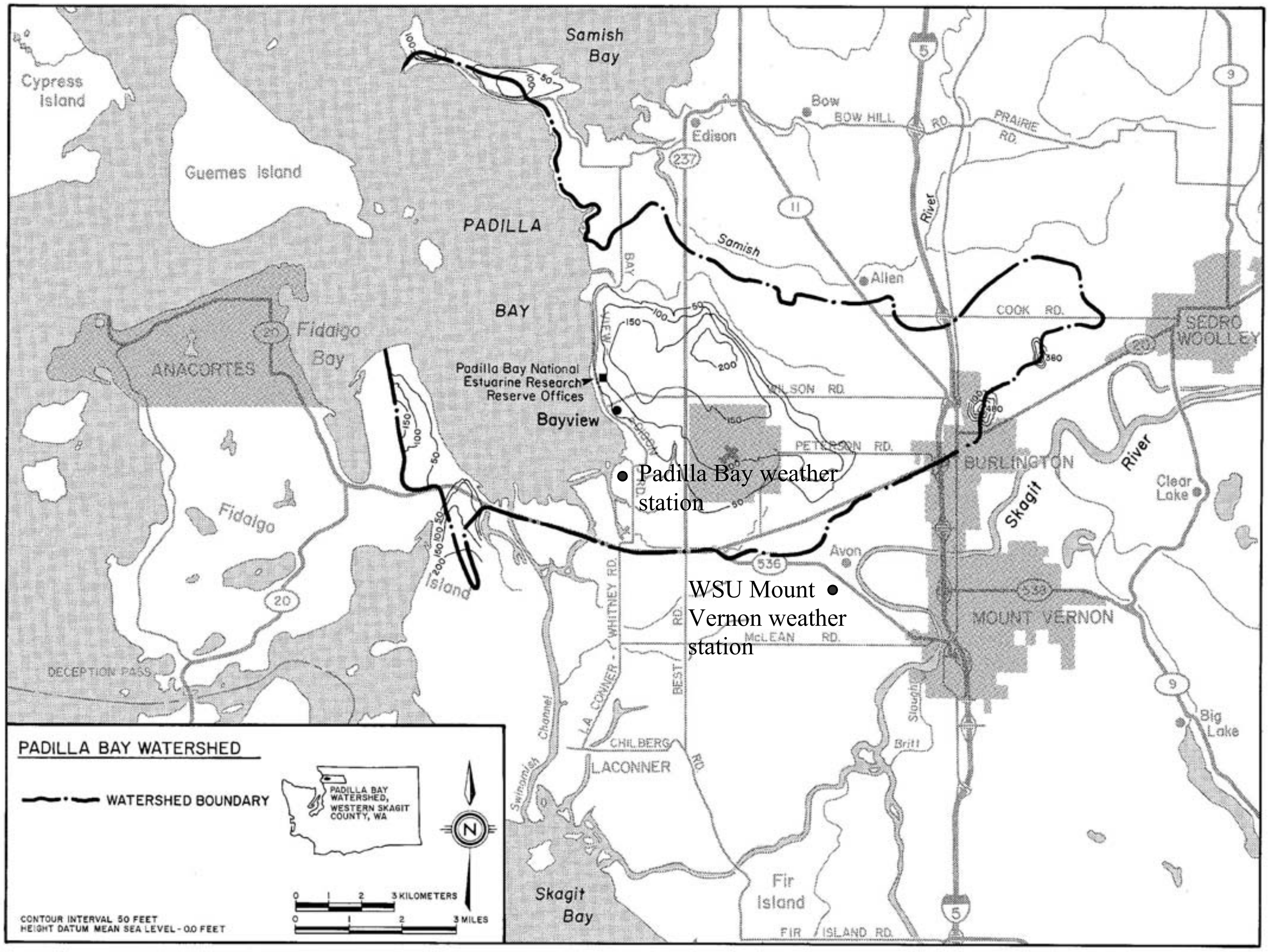


Figure 9. Padilla Bay watershed in relation to weather stations at Anacortes, Mount Vernon, and Sedro Woolley. Fifty foot contours are shown only within the Padilla Bay watershed.

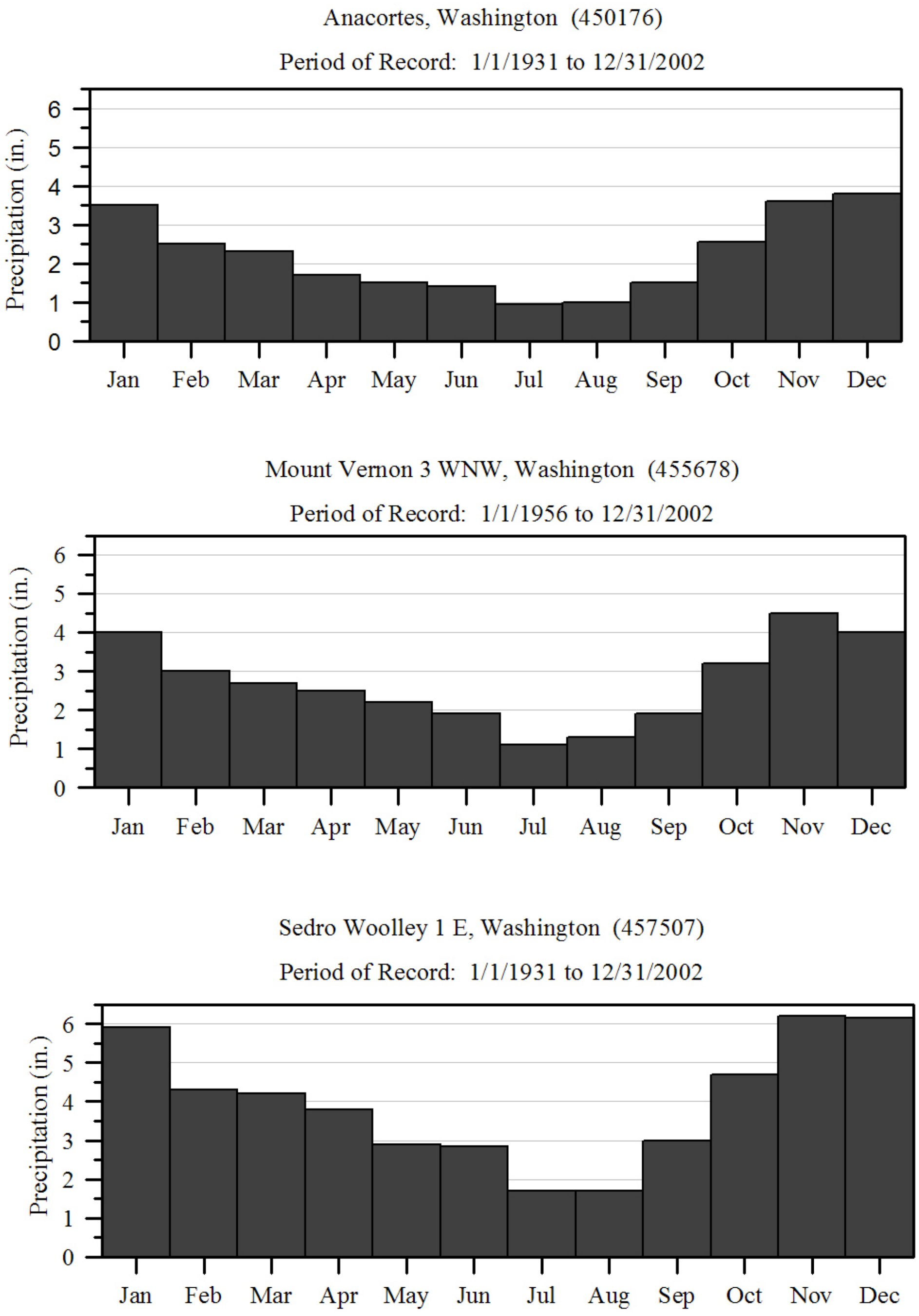


Figure 10. Mean monthly precipitation at Anacortes (directly west of Padilla Bay), Mount Vernon Experiment Station (just south of the Padilla Bay watershed), and Sedro Woolley (just east of the Padilla Bay watershed). Data from NOAA, Western Regional Climate Center.

Seasonally, rainfall is higher during fall and winter months with 75% of the annual average falling from October through April (Fig. 10). June through September are usually dry with very little rain falling during these months. Small coastal streams, such as those draining the Padilla Bay watershed, have very little or no flow by the end of this dry period. Thus, water flowing in and out of the tide gates on each of these sloughs tends to be Padilla Bay water with a salinity of 25 to 30 PSU rather than fresh water flowing out of the stream. During the wet season rainfall is usually light to moderate intensity and continuous over a period of time rather than heavy downpours for brief periods. Thus, storm water runoff and storm water peaks are less pronounced in the Pacific Northwest than in most other parts of the country, and salinity fluctuations in Padilla Bay are not as strongly storm driven as many other estuaries.

WIND CLIMATE

Prevailing winds at Padilla Bay during the wet season are from the south and southwest, similar to the pattern for the rest of the Puget Lowlands (Downing 1983) (Fig. 6). The strongest winds are generally recorded during the wet season from the south to southwest. Occasionally cold continental air masses move south from Canada during the winter resulting in strong easterly outflow winds in Padilla Bay and watershed. During late spring and summer, winds are calmer and usually from a generally southerly direction (Downing 1983). However, wind direction is more variable during late spring and summer with occasional moderate winds from the west or northwest (Fig. 6).

LIGHT

The light received at Padilla Bay has a strong seasonal fluctuation because of the location of Padilla Bay, 48.5 degrees north of the equator. Summer days are long and provide many hours of light for plant growth. In contrast, winter days are short, the sun angle is low, and the sky is often overcast. Very little light reaches the water surface. Total photosynthetically active radiation (400-700 nm) received per day is about five times greater in July than in January when sunny days are compared (Fig. 11). During even the cloudiest day in July, more light reaches the water surface of Padilla Bay than during a completely clear day in January (Fig. 11). This strong seasonal fluctuation in incident light is probably one of the major factors influencing the seasonal pattern of growth of estuarine plants in Padilla Bay.

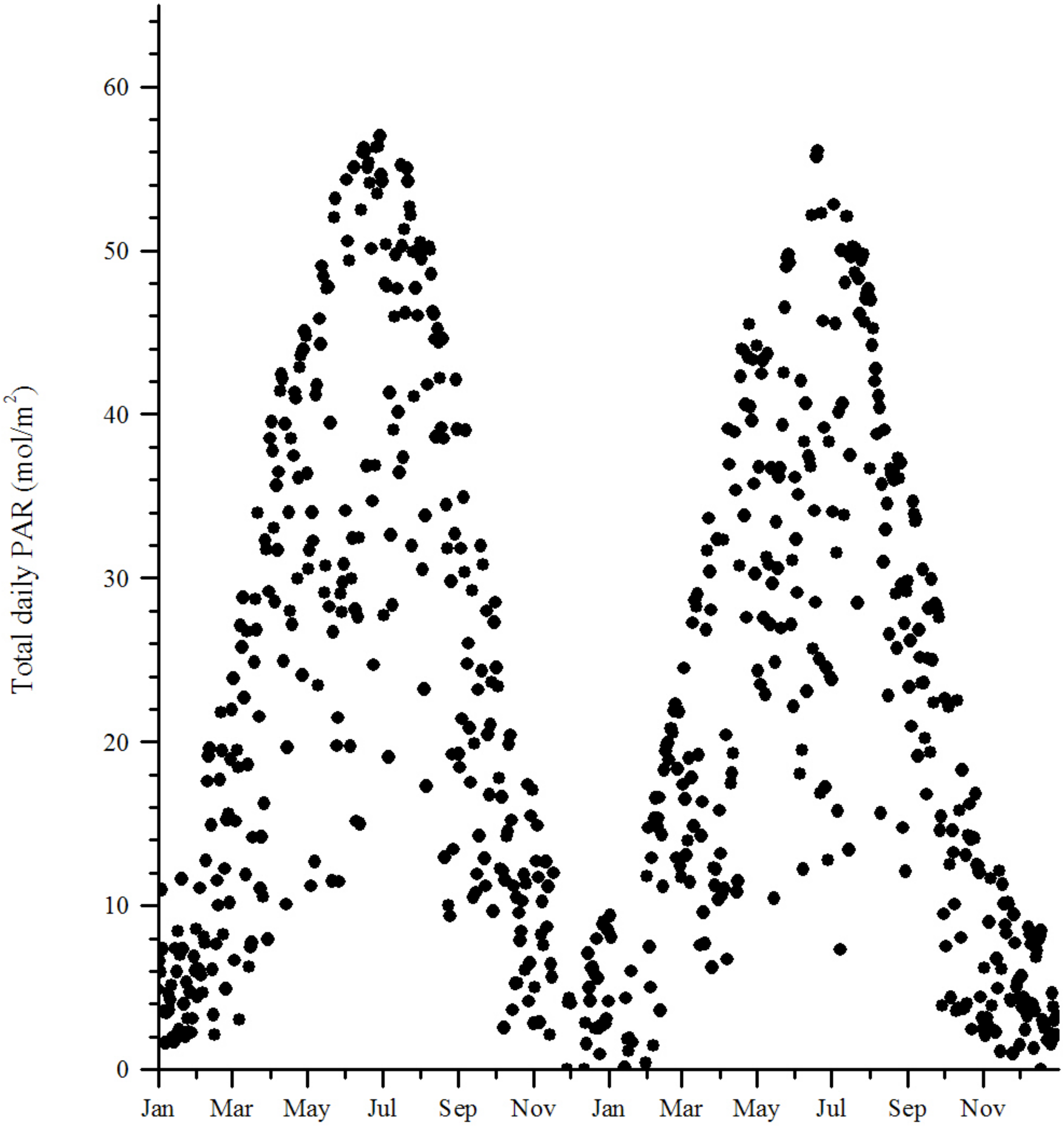


Figure 11. Daily integrated photosynthetically active radiation (mol m-2) at Padilla Bay National Estuarine Research Reserve during 2004 and 2005 (unpublished data Margerum, Burnett, and Bulthuis).

LANDUSE IN THE PADILLA BAY WATERSHED

The Padilla Bay watershed is a small coastal watershed of about 9300 hectares (23,000 acres) that is drained by four sloughs and various drainage ditches (Fig. 12). The two major topographic features are the raised marine terraces of Bay View Ridge, Samish Island, and March Point and the Holocene river deposits of the floodplain that cover about 55% of the watershed. Landuse in the watershed is divided between these two features with agriculture as the predominate use in the floodplain and a mixture of low density housing, light industrial, woods, agriculture, and miscellaneous uses on the raised terraces. Woods and forest cover about 7% of the Padilla Bay watershed, commercial and industrial uses about 7%, residential uses about 3%, and about 15% is vacant or has miscellaneous uses (Table 1).

Agriculture is the major land use in the watershed occurring in about 65% of the area (Table 1.**)** On the floodplain, 85% of the land is in agricultural use. Annual crop farming is the primary agriculture on the floodplain, occurring on 85% of the land, with berries, orchard, and perennial grass making up most of the remaining 15% (Fig. 13, Table 2). The annual crop farming in the Skagit Valley and Padilla Bay watershed is diverse and shifts with economic and agricultural trends. Major crops in the valley over the last decade include potatoes, vegetable seed, peas, cucumbers, corn, grain, rye seed, berries, bulbs, and spinach. After harvest of annual crops in the autumn, cover crops are planted on some of the fields for the winter while other fields remain bare during the wet season (Fig. 14).

The Padilla Bay watershed is undergoing changes in land use during the 1990s and first decade of the new century. Bay View Ridge has been identified as an area for future urban growth and the city of Burlington has expanded into floodplain lands that were used for agriculture until the late 1990s. The general economic and population growth in Skagit County continues to put pressure on agricultural and “undeveloped” acreage in the watershed. Forest cover on Bay View Ridge has declined over the last ten years as land has been cleared for either residential development or light industrial development. The Padilla Bay watershed, like many coastal watersheds in the United States, is changing, with the rate of land use change and development accelerating

Table 1. *Land use/land cover in the Padilla Bay watershed in 1993. (From Padilla Bay/Bay View Watershed Management Committee and Skagit County Dept. of Planning and Community Development 1995).*

Land use/land cover	Hectares	Acres	Percent of total
Forest	123	305	1.3
Rural/Woodlot	1498	3701	16
Parks/Research Reserve	87	215	0.9
Schools	25	63	0.3
Agriculture	4340	10723	47
Rural/Agriculture	1802	4452	19
Residential-Single Family	334	826	3.6
Residential Multi-Family	14	35	0.2
Commercial/Industrial	513	1267	5.5
Lakes/Ponds	11	28	0.1
Vacant/Open Space	515	1271	5.5
Other	44	107	0.5
TOTAL	9306	22993	100

Table 2. *Area of the floodplain portion of Padilla Bay watershed in various types of crops during 1999. (from Bulthuis and Shull, unpublished data).*

Crop Type	Hectares	Acres	Percent of Floodplain in Watershed
Berries	234	577	6
Orchard	86	213	2
Cottonwoods	87	215	2
Nursery	10	25	<1
Perennial Grass	280	691	7
Annual Crops	3448	8521	82
Unknown	57	141	1

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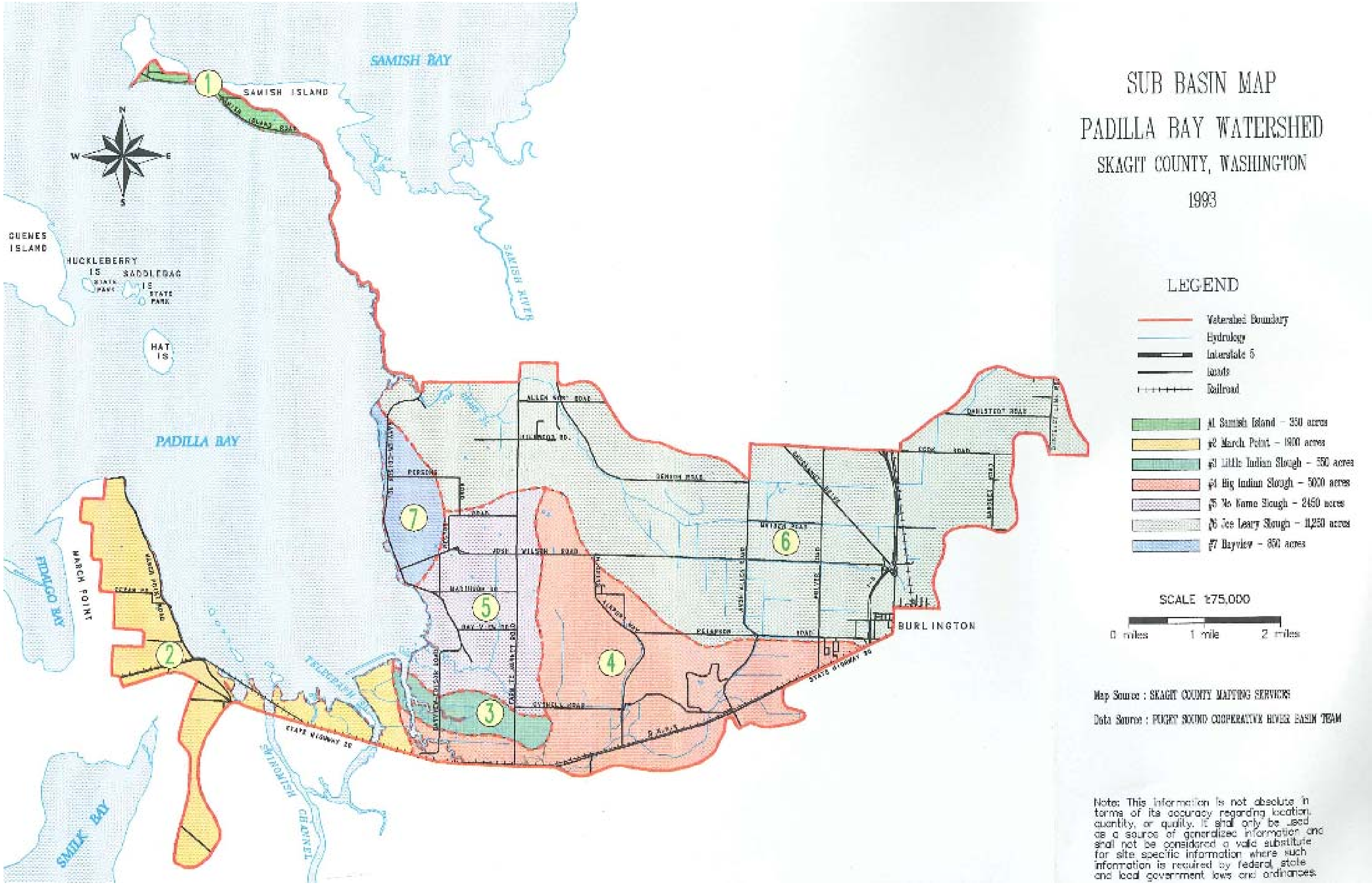


Figure 12. Sub-basins of the Padilla Bay watershed: 1) Samish Island, 2) March Point, 3) Little Indian Slough, 4) Big Indian Slough, 5) No Name Slough, 6) Joe Leary Slough, and 7) Bay View. (From Padilla Bay/Bay View Watershed Management Committee and Skagit County Department of Planning and Community Development 1995)

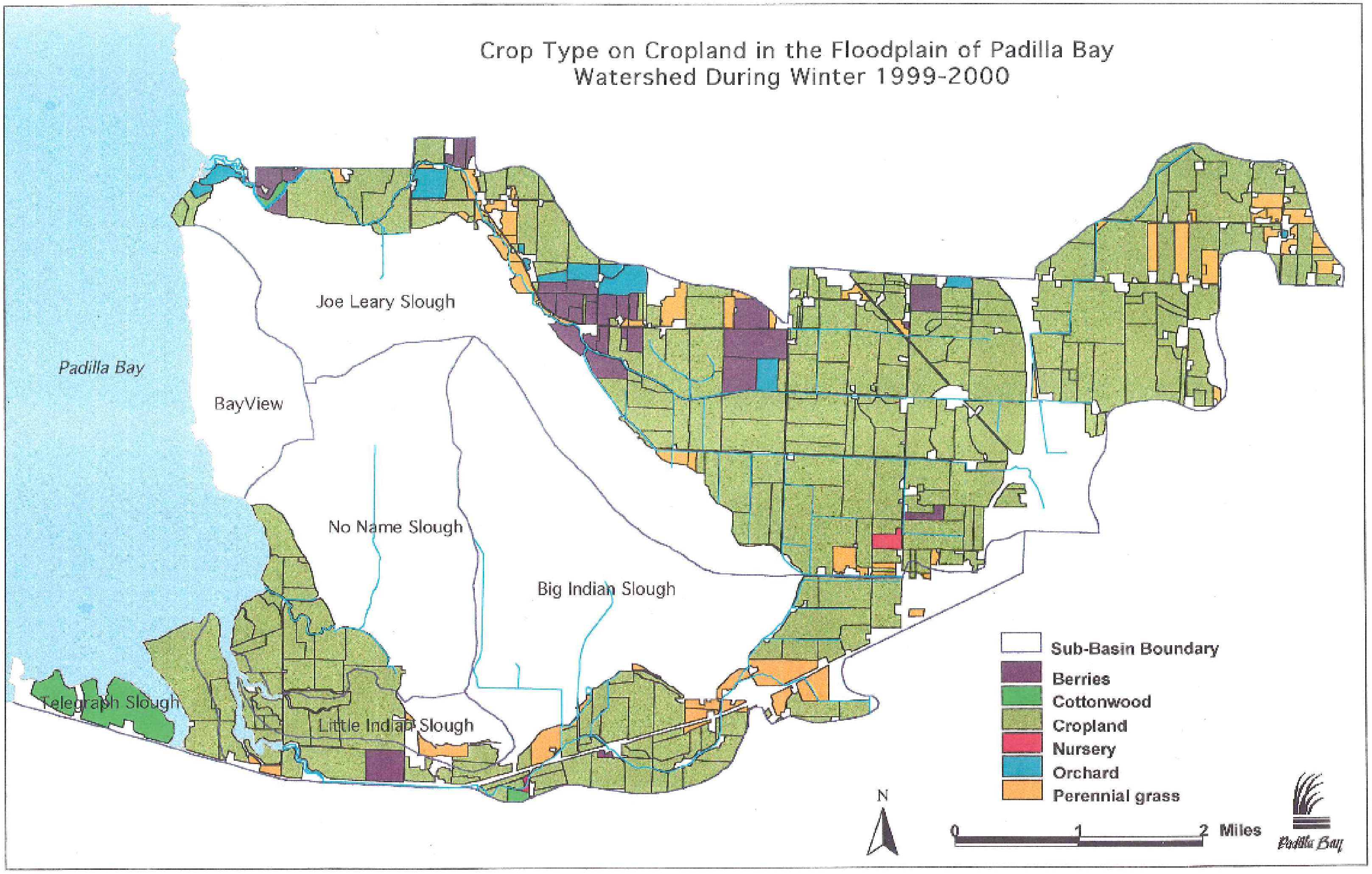


Figure 13. Type of crops planted on agricultural fields in floodplain portion of the Padilla Bay watershed during 1999. “Cropland” were annual crops including potatoes, grains, peas, seed crops, corn, and cucumbers. (From Bulthuis and Shull unpublished data.)

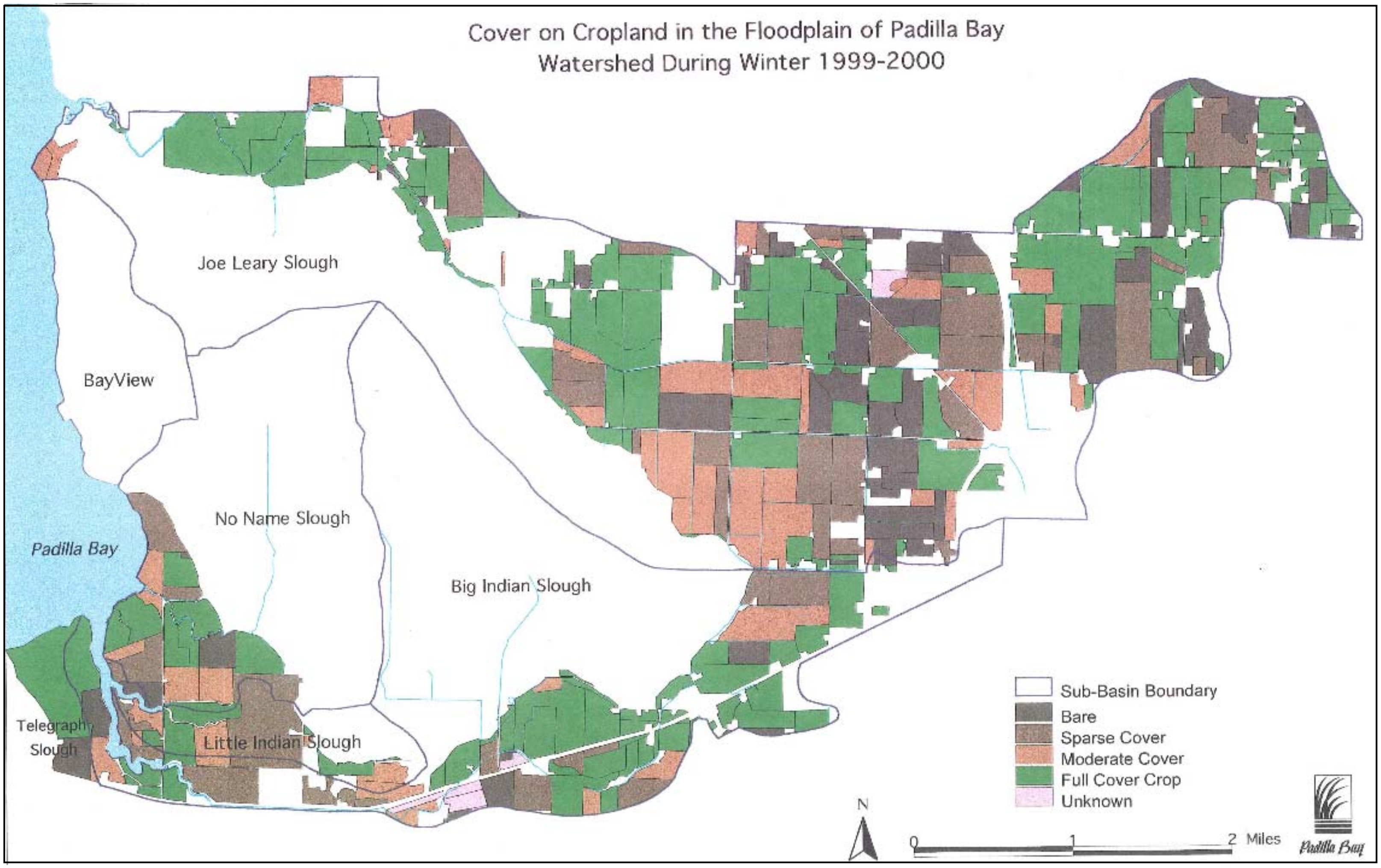


Figure 14. Cover crop during the winter of 1999-2000 on the agricultural fields in the floodplain portion of the Padilla Bay watershed that had annual crops or perennial grass on the fields during the 1999 growing season. (From Bulthuis and Shull unpublished data)

CHAPTER 3

HYDROLOGY, CIRCULATION, AND HYDROCHEMISTRY

PADILLA BAY WATERSHED

Padilla Bay had been one of the distributary mouths of the Skagit and Samish Rivers. However, by the late 1800's when European settlement of the area began, Padilla Bay apparently received water from the Skagit River only during periods of very high flows and floods. With diking of the Skagit River and diking and draining of the Skagit River delta marshes in the late 1800s and early 1900s, Padilla Bay was cut off from direct flow from the Skagit River. The remnant Padilla Bay watershed covers about 9300 hectares (23,000 acres), most of which is Skagit River floodplain less than 6 m (20 feet) above sea level with raised marine terraces of Bay View Ridge, Samish Island, and March Point rising up to 200 feet above the floodplain.

WATERSHED HYDROLOGY

Most of the water from the watershed flows to Padilla Bay via four sloughs that drain parts of Bay View Ridge and the floodplain (Fig. 12). The floodplain parts of the watershed have been modified to facilitate drainage of the former floodplain marshes for agriculture. Thus, parts of the "headwaters" of the sloughs are field-side, dike-side, or road-side ditches that are irregularly maintained and bring drainage water to the sloughs. All of the sloughs in the Padilla Bay watershed have been dammed, diked, and fitted with tide gates (pipes that extend under the dike/dam and have hinged caps on the marine side that allow fresh water to flow out during low tide and prevent salt water flow into the sloughs during high tide). In addition to the four major sloughs, there are numerous small road-side or field-side drainages that flow to Padilla Bay. On the floodplain portion of the watershed, these drainages flow through tide gates or else water is pumped over the dike and into the bay.

Joe Leary Slough is the largest sub-basin in the watershed draining about 4700 ha (11,600 acres) and originating in floodplain fields about 48 km (30 miles) east of Padilla Bay near Sedro Woolley (Fig. 12). The upper portions of this slough are all field and road drainage ditches which flow together under Interstate Highway 5. The main stem is then a straight ditch (sometimes called Maiben Ditch) through the former Olympia Marsh to the base of Bay View Ridge from where the main stem follows a meandering channel (occasionally modified) that collects some water off Bay View Ridge and flows to the dam near the mouth of the slough. A small reservoir has been dredged on the freshwater side of the tide gates and water flows to Padilla Bay during low tide through twelve pipes under the dam which are fitted with tide gates on the marine side.

Big Indian Slough is the second largest sub-basin (2025 hectares, 5,000 acres) and drains a substantial portion of Bay View Ridge including a small airport, light industrial and residential areas, and a golf course before flowing through the agricultural floodplain portion to Padilla Bay through six tide gates as well as pumps that are activated during times of high freshwater. No Name Slough sub-basin (990 hectares, 2,450 acres) is mainly on Bay View Ridge with low intensity agricultural use and rural housing before meandering a short distance through the floodplain to the shore at the Padilla Demonstration Farm. No Name Slough flows through four tide gates as well as two pumps. Little Indian Slough (220 hectares, 550 acres) drains a small industrial area of Bay View Ridge and flows through half a dozen fields and through a tide gate to Padilla Bay. The lower portions (downstream of the tide gates) of Big Indian and Little Indian Sloughs have been diked far enough back to allow some meander of the low tide channel and development (or preservation) of salt marsh along the edges of the channel.

FRESHWATER DISCHARGE TO PADILLA BAY

Freshwater Flow to Padilla Bay. Total freshwater discharge to Padilla Bay is small compared to the tidal prism of Padilla Bay and compared to most estuaries. Entranco and Nelson (1989) estimated a mean annual discharge of about 3 x 10^6 m^3 (27,000 acre feet) to Padilla Bay based on changes in water height and estimated basin volumes. Joe Leary Slough contributes about 53% of the total, Big Indian Slough 19%, and No Name Slough

10% (Fig. 15). During 1995-1996 flow in Joe Leary Slough was measured within one of twelve outflow pipes with an area velocity meter every 5, 10, or 30 minutes (Bulthuis 1996c). Assuming similar volumes flowing through the other eleven pipes, annual flow for 1995-1996 was estimated at 34 x 10^6 m^3 (27,000 acre feet) (Bulthuis 1996c). This estimate is about twice the estimate of Entranco and Nelson (1989). The estimate by Bulthuis (1996c) is probably an over estimate because the 12 outflow pipes in Joe Leary Slough have different heights and slopes and do not pass equal amounts of water (as assumed by Bulthuis 1996c).

The seasonal discharge reflects seasonal rainfall in this small watershed with peak discharge during November through February and little flow to Padilla Bay during July through October. Daily discharge also reflects rainfall. Total daily flow estimated from flow measurements every 5, 10, or 30 minutes in one of the twelve discharge pipes in Joe Leary Slough, indicated up to 500,000 m^3 peak daily flow out of the slough compared to about 100,000 m^3 during April and May when there was little precipitation (Fig. 16). Comparison of rainfall and discharge data indicate that daily rainfall of about 30 mm (1.2 in) will increase flow for 3 to 7 days followed by a slow decline in daily discharge if there is no further rain (Fig. 16).

Because flow to Padilla Bay is restricted by tide gates, there is a strong tidally controlled pattern to the hourly discharge. Flow measurements taken each hour at one of the outflow pipes at Joe Leary Slough during October (dry season) and February (wet season) indicate how flow responds to tidal height (Fig. 17). Water height in the slough on the freshwater side slowly increases until the tide gates open (Fig. 17). Water height falls rapidly as the slough discharges to Padilla Bay and abruptly begins rising again when marine water height equals freshwater height and the tide gate covers shut again (Fig. 17).

The total daily discharge of freshwater to Padilla Bay is small compared to the daily tidal exchange to Padilla Bay. Using the highest daily discharge estimates for Joe Leary Slough (Bulthuis 1996c) of about 500,000 m^3; and doubling this estimate for all of

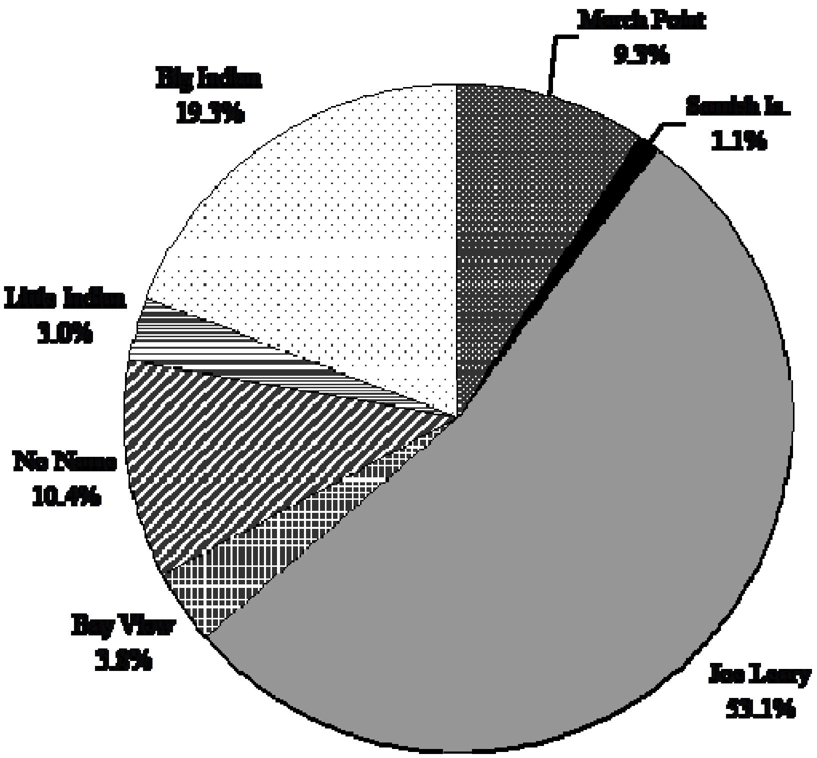


Figure 15. Relative percentage of total runoff from the Padilla Bay watershed in each sub-basin of the watershed. See Figure 12 for location and boundaries of each sub-basin. (From Entranco and Nelson 1989)

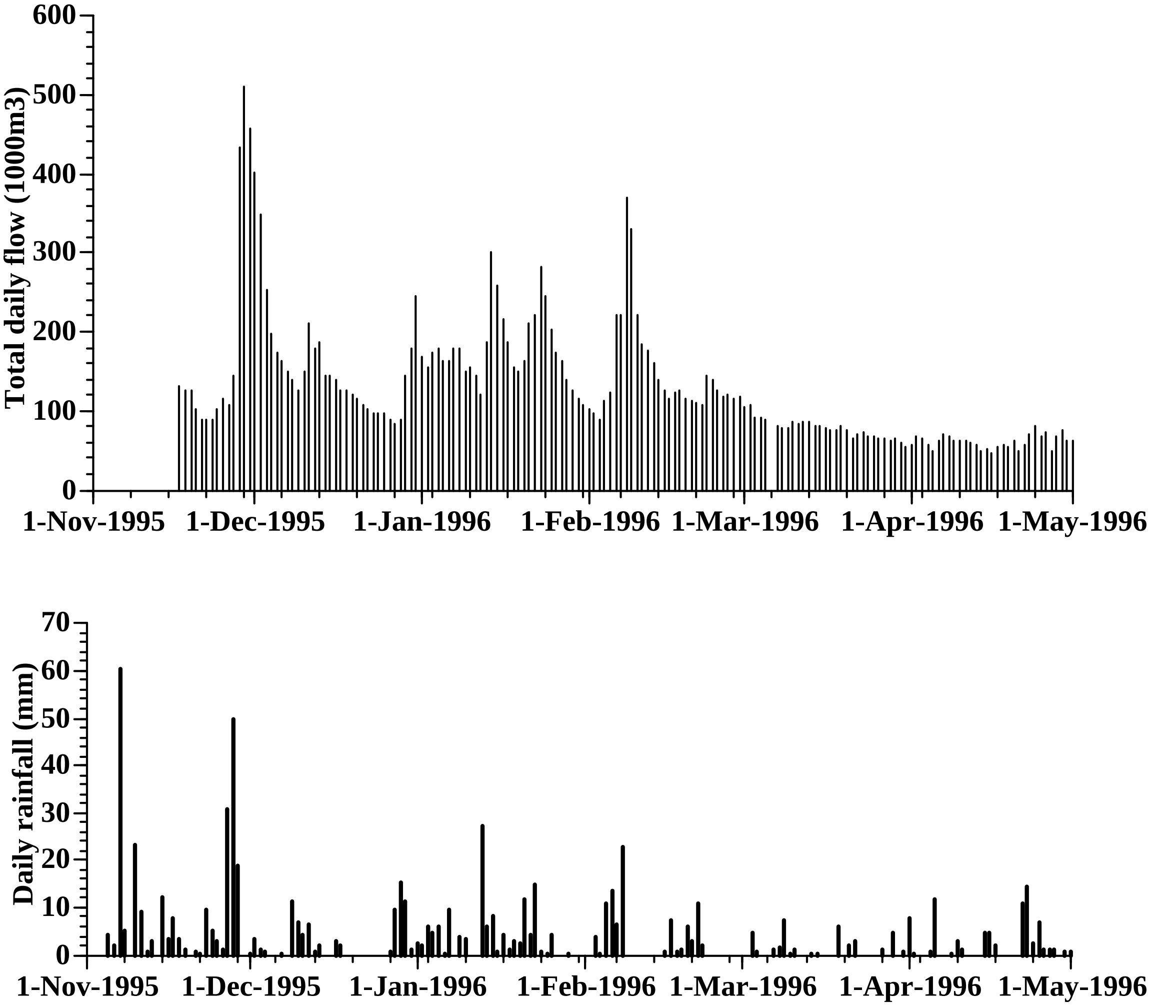


Figure 16. Estimated total flow out of Joe Leary Slough tide gates and daily rainfall recorded at WSU-Mount Vernon Experiment Station from November 1995 through April 1996. Flow in Joe Leary Slough was estimated from flow data collected every 10 or 30 minutes in one of twelve tide gate pipes during the period mid-November 1995 through April 1996. (From Bulthuis 1996c)

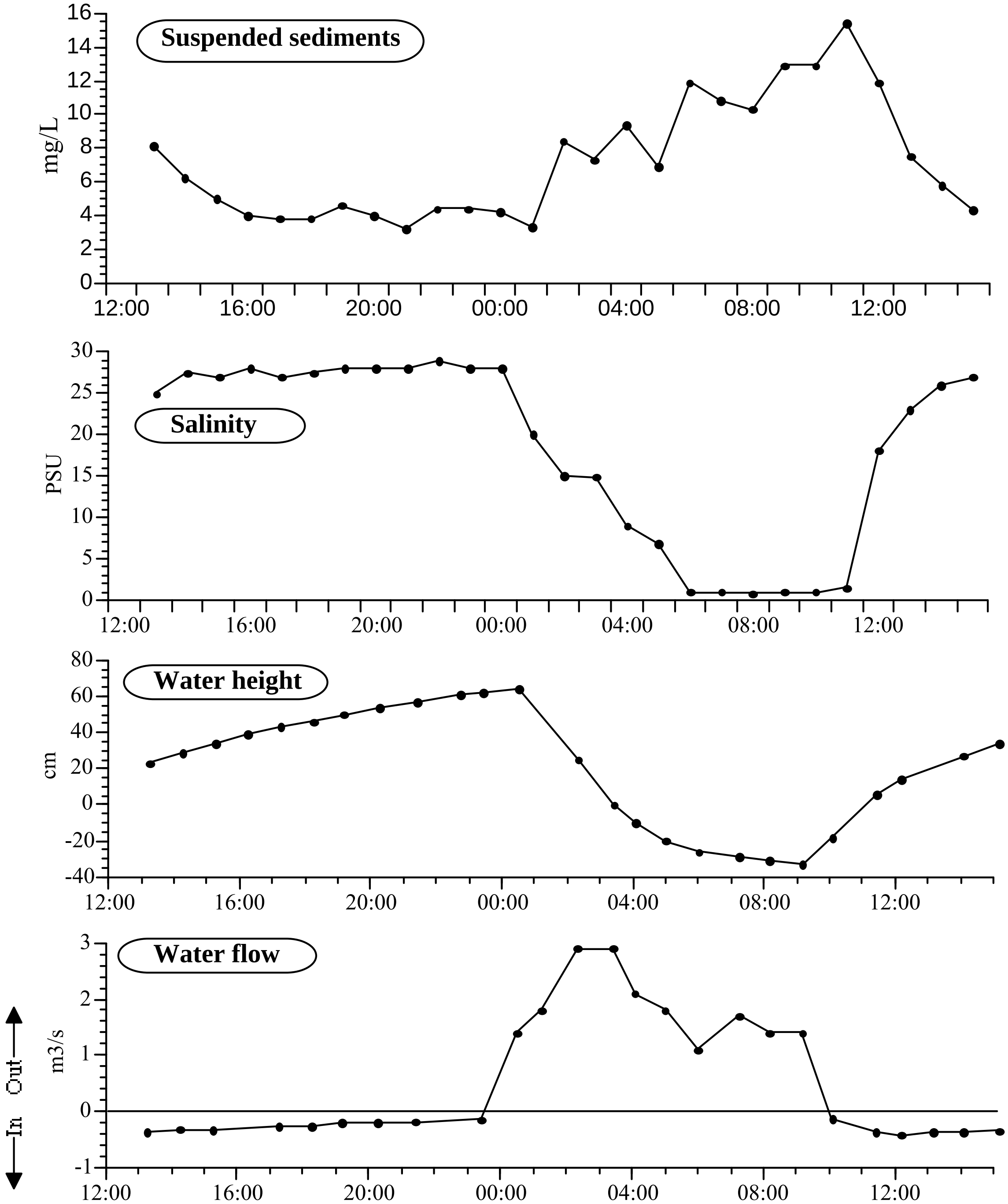


Figure 17. Suspended sediments and salinity (PSU) at mid-water depth on the fresh water side of the tide gates in Joe Leary Slough at hourly intervals on October 11 & 12, 1990. Water height on the fresh water side of the tide gates relative to chart datum. Estimated flow "out" of the slough to Padilla Bay and "in" to the slough from Padilla Bay is shown for one of the twelve tide gate pipes. (From Bulthuis 1996d)

Padilla Bay (because Entranco and Nelson 1989 estimated Joe Leary as about 50% of the total discharge to the bay) yields an estimate of about one million m^3 as a maximum daily discharge to Padilla Bay. Daily tidal exchange during neap tide may be estimated by taking the total area of Padilla Bay (about 6,500 hectares) and assuming a restricted neap range of 2 m. Daily tidal exchange under these conditions is about 130 million m^3 compared to a maximum daily discharge of one million m^3. Thus, maximum daily freshwater discharge is less than 1% of the daily tidal exchange in Padilla Bay.

Freshwater discharge to Padilla Bay is thus characterized by: flow from a small watershed relative to the size of the bay; regulation of almost all flow through tide gates or pumps; a diurnal flow pattern controlled by tides; a seasonal and daily pattern that follows seasonal and daily rainfall; and a maximum daily discharge that is less than 1% of the daily tidal exchange to Padilla Bay. All of these characteristics, but particularly the small amount of freshwater entering Padilla Bay compared to the water exchanged with the Strait of Georgia, have major implications for the water quality in Padilla Bay, for the sources of nutrients for plants in Padilla Bay, and for the threats to water quality in Padilla Bay.

Suspended solids discharge to Padilla Bay. The discharge of suspended solids to Padilla Bay follows the pattern of freshwater discharge. The hourly pattern of concentration of suspended solids at the mouth of the sloughs correlates with tidal height and flow out of the sloughs (Fig. 17). The seasonal pattern of concentration of suspended solids tends to be higher in winter (Fig. 18, Table 3), so that the seasonal differences between wet and dry times of the year are even more pronounced than for water discharge. In addition, day to day fluctuations in the concentration of suspended solids seemed to be mainly the result of rainfall the previous day (Bulthuis 1996c; Fig. 19). Because high concentrations of suspended solids correlated with high discharge in Joe Leary Slough, the greatest input of suspended solids to Padilla Bay during 1995-96 occurred during a few large storm events (Bulthuis 1996c). During a year long study of flow and suspended solids in 1995-96, 40% of the annual total suspended solids flowing from Joe Leary Slough to Padilla Bay came during one week when an estimated 575

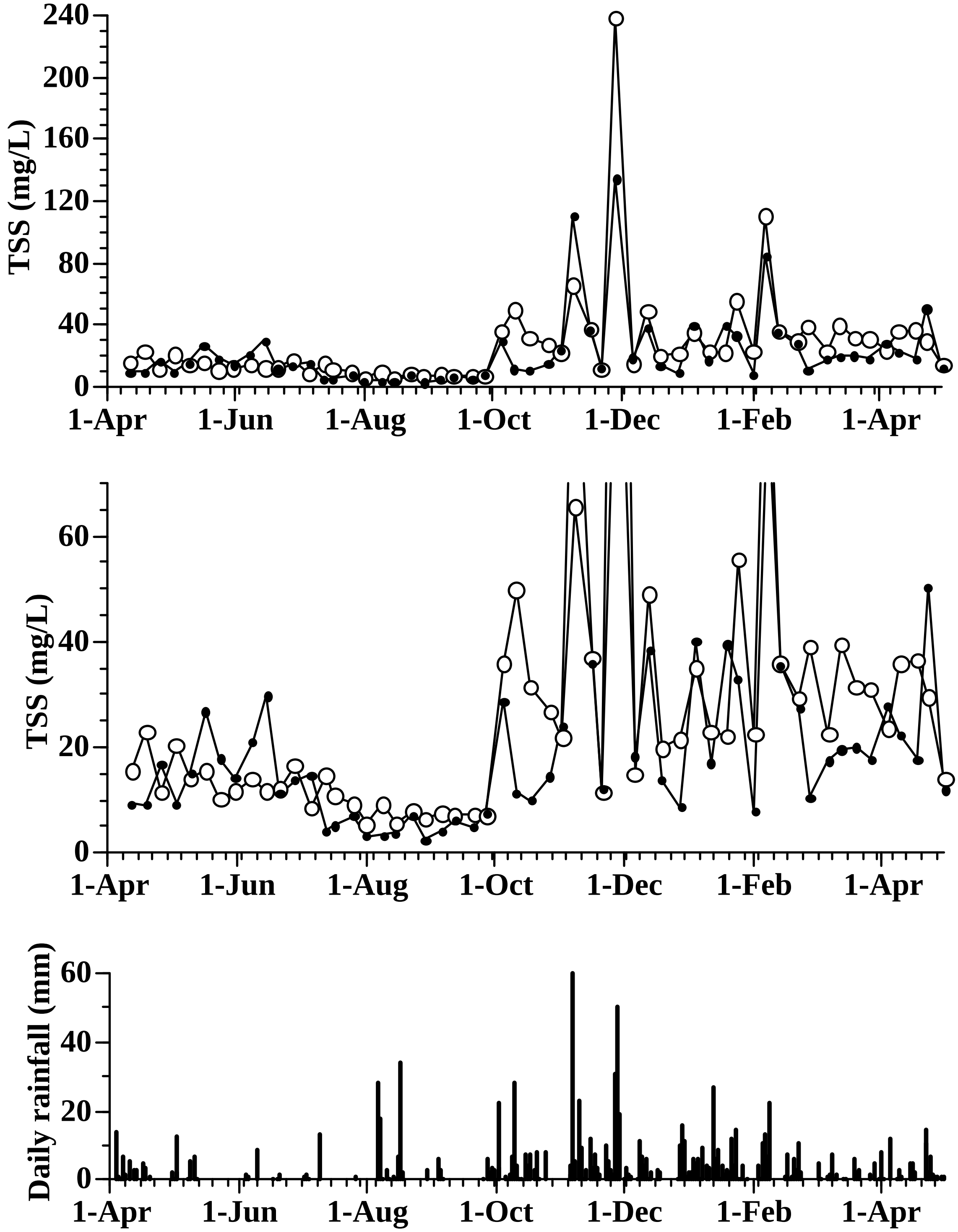


Figure 18. Total suspended solids (TSS, on two scales) in Joe Leary Slough (open circles) and No Name Slough (closed dots) measured weekly at the mouths of the sloughs during ebbing tide. Rainfall measured at WSU-Mount Vernon Experiment Station from April 1995 through April 1996. (From Bulthuis 1996c)

Table 3. *Concentrations of total suspended solids at the mouths of Joe Leary, Big Indian and No Name Sloughs in various studies and seasons of the year. The means are grand means for all of the samples collected during the stated period in the particular study (mg/L).*

Year/Season	Joe Leary mean	Big Indian mean	No Name mean	Reference
1990-91 Oct-May	55.0			Bulthuis 1996a
1991 Jun-Sept	17.4			Bulthuis 1996a
1995-96 Jun-Sept	9.5		8.7	Bulthuis 1996b
1995-96 Oct-May	40.6		31.0	Bulthuis 1996b
1998-1999	50.3	23.6	23.4	Bulthuis 1996b
1999-2000 Oct-May	47.6	18.7	29.7	Bulthuis 1996b

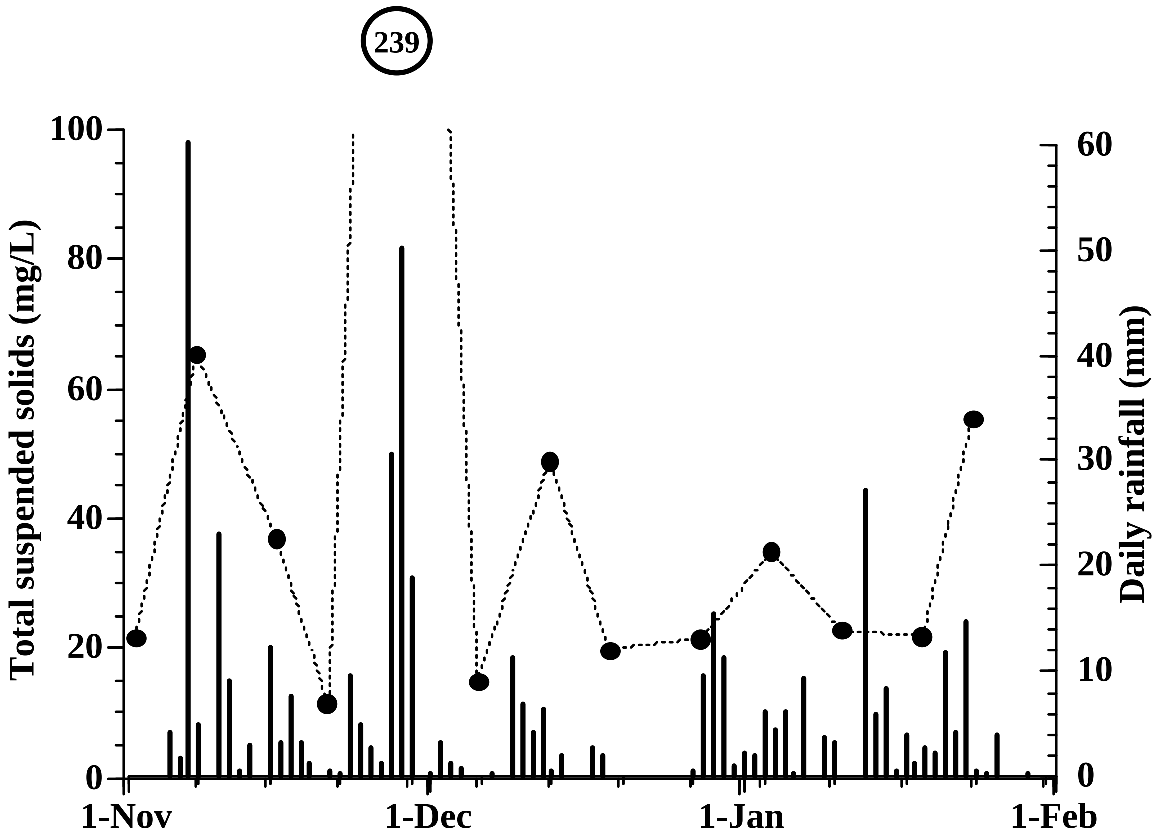


Figure 19. Total suspended solids in Joe Leary Slough sampled one day per week (dots and dashed line) and daily rainfall at WSU-Mount Vernon Experiment Station (histogram) during November 1995 through January 1996. (From Bulthuis 1996c)

metric tons of sediment flowed into Padilla Bay (Bulthuis 1996c). The total estimated annual load to Padilla Bay from Joe Leary Slough was about 1,400 metric tons during 1995-96 (Bulthuis 1996c).

Winter cover crops are an important factor in determining the annual load of suspended sediments that flow to Padilla Bay. Several inter-related circumstances contribute to this situation: rainfall and water discharge to the bay are higher during winter, the concentration of suspended solids in the slough are higher during winter, annual crop farming is the major agricultural use in the watershed, and the presence of a cover crop is an important factor in determining the concentration of suspended solids flowing off of annual crop fields. In one study, Bulthuis (1996d) reported concentrations of suspended solids 3 to 10 times higher in fields without cover crop compared to those with cover crop. In another study conducted on the Padilla Demonstration Farm and three other farms in the Skagit floodplain, cover crop decreased suspended solids by 40 % and 35 % (Bulthuis 2001, Fig. 20).

The concentration of total suspended solids differs in the various sloughs in the Padilla Bay watershed. Joe Leary Slough has consistently had higher concentrations of suspended solids than the other Padilla Bay sloughs in a variety of studies (Table 3). Bulthuis (1993b) compared available data for Joe Leary Slough and found high concentrations of suspended solids compared to other streams and sloughs in western Washington.

Discharge of nutrients to Padilla Bay. There are few data on nutrients in the freshwater sloughs of the Padilla Bay watershed and few data on which to base estimates of the nutrient load to Padilla Bay. Cassidy and McKeen (1986) reported concentrations at the mouths of Big Indian and Joe Leary Sloughs, but samples were taken on the marine side of the tide gates, and concentrations were for mixtures of water from both the sloughs and Padilla Bay. Extracting only the samples with salinity of 5 PSU or less from Cassidy and McKeen's study, Bulthuis (1993b) reported dissolved inorganic nitrogen concentrations (nitrate plus nitrite plus ammonium) from < 1 mg N/L to 5 mg N/L at the mouths of these two sloughs. Total phosphorus ranged from 0.03 to 71.0 mg P/L. In the only other study

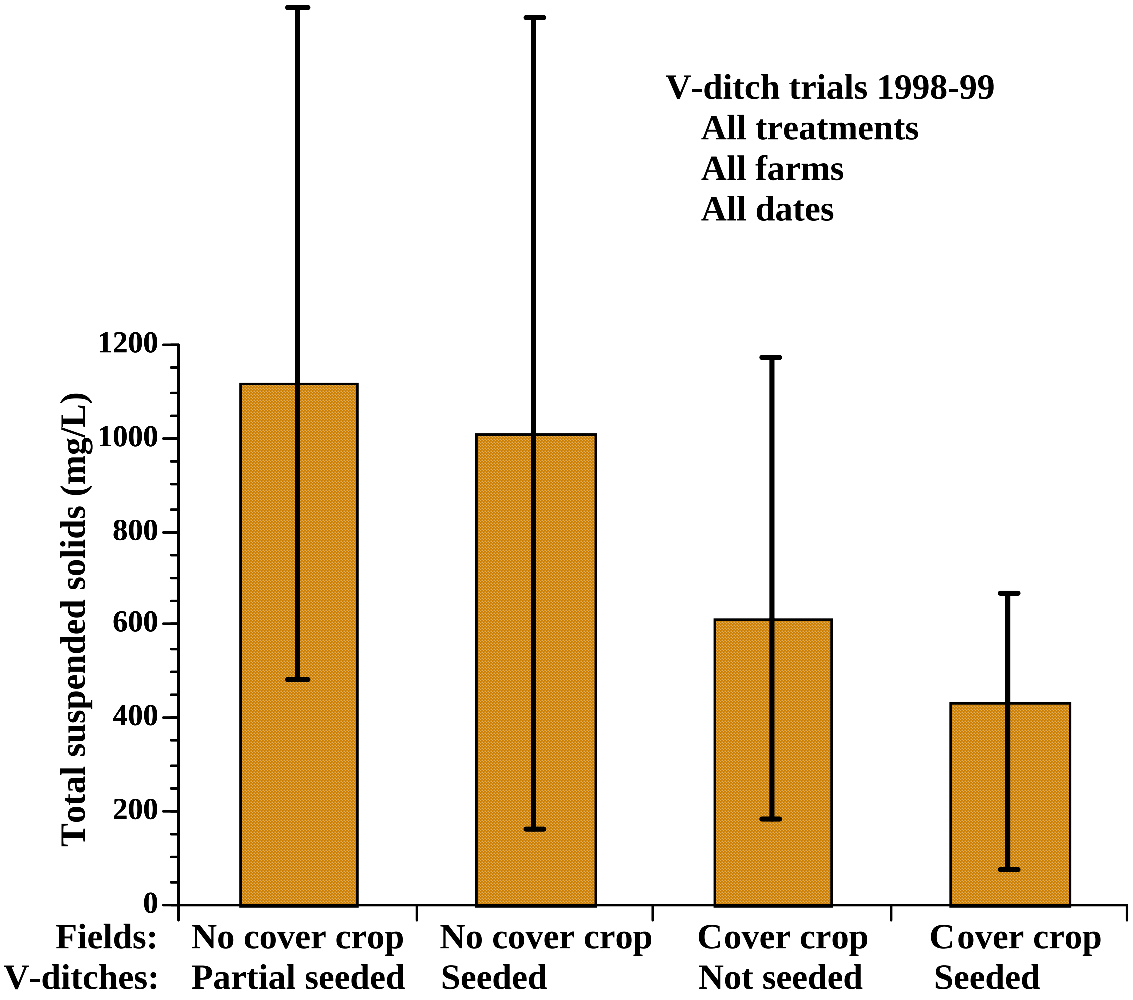


Figure 20. Mean and range of total suspended solids (mg l^{-1})in v-ditches from four types of trials (cover crop or no cover crop on the field; wheat seed planted in the v-ditch or not planted in the v-ditch) on three farms sampled during four rain events during December, January, and February 1998-99. (From Bulthuis 2001)

of nutrients in the watershed, Bulthuis (1996c) reported seasonal differences in dissolved inorganic nutrients: wet season concentrations of 1-5 mg N/L of dissolved inorganic nitrogen and 0.02 – 0.15 mg P/L of dissolved phosphate in weekly samples taken during flow out of the sloughs; and dry season concentrations of 0.04 – 1 mg N/L of dissolved inorganic nitrogen and 0.03 – 0.3 mg P/L of dissolved phosphate (Fig. 21). (The high dissolved phosphate concentrations in No Name Slough during the dry season reflect Padilla Bay water seeping into the slough. Salinities were consistently greater than 20 PSU during this time.) For Joe Leary Slough, where flow was monitored, estimated annual loads to Padilla Bay were 74 metric tons of N of dissolved inorganic nitrogen and 1.9 metric tons of P of dissolved orthophosphate (Bulthuis 1996c). A doubling of those amounts (Joe Leary Slough flow is about half of the watershed total) provides a rough estimate of the discharge of dissolved inorganic nitrogen and phosphorus discharged annually to Padilla Bay. There are no data on which to estimate total nitrogen or phosphorus loads (including particulate nitrogen and phosphorus and dissolved organic nitrogen and phosphorus.) However, because of the short residence time of any freshwater discharged to Padilla Bay, the dissolved inorganic nitrogen and phosphorus that are readily available for uptake by plants are probably the most biologically important fractions. In summary, dissolved inorganic nitrogen and phosphorus were discharged primarily during the wet season, reflecting the pattern of freshwater flow to the bay.

Discharge of pesticides and contaminants to Padilla Bay. The freshwater that is discharged to Padilla Bay may also bring pesticides and contaminants from the watershed into Padilla Bay. The most likely sources of persistent contaminants from the Padilla Bay watershed are from: 1) agricultural pesticides because of the predominance of agricultural land use in the watershed; 2) industrial waste from the small industrial sites on Big and Little Indian Sloughs; and 3) landfill leachate. There have been few measurements of contaminants flowing into Padilla Bay.

Agricultural herbicides were the focus of a study by Mayer (Mayer 1989; Mayer and Elkins 1990) in which the concentrations of herbicides used in the Padilla Bay watershed

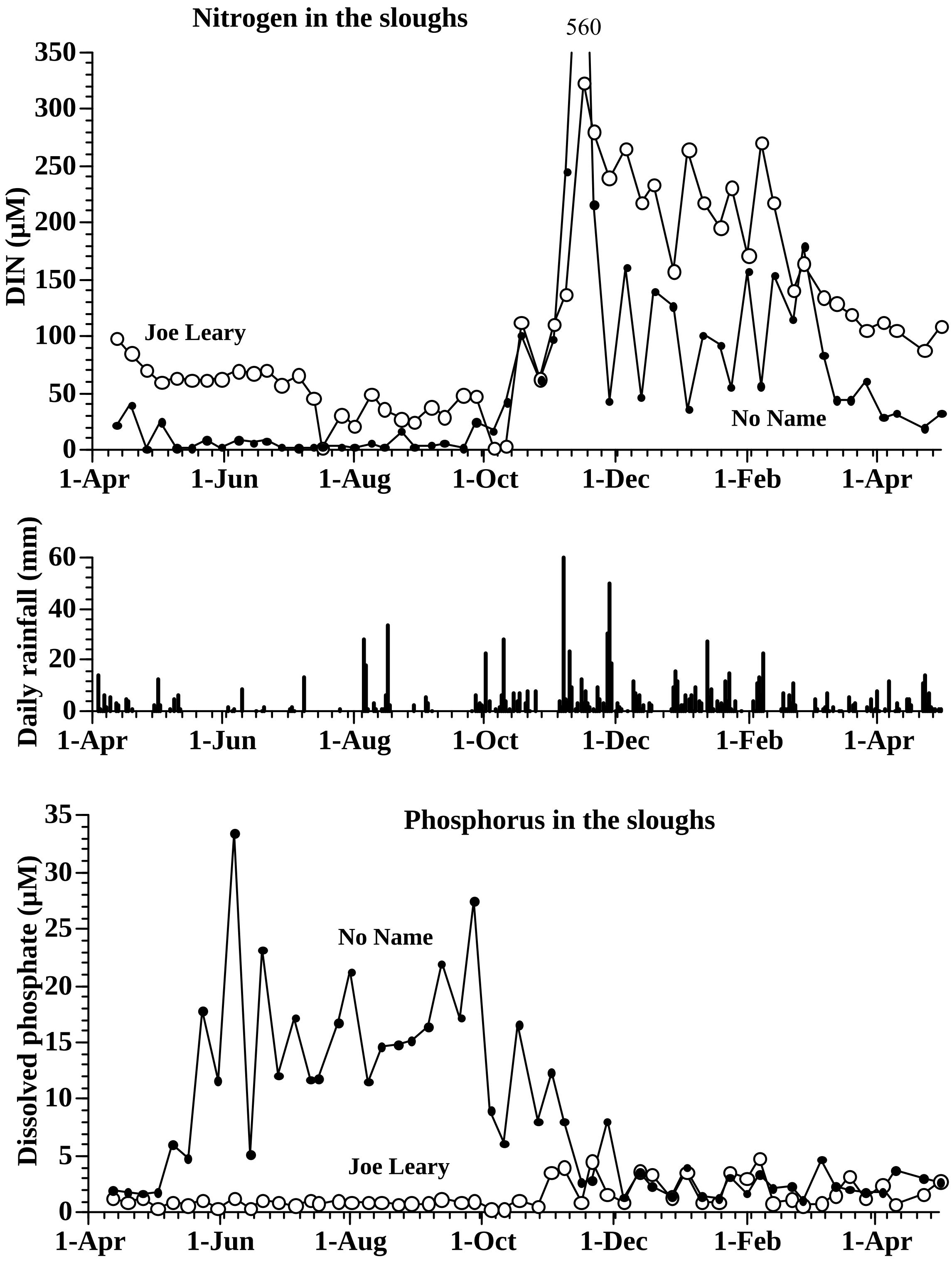


Figure 21. Dissolved inorganic nitrogen (DIN: nitrate, nitrite, and ammonium) and dissolved phosphate in samples taken weekly at the mouths of Joe Leary Slough (open circles) and No Name Slough (closed dots) from April 1995 through April 1996 and daily rainfall at WSU Mt Vernon Experiment Station. (From Bulthuis 1996c)

during spring and summer of 1987 and 1988 were measured in slough water and sediments and in Padilla Bay water and sediments following rain events in the watershed. No herbicides were detected prior to rainfall and only two (Dicamba and 2, 4-D) of 14 herbicides were detected in water or sediments after rainfall (Mayer 1989). The concentrations that were detected were below the concentrations that were considered ecologically significant. Bulthuis and Anderson (1996) reported no detectable concentrations for 19 of 21 organic pesticides in sediments from No Name Slough and adjacent fields and concentrations just above the detection limit in one of five samples for the other two pesticides. Data from these three studies are limited in area sampled and compounds analyzed, but all three indicate very little discharge of pesticides from agricultural sources to Padilla Bay.

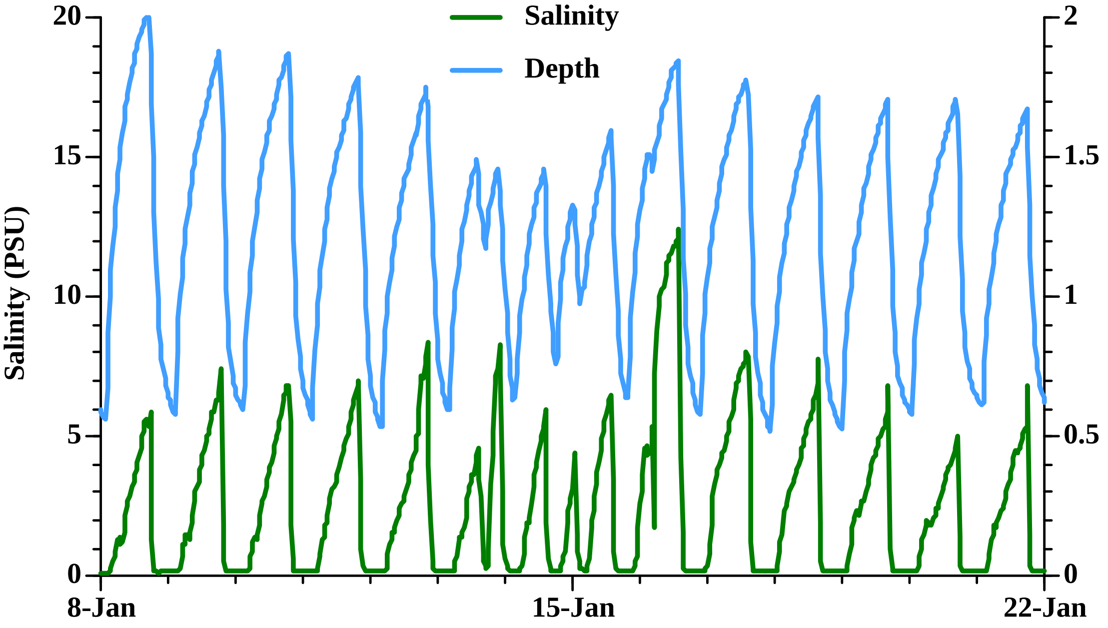
Industrial land use in the watershed covers a very limited area and contaminants from such sources are considered unlikely to be discharged to Padilla Bay via the sloughs. A landfill was operated by Skagit County on Bay View Ridge above Joe Leary Slough. Limited sampling of groundwater, slough water, and slough sediments indicated very little movement of contaminants downstream in Joe Leary Slough (unpublished data from Milat and Pfaff 1990a, 1990b; Noone-Fisher 1991; Columbia Analytical Services 1992).

The freshwater that is discharged to Padilla Bay may also bring bacterial contamination from the watershed into Padilla Bay. Bacterial contamination may restrict recreational collection of shellfish in Padilla Bay. Total and fecal coliform concentrations measured at the mouths of the sloughs indicate possible discharge to Padilla Bay. In a summary of several small studies of fecal coliforms, Bulthuis (1993b) reported that the geometric mean of fecal coliforms at the mouths of Joe Leary, Big Indian, and No Name Sloughs were all above the Washington State Standard for Class A water of 100 colonies/100 ml. In a report covering five years of citizen monitoring, Henry (2003) reported concentrations below this standard at the mouths of No Name and Joe Leary Sloughs each year with the exception of one year (2000) at Joe Leary Slough. Sampling by the Samish Tribe off Bay View State Park in Padilla Bay indicated occasional high concentrations near storm water outfalls from Bay View (unpublished data presented to the Bay View Shellfish Taskforce 2002). Because of these data, Washington Department of Health declared the shellfish in the vicinity to be unsafe for human consumption. These few studies indicate that freshwater discharge from sloughs and from stormwater outfalls is bringing sufficient bacterial contamination into Padilla Bay, particularly to the nearshore areas, to impact the use of shellfish for human consumption.

Summary of Freshwater Discharge to Padilla Bay. Total freshwater flow to Padilla Bay is very small relative to the daily tidal prism. Even the highest daily flows following heavy rain in the watershed are less than 1% of the minimum daily tidal prism. Substances that remain dissolved or in suspension are likely to have a short residence time in Padilla Bay. Freshwater flow to Padilla Bay is regulated by tide gates, is strongly seasonal with high flows during the wet season (November to March), and fluctuates daily with rainfall. Suspended solids concentrations to Padilla Bay are high relative to other freshwater streams in Western Washington, higher in winter than summer, higher following rainfall, and higher draining fields without a winter cover crop. Inorganic nitrogen and phosphorus concentrations were also higher in winter and contribute only low amounts of nutrients to Padilla Bay during the summer growing season. The limited number of studies on freshwater discharge of contaminants indicate little evidence of pesticides or persistent compounds, but sufficient volumes of bacterial contaminants to degrade nearshore areas for collection of shellfish for human consumption.

WATER QUALITY OF SLOUGHS IN THE PADILLA BAY WATERSHED

The freshwater in the sloughs of the Padilla Bay watershed are generally sharply divided from Padilla Bay waters by the dams and tide gates that regulate flow at the mouths of the sloughs. The tide gates do not always shut completely and salt water from the bay sometimes leaks through the tide gates as well as seeping and through the dams or dikes and into the sloughs. The bottom waters of the pool on the “freshwater” side of the dam on Joe Leary Slough indicates daily incursions of salt water during both the dry season and wet season (Fig. 22). In Joe Leary Slough these salinity intrusions are transient (flushed out each day) and have not been detected upstream of the Bay View-Edison Road bridge (200 m upstream of the tide gates). In No Name Slough, the seepage



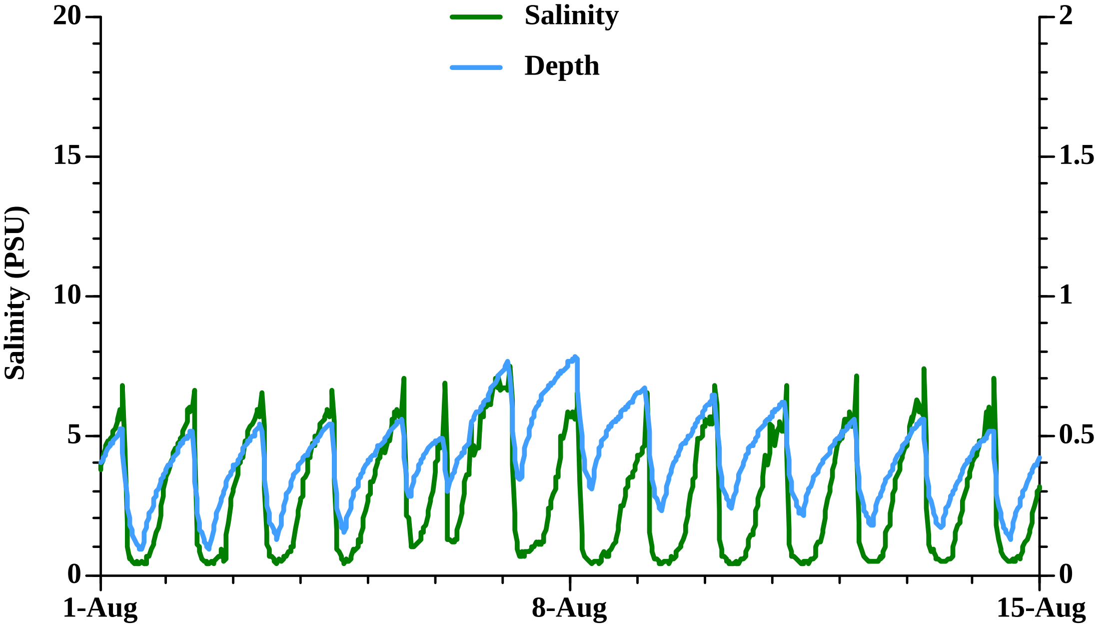


Figure 22. Salinity (PSU) and depth (m) in Joe Leary Slough on the “freshwater” side of the tide gates during two weeks in January (wet season) and in August (dry season) during 2004. Measurements were made every 30 minutes with a multiparameter sonde. (From Cottrell, Margerum, and Bulthuis unpublished data)

through tide gates and dikes was enough to keep water in the lower portion of the slough the same salinity as Padilla Bay during the dry season (Fig. 23).

Temperature of sloughs in the watershed. The sloughs of the Padilla Bay watershed generally flow through agricultural fields without any streamside vegetation. Temperature, therefore, tends to fluctuate daily and seasonally with daily maxima above 18ºC (64ºF), the Washington State water quality standard for Class A waters (Bulthuis 1993b, 1996c, 1996d, Weinman et al. unpublished data). Dugger (2000) reported temperatures suitable for eggs and juvenile rearing of Coho salmon in main stem of No Name Slough on Bay View Ridge, but in the floodplain portion of No Name Slough and in agricultural ditches the temperatures were too high for juvenile rearing of Coho salmon.

Dissolved oxygen in sloughs of the watershed. Dissolved oxygen in the water is important for many aquatic biota. Washington State water quality criteria for Class A waters state that dissolved oxygen shall exceed 8 mg/L. This standard was rarely met in Cassidy and McKeen’s study in 1985-86,and rarely met in two other studies that sampled dissolved oxygen May through August (Bulthuis 1993b). At the mouth of Joe Leary Slough, the dissolved oxygen in the bottom waters dropped to zero in early October of 1995 and stayed anoxic for most of the month (Bulthuis 1996c). A similar drop in dissolved oxygen was recorded the following year, but not in subsequent years (Bulthuis, unpublished data).

Turbidity in sloughs of the watershed. Suspended solids and turbidity in the sloughs of the Padilla Bay watershed are high and higher than most other small freshwater sloughs or streams in western Washington (Bulthuis 1993b). Turbidity correlated well with total suspended solids, but the regression equations were different for No Name and Joe Leary Sloughs, presumably because of different sediment characteristics in the two sloughs (cf Figs. 5 and 12). Joe Leary Slough drains primarily Skagit River floodplain soils and No Name Slough drains the raised marine terrace of Bay View Ridge that is composed of glacial outwash. (Bulthuis 1996c).

Fecal coliform bacteria in sloughs of the watershed. Fecal coliform colonies are a measure of the bacteria in the water which may be associated with disease causing bacteria. Aliquots of water are tested for the number of "colony forming units" (CFU) in the water. CFU may be measured with direct counts of colonies growing on membrane filters after aliquots are filtered through a membrance filter and the filters incubated at the appropriate temperature; or CFU may be estimated by the amount of gas produced in tubes incubated at the appropriate temperature (American Public Health Association et al. 1995). Data from the two methods cannot be compared directly. There have been a few studies of fecal coliforms in sloughs of Padilla Bay watershed, and both methods have been used.

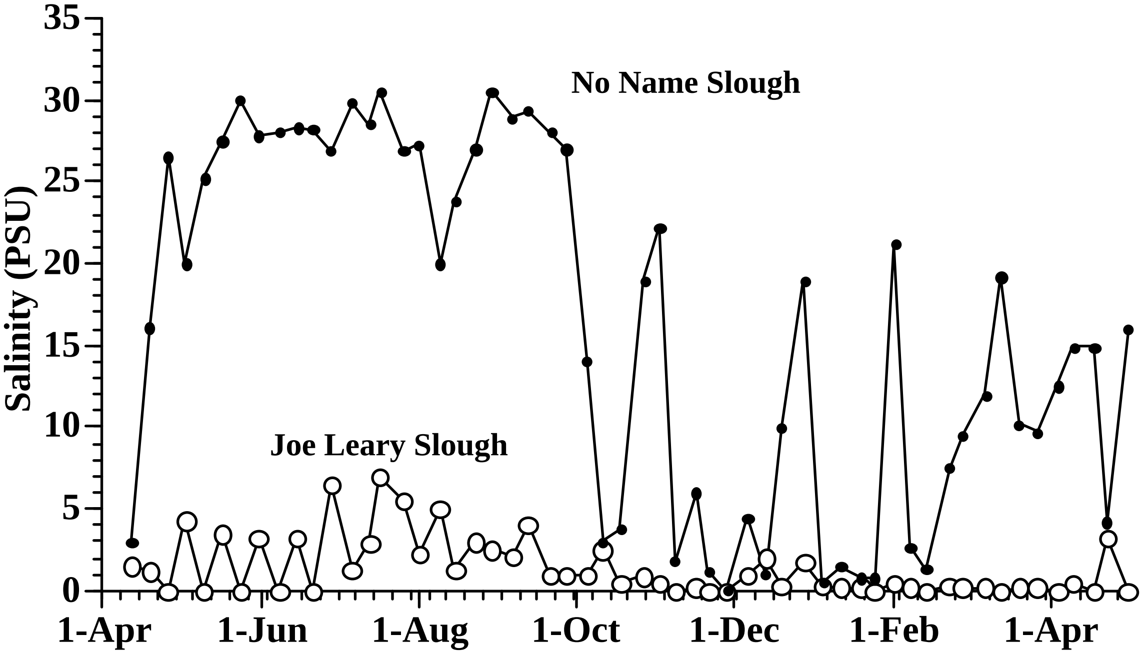


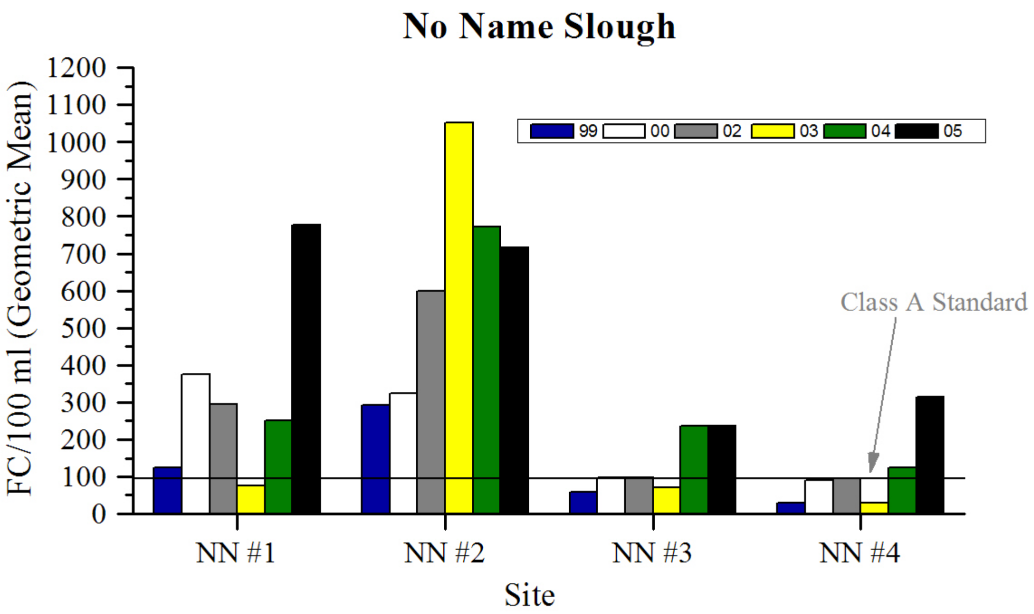
Figure 23. Salinity in Joe Leary Slough (open circles) and No Name Slough (closed dots) from April 1995 through April 1996. Samples were taken weekly near the time of low tide when flow out of the tide gates would be expected to be near the daily maximum during daylight hours. (From Bulthuis 1996c)

Bulthuis (1993b) summarized data from two reports and two unpublished investigations: High numbers of fecal coliforms were reported in Joe Leary, Little Indian, Big Indian, and No Name Sloughs with geometric means above 100 CFU (part of the Washington State standard for Class A waters) in all sloughs except Little Indian Slough.

Henry (2005) reported on seven years of sampling by citizen volunteers in Joe Leary and No Name Sloughs at four sites in each slough (Figs. 24 and 25). The concentration of fecal coliforms in Joe Leary Slough generally declined over the five years although the geometric mean for each year (September through May) was above the Class A standard at the two uppermost Joe Leary sites most years (Fig. 24). No Name Slough had consistently high means. The fecal coliforms in Joe Leary and No Name Sloughs were consistently higher than upper and lower Samish River and upper and lower Nookachamps Creek where citizen volunteers conducted similar surveys (Henry 2005). The apparent sources of fecal coliforms (based on land use in the vicinity of stations with high counts) are runoff from dairy farms in the Joe Leary Slough watershed and from failing septic systems in the No Name Slough watershed.

In summary, the few studies of fecal coliforms in the watershed indicate contamination of the sloughs from a variety of sources, so that water quality regularly does not meet the Washington State standards for Class A waters.

Fish in sloughs of the watershed. Water quality in the sloughs of the Padilla Bay watershed is generally poor and the presence, survival, and growth of fish in these waters is not known. There are no completed studies on fish in the sloughs of the watershed. However, Three-spine Sticklebacks have been seen regularly in both Joe Leary Slough (at tide gates) and in No Name Slough. Henry (1999) reported a “fish kill” of Sticklebacks at the mouth of Joe Leary Slough, probably in association with a loss of dissolved oxygen from the water (anoxia). In No Name Slough and Big Indian Slough,



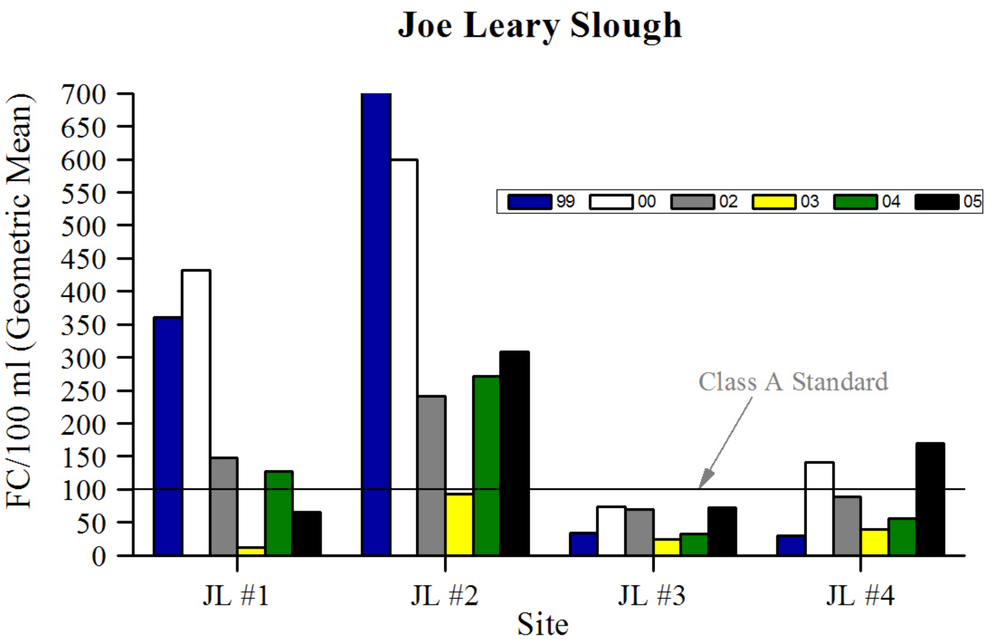


Figure 24. Geometric mean of number of fecal coliform bacteria (fecal coliforms/100 ml) in water samples collected during October through May at four sites each in No Name Slough and Joe Leary Slough by Skagit County Stream Teams from 1999 to 2005. Note different scales in the two charts. See Fig. 25 for locations of sample sites. (From Henry 2005.)

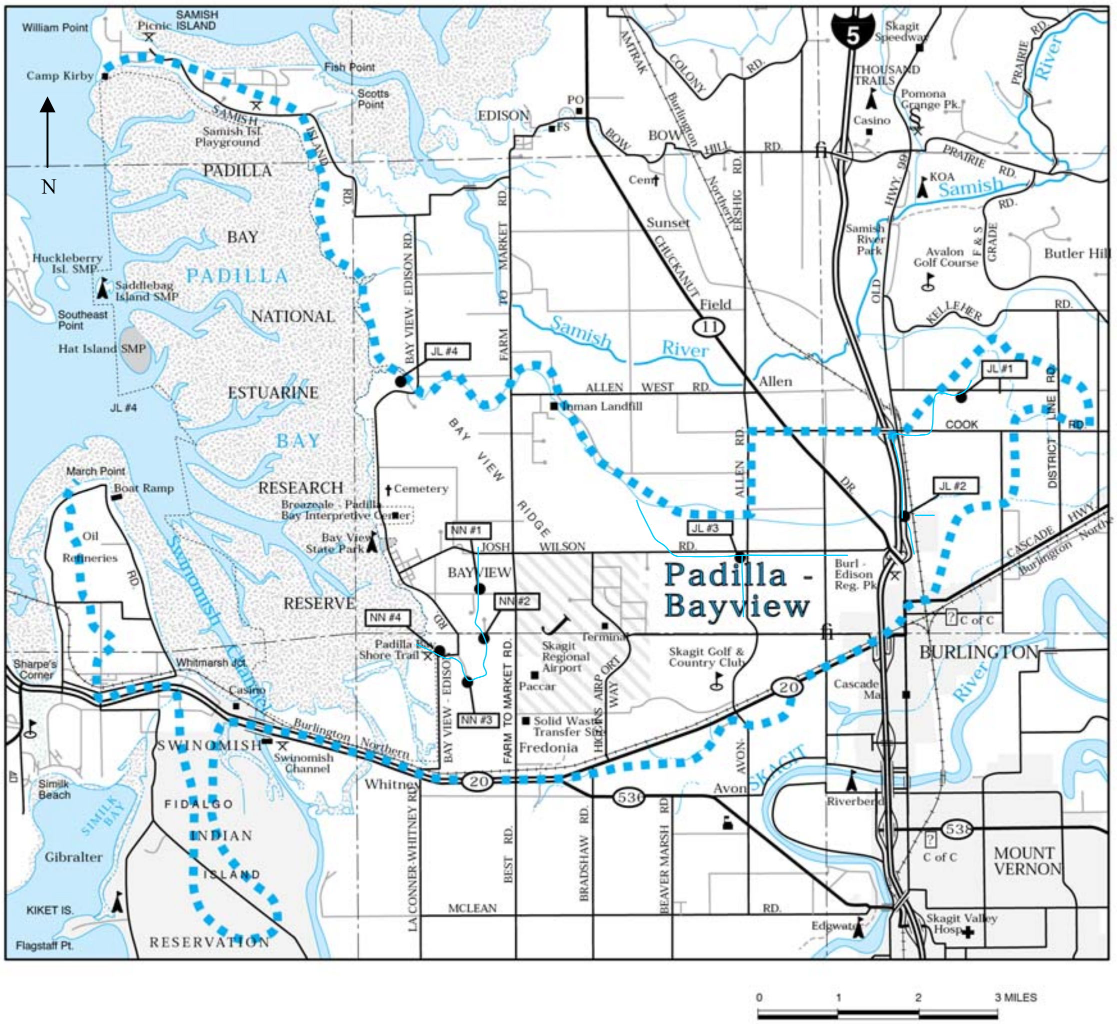


Figure 25. Location of sampling sites (labels in boxes) in Joe Leary Slough (JL #1 to JL #4) and in No Name Slough (NN #1 to NN #4) sampled by Skagit Stream Teams in the Padilla Bay/Bay View watershed. (From Henry 1999, 2003, and 2005)

mature Coho Salmon have been reported spawning in the sloughs (Barkdall, personal communication). In No Name Slough, the growth of the fry has been noted over the course of the year, presumably leaving the slough during early wet season freshets. Surface flow in No Name Slough dries up during the dry season July to September and Coho juveniles are confined to perennial pools.

Summary of water quality in the sloughs. Water quality in the freshwater sloughs of the Padilla Bay watershed is generally poor. These sloughs have very little exchange of salt water with Padilla Bay; high salinity water only entering via leaking tidegates and seepage through the dams and dikes. Temperature fluctuates widely and, without streamside vegetation, regularly exceeds the state water quality standards. Dissolved oxygen concentrations are seasonally low and periods of hypoxia and anoxia have been reported. Turbidity and suspended solids are high, particularly in the floodplain portions of the sloughs. Fecal coliform enter the sloughs from a variety of sources (including dairy farms and failing septic tanks) and water in the sloughs regularly do not meet state standards for temperature, dissolved oxygen, and fecal coliforms.

TIDES AND CURRENTS

Padilla Bay is a meso-tidal estuary with mixed semi-diurnal tides. Mean tidal range is 1.6 m (5.1 feet); mean spring tidal range is 2.6 m (8.4 feet). During spring tides the diurnal tidal range is as great as 4.0 m (13.1 feet) during June and December and 3.1 m (10.2 feet) during March and September.

Tidal exchange is of particular importance for Padilla Bay because most of the bay east of Hat Island is intertidal. Therefore tides are the major force for currents in the bay and water characteristics in the bay are determined mainly by the source water for the tidal flushing. Because of the daily exchange of water, there is little opportunity for stratification to develop; Padilla Bay is a vertically well mixed estuary.

Tides drive the currents within Padilla Bay, but there have been no measurements of currents in the tidal channels east of Hat Island in Padilla Bay or over the intertidal flats in Padilla Bay. There were a few studies of the currents in Swinomish and Guemes Channels west of Hat Island associated with proposed and existing industry on March Point and Anacortes (McKinley et al. 1959; Shannon Point Marine Lab Physical Oceanography Class 1991; Sylvester and Clogston 1958; U.S. Army Engineer District, Seattle, Washington 1976; URS Corporation (≈1985); Seattle Marine Laboratories 1974; Summers et al. 1985). These studies indicated a net northerly flow in the Swinomish Channel which connects Skagit Bay (mean spring tidal range of about 3.5 m) and Padilla Bay (mean spring tidal range of about 2.6 m; McKinley et al. 1959; U.S. Army Engineer District, Seattle, Washington 1976; Sylvester and Clogston 1958). In Guemes Channel, a net westerly flow was reported by Seattle Marine Laboratories (1974) and the City of Anacortes (1984).

Flood currents bring water from a variety of potential sources into Padilla Bay (e.g. Skagit Bay, Rosario Strait, Strait of Georgia, Fig. 26). Therefore, Bulthuis, Conrad, and Frankenstein conducted a series of studies on the surface currents during flood tides from Swinomish Channel, Guemes Channel and the strait west of Samish Island (Bulthuis and Conrad 1995a, Bulthuis and Conrad 1995b, Bulthuis and Frankenstein unpublished data).

During flooding tides the water in Swinomish Channel and in the dredged portions of the channel in Padilla Bay generally flows south out of Padilla Bay and toward Skagit Bay, rather than flowing into Padilla Bay (Bulthuis and Conrad 1995b). Drift sticks released near the northern end of the dredged portions of Swinomish Channel at the time of low water on a spring tide moved southeast and did not enter Padilla Bay (Fig. 27). Drift sticks released in the dredged Padilla Bay portion of Swinomish Channel during the last half of the flood tide moved south in the channel and during the last hour or so of flood tide drifted slowly over the flats into Padilla Bay (Fig. 28). Thus, the flow of water in the dredged Padilla Bay portion of Swinomish Channel during flood tide is almost wholly a

Figure 26. Straits and channels around Padilla Bay from which water flows to and from Padilla Bay. Landsat image taken June 16, 2000, modified by Shull.

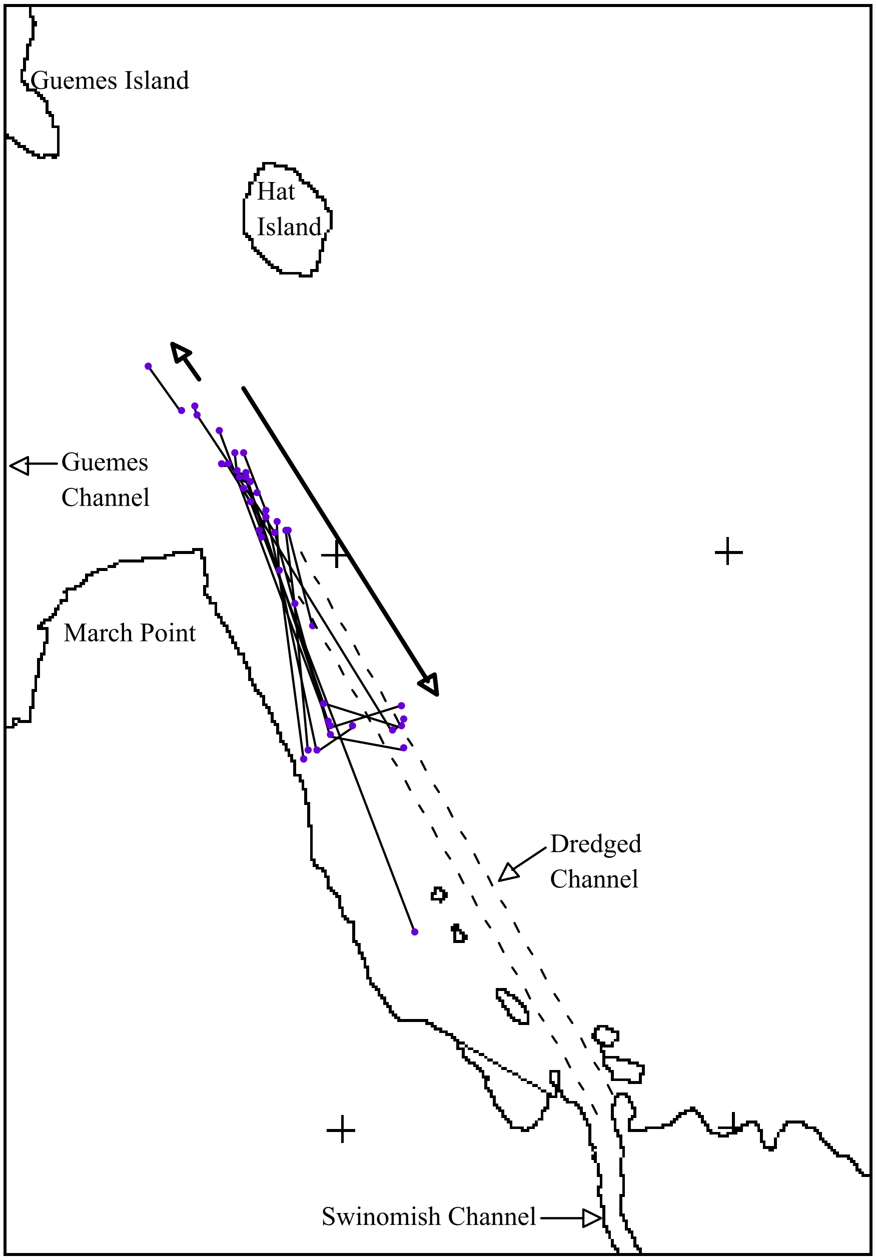


Figure 27. Movement of drift sticks after LLW (13:00) on August 4, 1993 during a flooding tide (predicted HHW was 19:46). Lines connect the different locations of the individual drift sticks. The last drift stick was retrieved at 20:33. One stick travelled northwest, the rest of the sticks travelled southeast. (From Bulthuis and Conrad 1995b)

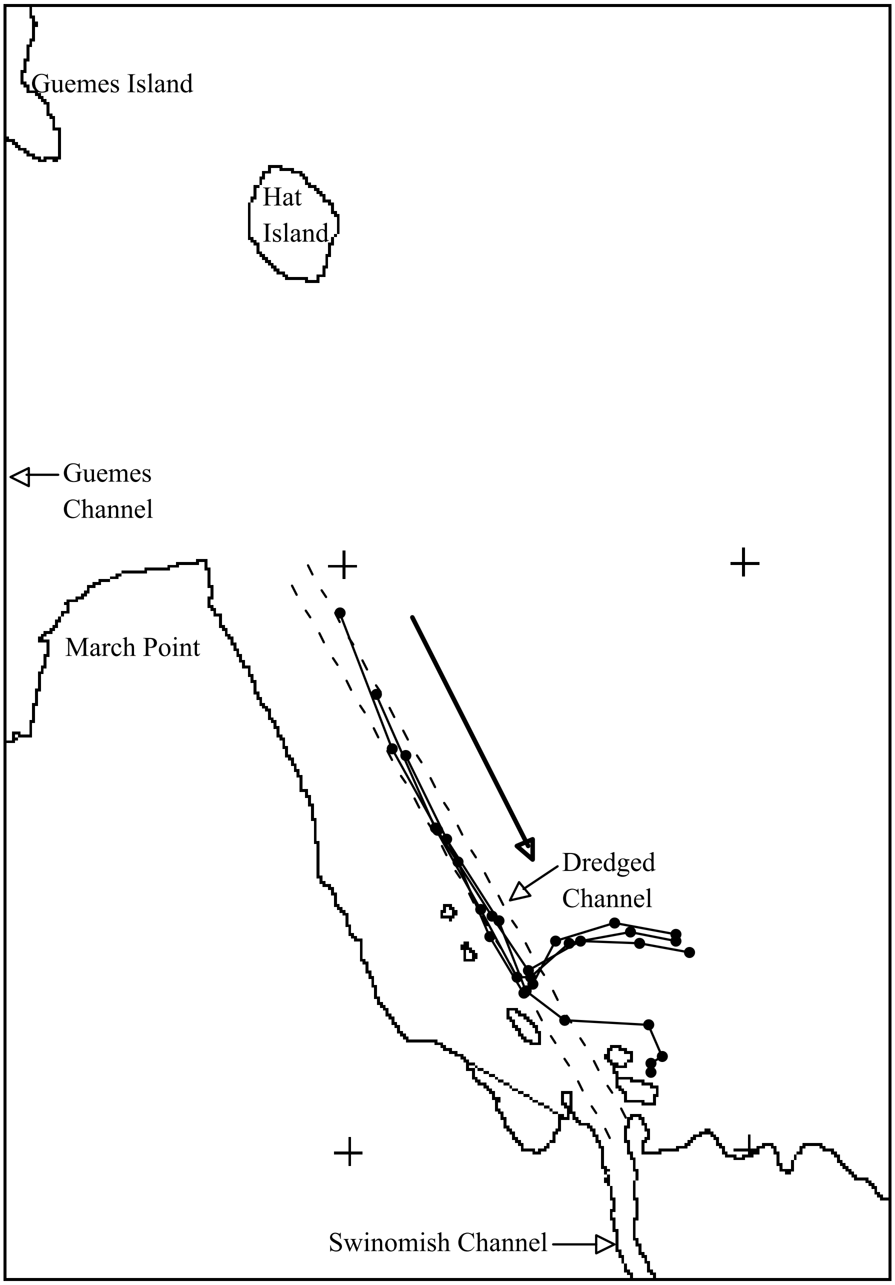


Figure 28. Movement of four surface drift sticks that were released at about 13:00 on September 13, 1993 during the later part of a flooding tide (LLW in Swinomish Channel was predicted to occur at 09:31 and HHW at 16:28). Dots indicate where the latitude and longitude of individual drift sticks was determined; lines connect the different locations of the individual drift sticks. The drift sticks were recovered (at the location of the last dot on each line) between 16:54 and 17:57. (From Bulthuis and Conrad 1995b)

movement in the channel with only a small movement of water into Padilla Bay during the last hour or so of flood tide. Similarly ebb flow from Swinomish Channel remains in the dredged portion of the channel, flowing north and toward Guemes Channel (Bulthuis and Conrad 1995b).

Because of the differences in tidal range between Skagit and Padilla Bays, neither low water and low slack nor high water and high slack coincide in time at the northern end of Swinomish Channel (under State Route 20 bridge) (Fig. 29). Water continues to flow north after high water (Bulthuis and Conrad 1995b). However, water is also ebbing from Padilla Bay at this time, so the water from Skagit Bay and Padilla Bay flow together northwest and toward Guemes Channel (Bulthuis and Conrad 1995b).

Flood tide surface currents in the area between Hat Island, March Point, and Southeast Point on Guemes Island are variable (Island Canoe 1987, Bulthuis and Conrad 1995a). Surface currents from Guemes Channel flow east between Southeast Point on Guemes Island and March Point during flood tides. The water then divides and flows in three directions (Figs 30 and 31; Bulthuis and Conrad 1995a). Most of the water flows either north between Saddlebag and Guemes Islands or south down the Swinomish Channel. A small portion of water continues to move east into Padilla Bay. The surface water directly south of Hat Island at low water slack seems to be the major source of water that flows into the southern half of Padilla Bay (Fig. 32; Bulthuis and Conrad 1995a).

North of Hat Island, the surface currents during flood tide apparently come from the strait between Samish and Guemes Islands (Bulthuis and Frankenstein, unpublished data). Water on the west side of this strait flows north and south with ebb and flood currents (Canadian Hydrographic Service 1983, Island Canoe 1987, Bulthuis and Frankenstein, unpublished data). The surface water on the east side of this strait and directly west of the intertidal flats in Padilla Bay at low water slack flows directly east into Padilla Bay (Bulthuis and Frankenstein unpublished data). The orientation of the channels (east-west) in the northern half of Padilla Bay is consistent with these observations.

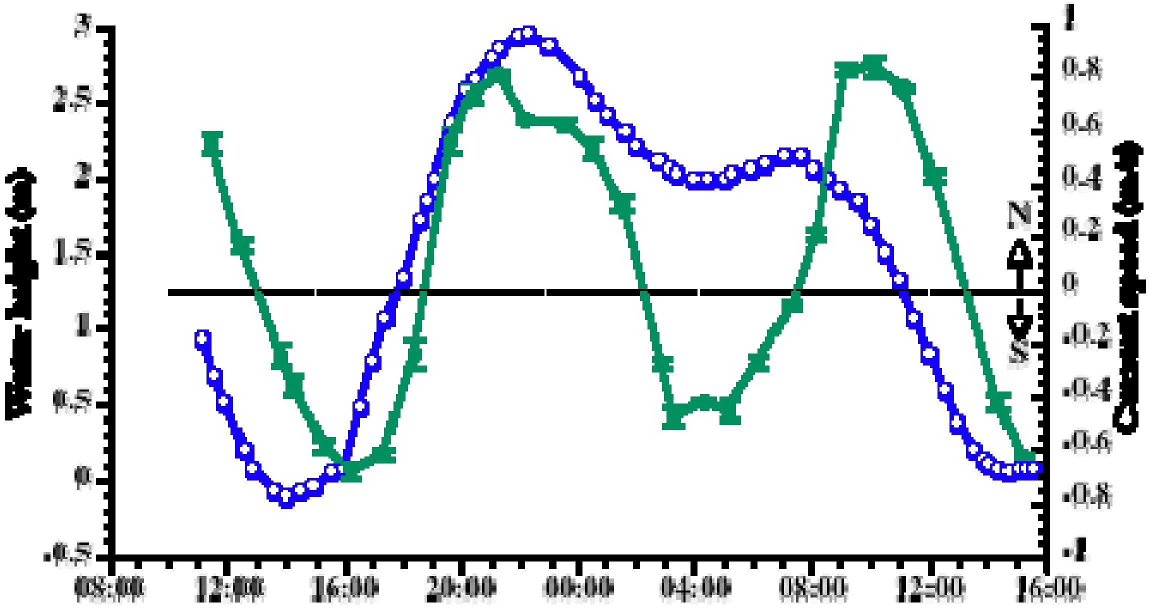


Figure 29. Water height (open circles, blue line, in m relative to MLLW) and surface current speed (closed circles, green line, in m/s, mean ± s.e.) in the Swinomish Channel under the Highway 20 bridge at the entrance to Padilla Bay on May 20 and 21, 1992. Positive current speeds (above the dashed line) are north flowing, negative current speeds (below the dashed line) are south flowing. (From Bulthuis and Conrad 1995b)

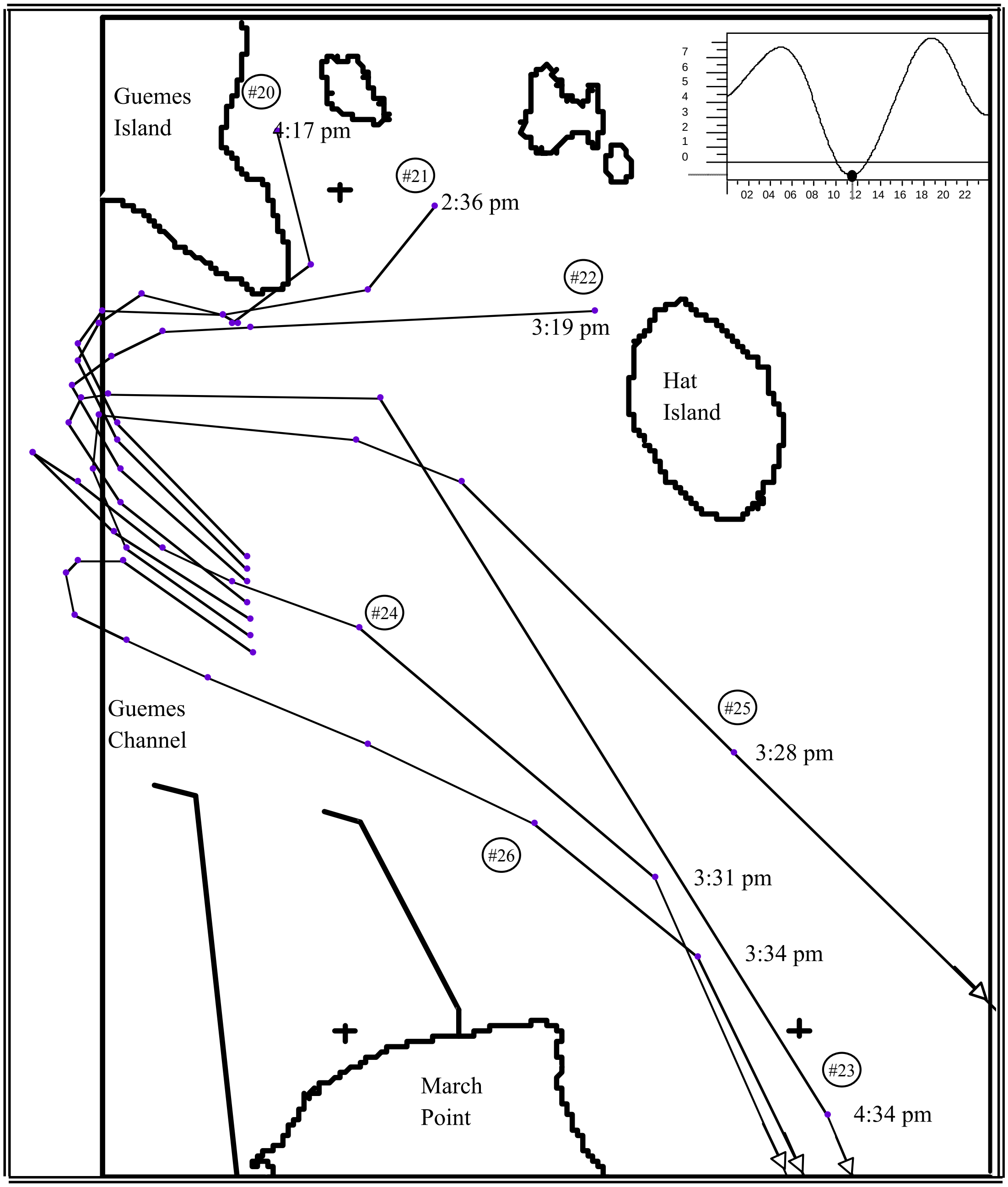


Figure 30. Movement of six drift sticks (numbered 20 to 26) that were deployed between Guemes Island and March Point near the eastern end of Guemes Channel on August 18, 1993 about 11:15 near the beginning of a flood tide (LLW in Guemes Channel at Anacortes was predicted for 11:27 am, HHW for 6:35 pm). Dots indicate where the latitude and longitude of individual drift sticks were determined; lines connect the different locations of individual drift sticks; graph in upper right indicates the predicted tidal curve at Anacortes for the day (height in feet). (From Bulthuis and Conrad 1995a)

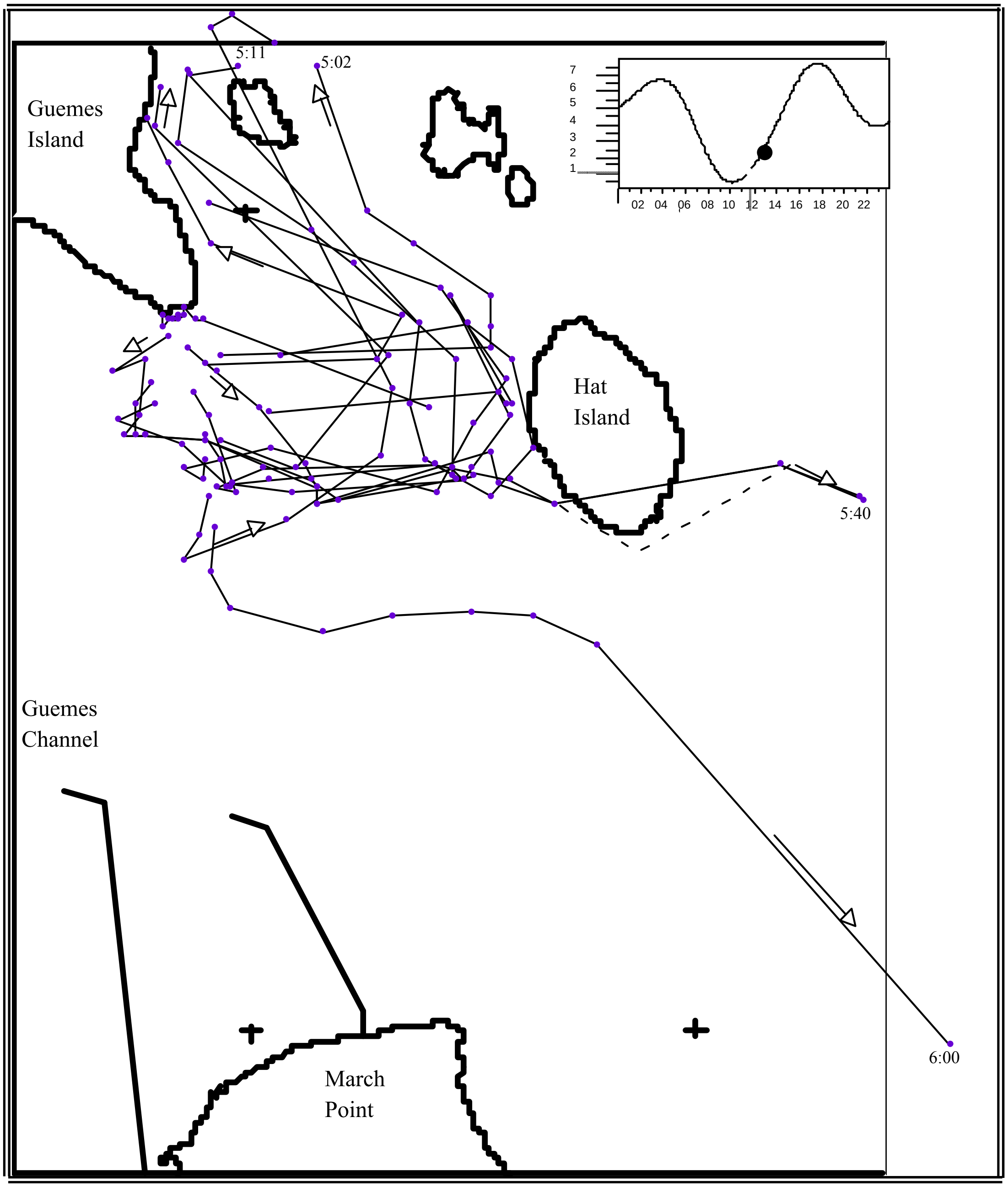


Figure 31. Movement of surface drift sticks that were deployed near the eastern end of Guemes Channel during the last half of flooding tide on August 30, 1993. Sticks were deployed about 12:50 pm south of Southeast Point, Guemes Island during early flood tide (LLW in Guemes Channel at Anacortes was predicted for 10:10 am, HHW for 5:28 pm). Dots indicate where the latitude and longitude of individual drift sticks were determined; lines connect the different locations of individual drift sticks; graph in upper right indicates the predicted tidal curve at Anacortes for the day (height in feet) and the dot the time of deployment. (From Bulthuis and Conrad 1995a)

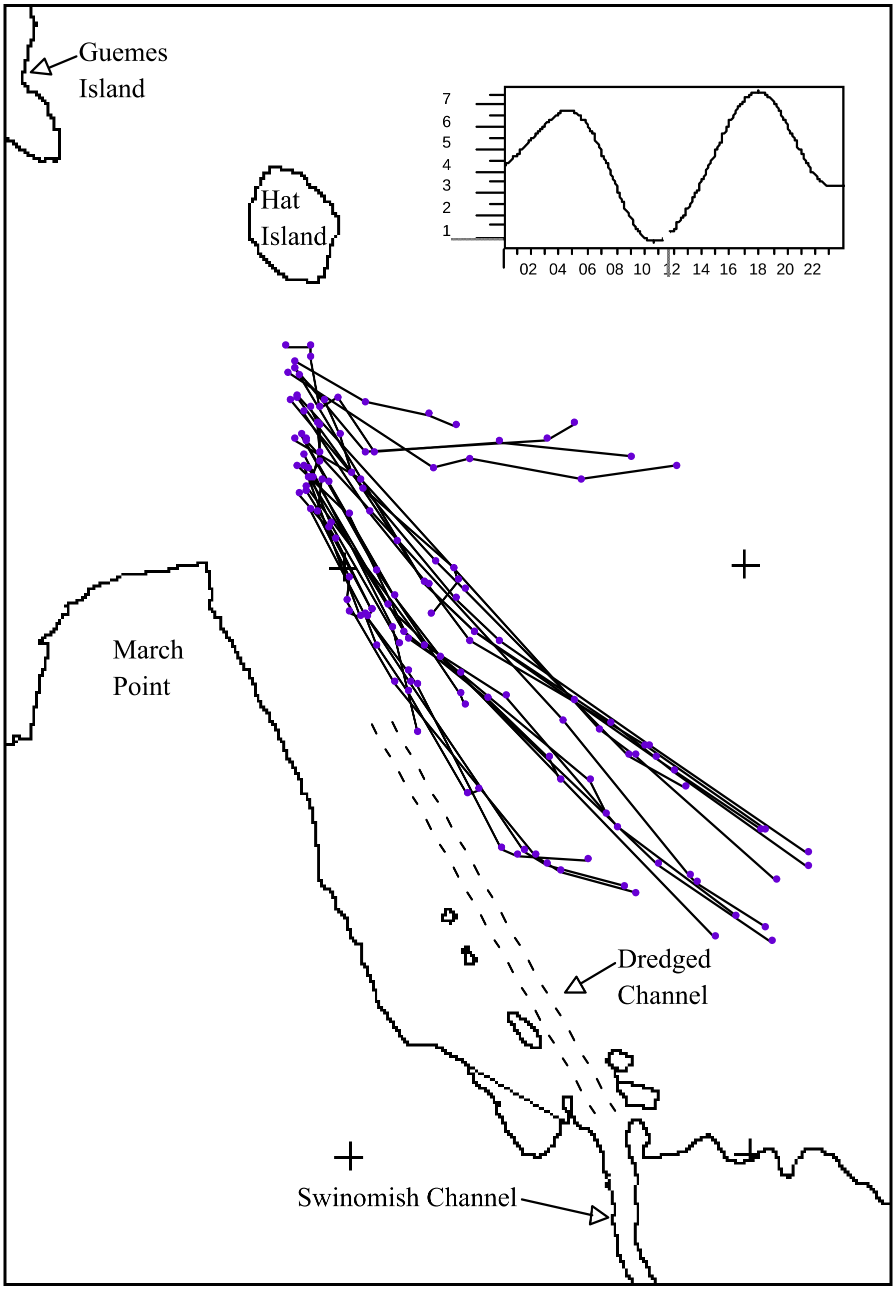


Figure 32. Movement of all surface drift sticks that were deployed at about hourly intervals from 10:50 am to 3:20 pm south of Hat Island on August 31, 1993. (LLW in Guemes Channel at Anacortes was predicted for 10:46 am, HHW for 5:51 pm). Dots indicate where the latitude and longitude of individual drift sticks were determined; lines connect the different locations of individual drift sticks; graph in upper right indicates the predicted tidal curve at Anacortes for August 31 (height in feet). (From Bulthuis and Conrad 1995a)

HYDROCHEMISTRY OF PADILLA BAY

The hydrochemistry of Padilla Bay is a reflection of the regional water that is part of the Salish Sea, including the Strait of Georgia and greater Puget Sound interacting with Padilla Bay. Because of the large tidal prism that is exchanged each day, the chemistry of Padilla Bay is an indication of regional water. The regional water is modified in Padilla Bay by interaction with the biota, especially the eelgrass community, and the sediments. The interaction and potential for interaction is accentuated by the shallowness of the bay. The hydrochemistry of Padilla Bay is only slightly modified by mixing with freshwater inputs because of the low volume of freshwater flow relative to the tidal prism.

SALINITY

The salinity in most of Padilla Bay is determined by the salinity of the regional water. Near the mouths of the sloughs some freshwater mixes with the incoming regional water. However, all the sizable freshwater flows to Padilla Bay are controlled by tide gates that shut as the tide rises, so freshwater flow into Padilla Bay is restricted to about the lowest quarter or less of the tide range. Salinity in Padilla Bay and the regional water is polyhaline, usually in the range of 24 to 32 PSU.

Much of our knowledge of the hydrochemistry of Padilla Bay comes from data collected as part of the Padilla Bay NERR water quality monitoring program since 1996. Multiparameter sondes measured depth, temperature, salinity, dissolved oxygen, pH, and turbidity every 15 to 30 minutes at four sites in Padilla Bay (Fig. 33). Two of the water quality monitoring sites are located in tidal channels in Padilla Bay: Bay View Channel site and Ploeg Channel site The datasondes are located about 0.75 m above the bottom and about 1 m below MLLW. The part of the water column that is being measured, thus, is changing during the diurnal tidal curve, with the upper meter of water being measured during negative tides and water at 3 to 4 meters depth when tide level is at mean higher high water or higher. The water that is flowing past the datasondes also has a history,

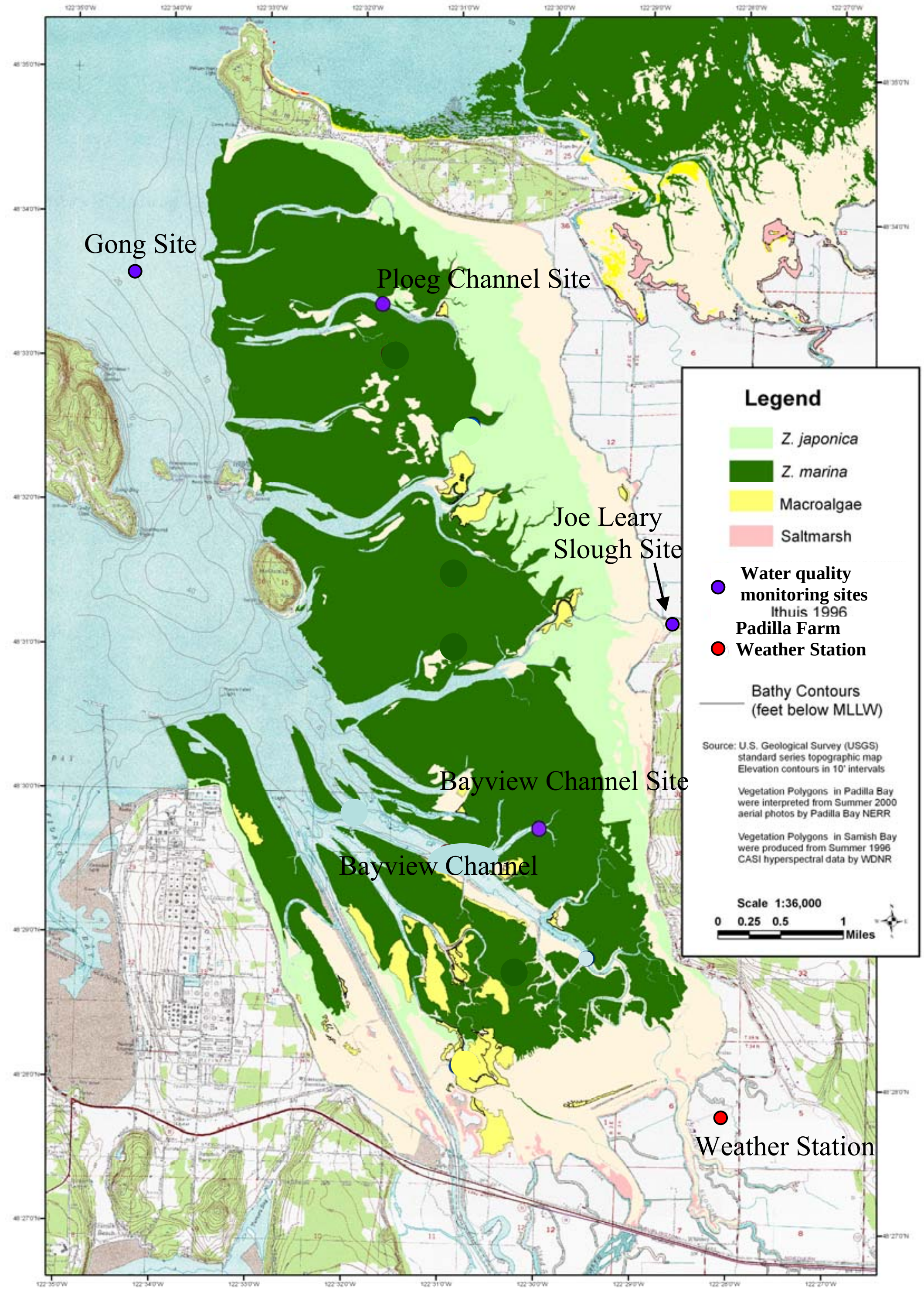


Figure 33. Location of the Padilla Bay NERR System-wide Monitoring Program water quality sites and the Padilla Bay NERR weather station. Vegetation cover in Padilla Bay from Bulthuis and Shull 2002, vegetation cover in Samish Bay from Washington State Department of Natural Resources 1996 as modified by Shull unpublished data.

having come off of the intertidal flats during ebb tide and early flood tide, and having come from outside Padilla Bay during the later part of the flood.

Salinity at the Bayview Channel site (Fig. 33) is indicative of the range and fluctuations of salinity in Padilla Bay because the water is well mixed as it is exchanged daily with regional water during tidal exchange. Salinity at the Bayview Channel site ranged from 20 to 33 PSU over the eight year period of 1996 to 2003 (Fig. 34). Monthly means varied from 25 to 32 PSU. Seasonally, salinity was lowest in April to June and highest in August and September (Fig. 34). The sources of the lower salinity water in Padilla Bay are the rivers flowing into the Strait of Georgia and Puget Sound, particularly the Fraser, Nooksack, and Skagit Rivers (Fig. 1). Peak flows in the Nooksack and Skagit Rivers are usually associated with autumn and winter weather systems that bring rain and rain on snow in November and December. Peak flow in the Fraser River usually occurs in May and June with snow melt. Thus, the minimum monthly salinities in Padilla Bay in April to June indicate the influence of the Fraser River on salinity in the bay. The minimum salinities each month may be from pockets of fresher water from the sloughs flowing into Padilla Bay or the Samish, Nooksack, Skagit, or Fraser Rivers.

In addition to the seasonal and interannual fluctuations in salinity there are daily tidal fluctuations as water is exchanged with the regional waters. Tidal fluctuations in salinity are illustrated by data for March 2002 at the Bayview Channel site (Fig. 35). Salinity fluctuated daily during March 19 to 25 from about 26 to 30 PSU (Fig. 35). Similar fluctuations in salinity were recorded twice a day with semidiurnal tides during March 28-30 (Fig. 35). Thus, daily fluctuations of 3-5 PSU are common in Padilla Bay, although during late summer and early autumn, daily fluctuations are usually less than one PSU.

TEMPERATURE

Water temperature ranged from –0.5^{o}C to 24.5^{o}C during an ten year record of temperature at Bayview Channel. Mean monthly temperatures were 12-16^{o}C during summer and 6-9^{o}C during winter (Fig. 36). Monthly range and variance were usually

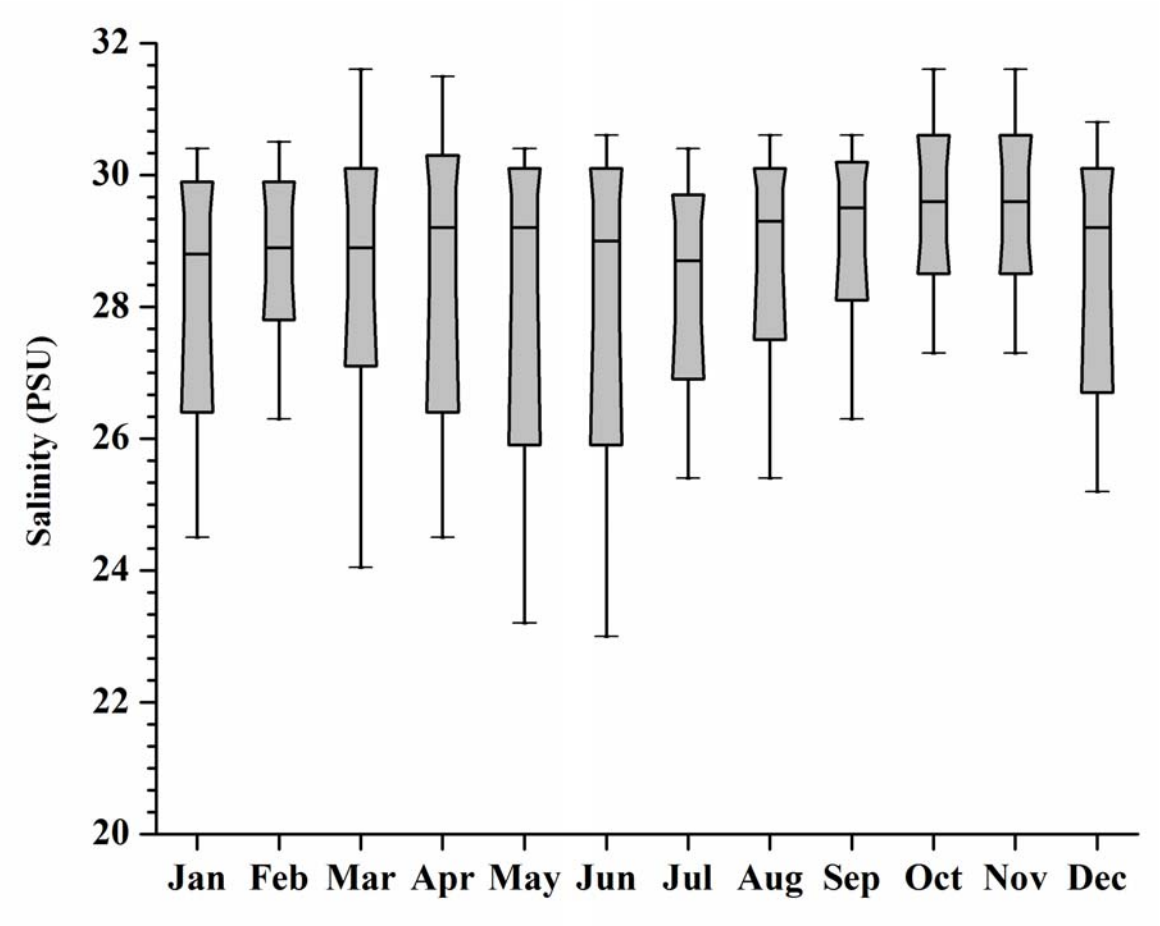


Figure 34. Salinity (PSU) measured at the Bayview Channel water quality site from 1996 to 2005. Measurements taken every 30 minutes. Box plots show 90th percentile, median, and 10th percentile; whiskers show 99th percentile and 1 percentile of salinity data recorded each month. Each monthly plot is a summary of more than 150,000 salinity measurements taken over 10 years. (From Cottrell, Margerum, and Bulthuis unpublished data.)

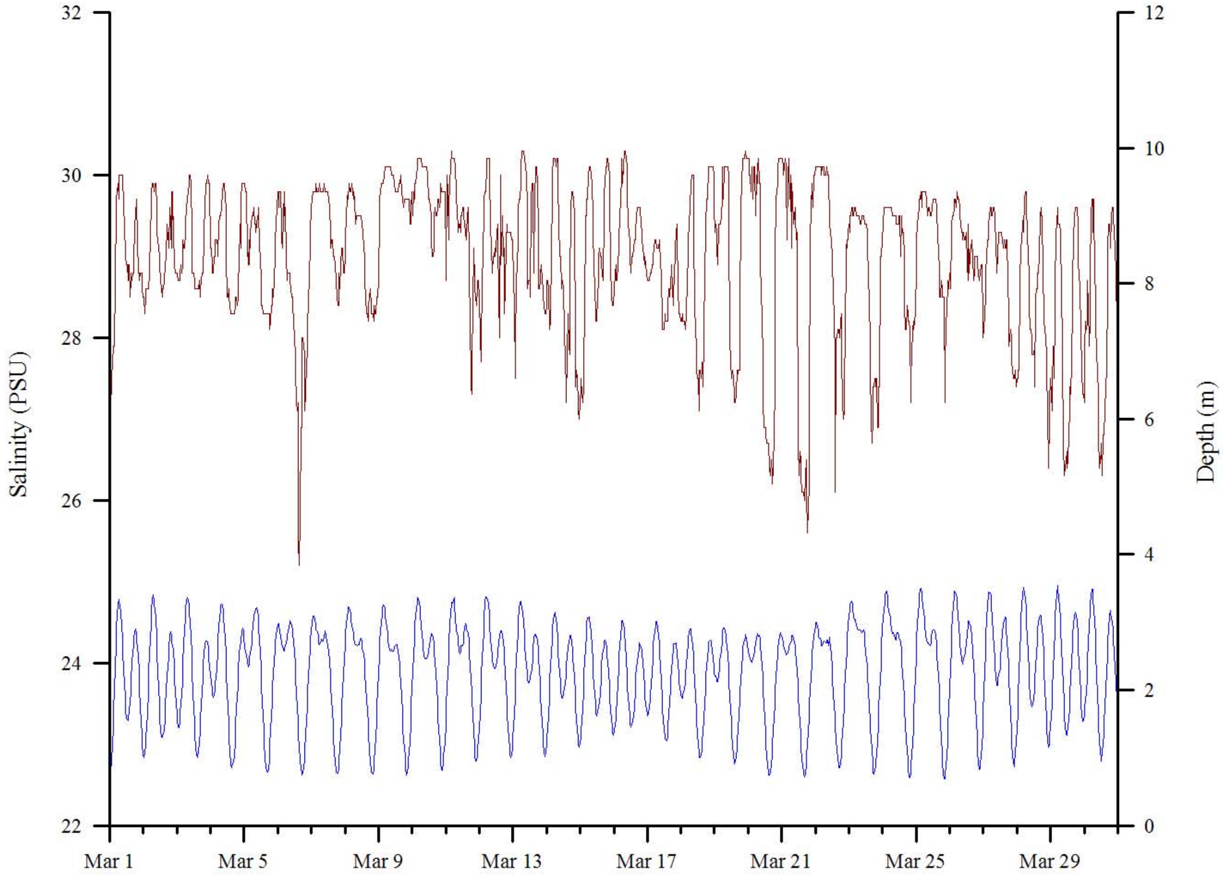


Figure 35. Salinity (PSU) and depth (m) measured at the Bayview Channel site every 30 minutes from March 1-31, 2002. Salinity is represented in red, depth in blue. (From Cottrell, Margerum, and Bulthuis unpublished data.)

greater in late spring and summer than in autumn or winter (Fig. 36). Exceptions to this pattern occurred during winter when there were several days of cold weather (e.g. November and December 1996, and December 1998) when water temperatures on the intertidal flats dipped to around 0^o.

There is some evidence of interannual differences in the warmest months and in the coldest months. For example, the summer of 1997 was cooler than 1996 or 1998. Maximum monthly temperatures of the warmest months were $3\text{-}5^o$ lower than the previous or following year and monthly means were 1-2° lower (Fig. 37, Wenner et al. 2001). Similarly, the median, 1 percentile and minimum monthly temperatures during the winter of 1997-98 were $1\text{-}3^o$ warmer than the previous year (Fig. 37). Such interannual differences in the maximum and minimum water temperatures may be important for biota, particularly those exposed on the intertidal flats where temperatures in the small pools may be higher or lower than in the bulk water measured at the Bayview Channel site.

In addition to the interannual and seasonal variability, water temperature fluctuates daily with the tidal stage and the time of day. Because of the extensive shallow water in Padilla Bay, water temperatures fluctuate with air temperature and solar exposure. This is particularly evident at Bayview Channel during times of low water. For example, during January 27-30, 2002, temperature decreased $2\text{-}4^oC$ during ebbing water (Fig. 38). During July 9-13, 2002 water temperature increased $6\text{-}8^oC$ during ebbing water (Fig. 38). In March 2002 this contrast occurred on adjacent days, water temperature during ebbing tide decreased March 18-21 and increased March 22-25 (Fig. 38).

The water temperature in Padilla Bay is relatively mild compared to water temperature fluctuations in other temperate estuaries. Mean monthly temperatures fluctuate only about 10^oC over the year while maxima and minima temperatures at the Bayview Channel site fluctuated $2\text{-}8^o$ daily, $2\text{-}12^o$ monthly, and up to 25^o annually.

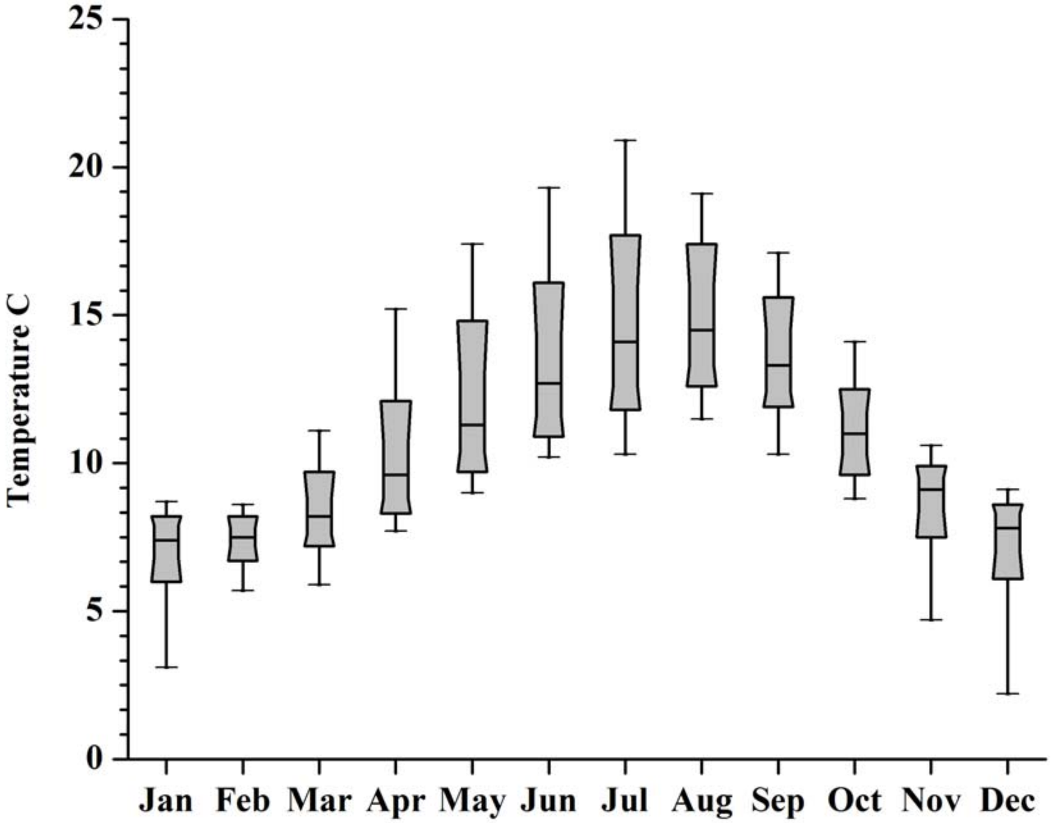


Figure 36. Temperature (°C) measured at the Bayview Channel water quality site from 1996 to 2005. Measurements taken every 30 minutes. Box plots show 90th percentile, median, and 10th percentile; whiskers show 99th percentile and 1 percentile of temperature data recorded each month. Each monthly plot is a summary of more than 150,000 data points taken over 10 years. (From Cottrell, Margerum, and Bulthuis unpublished data)

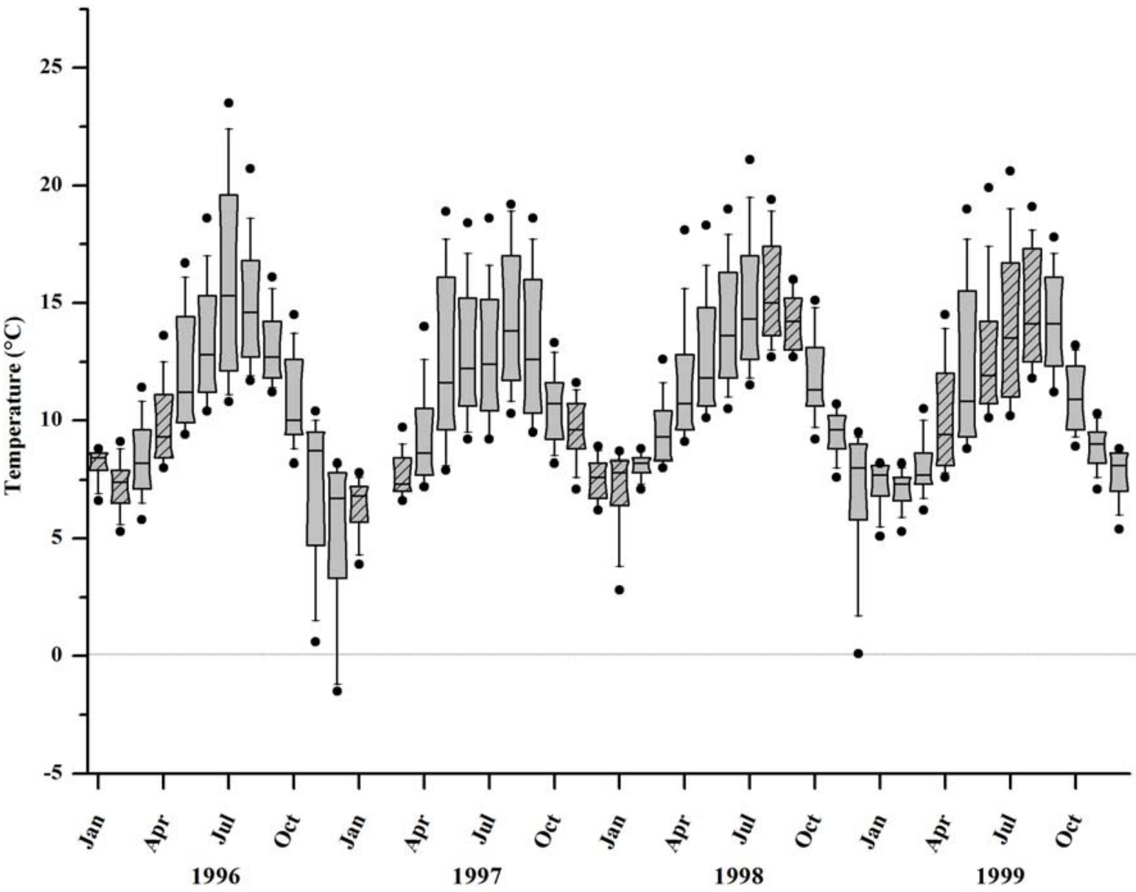


Figure 37. Monthly summaries of temperature (°C) measured at Bay View Channel water quality site from 1996 to 1999. Measurements were taken every 30 minutes except for months with hatched box plots when there were some data gaps. Box plots show 90th percentile, median, and 10th percentile; whiskers show 99th and 1 percentile; dots show maxima and minima of temperature data recorded each month. (From Cottrell, Margerum, and Bulthuis unpublished data)

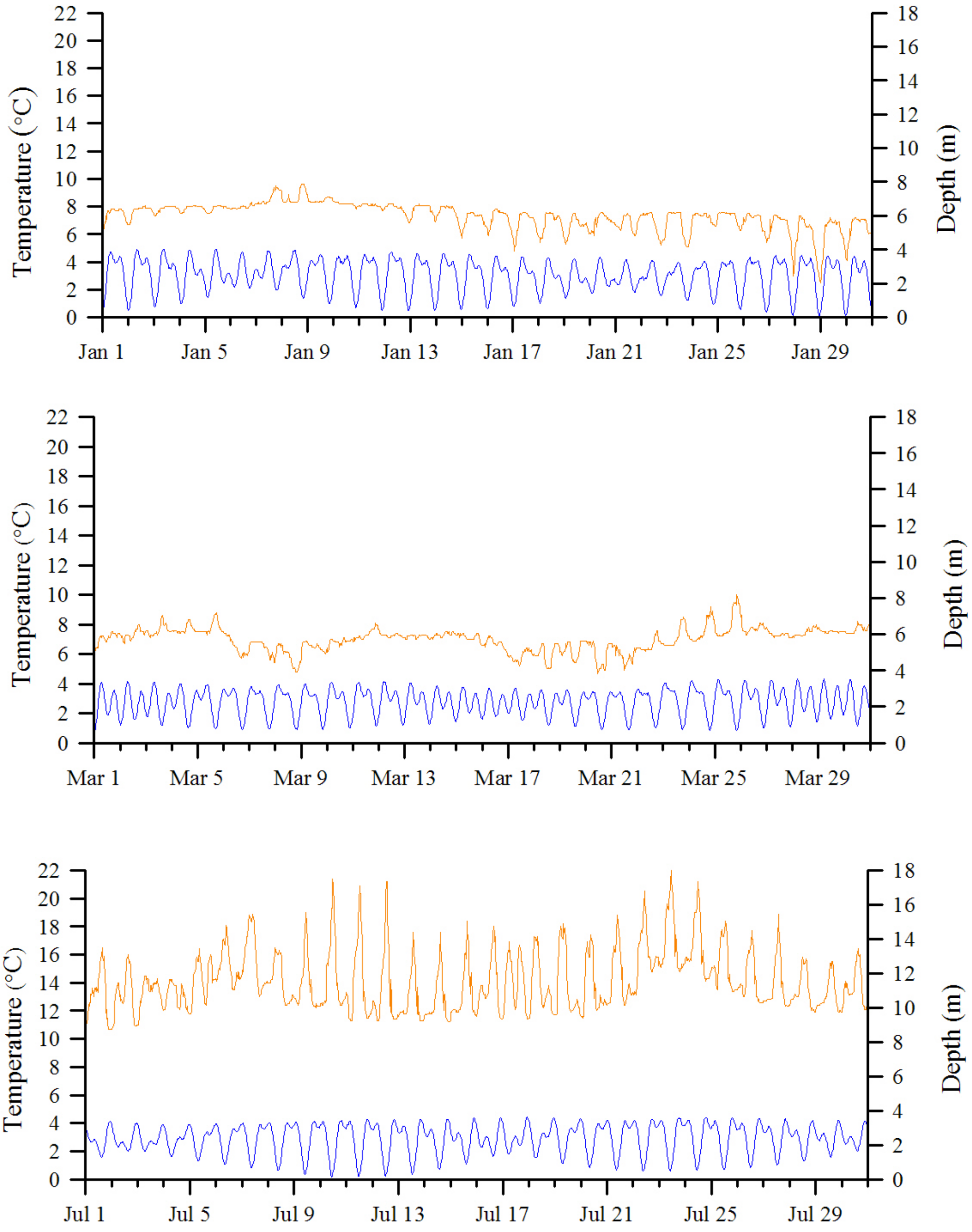


Figure 38. Temperature (°C) and depth (m) measured at the Bayview Channel water quality site during January, March and July 2002. Measurements were taken every 30 minutes. Temperature is represented in orange, depth in blue. (From Cottrell, Margerum, and Bulthuis unpublished data.)

DISSOLVED OXYGEN

Dissolved oxygen in Padilla Bay, as for other aspects of hydrochemistry, can best be understood in the context of the daily exchange of water with the straits west of Padilla Bay, the extensive intertidal flats, and the extensive cover of eelgrasses. Dissolved oxygen ranged from 24% saturation to 225% saturation at Bayview Channel during an eight year period from 1996 to 2003 (Fig. 39). The high maximum concentrations of dissolved oxygen occur during summer months when daily fluctuations are greatest. For example, on June 1, 1998, dissolved oxygen was lowest (70%) about 11:00 a.m. when the water started to ebb and increased to 225% at 5:00 p.m. when water started to flood (Fig. 40). At 5:00 p.m., the water depth was 1.2 m above the datasonde and water would be confined to the channels. The water flowing past the datasondes at that time was water that had flowed off of the eelgrass covered flats. [The intertidal flats that are covered with eelgrasses do not completely drain during low tides in Padilla Bay, even when the flats are 0.5 to 1 m above the low water level. Water is retained by a variety of mechanisms including depressions in the flats, berms at the channel edges and retention of the water by the eelgrass blades. Water retained by the eelgrass slowly flows across the flats through the eelgrass and into the small channels that feed the larger channels. Thus, water in the channels during late ebb tide is predominately water that has been in close contact with the eelgrass leaves on the flats and has recently flowed into the tributaries and channels.] Therefore, the water flowing past the datasondes at 5:00 pm on June 1 was water that had been flowing past the eelgrass leaves. The eelgrass community, including the epiphytes and intermixed macroalgae, add dissolved oxygen to the water. The density of eelgrass plants and algae, and their high productivity during this time of day, contribute to super saturation of the water. The fact that the water was supersaturated to 225% indicates the high productivity of the eelgrass community (Fig. 40). After 5:00 p.m. the dissolved oxygen declined at Bayview Channel site. This decline was due to the flow of incoming water (note increasing depth). This pattern of super saturation of dissolved oxygen during daylight low tides and decreased dissolved oxygen during night-time high tides is a common phenomenon in Padilla Bay during summer. These daily fluctuations are reflected in the monthly summaries for dissolved oxygen with high maxima and very wide variance (up to 70% saturation difference

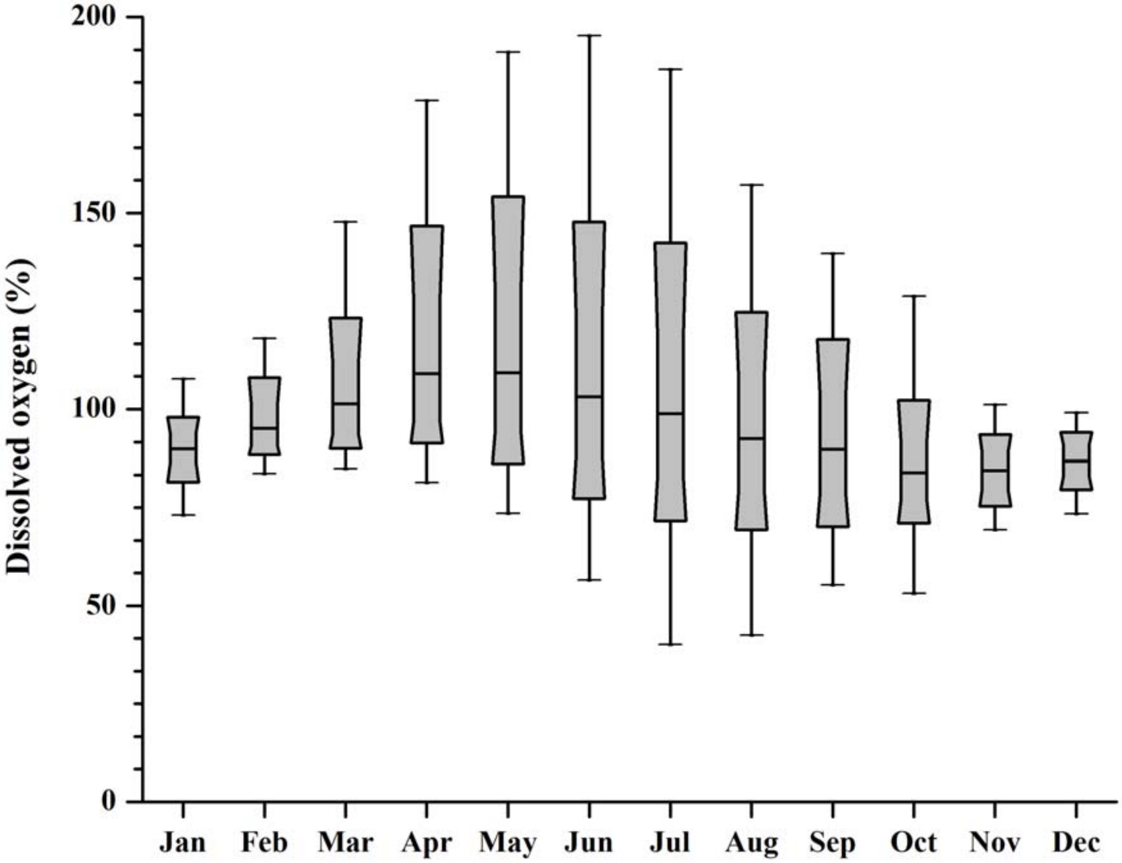
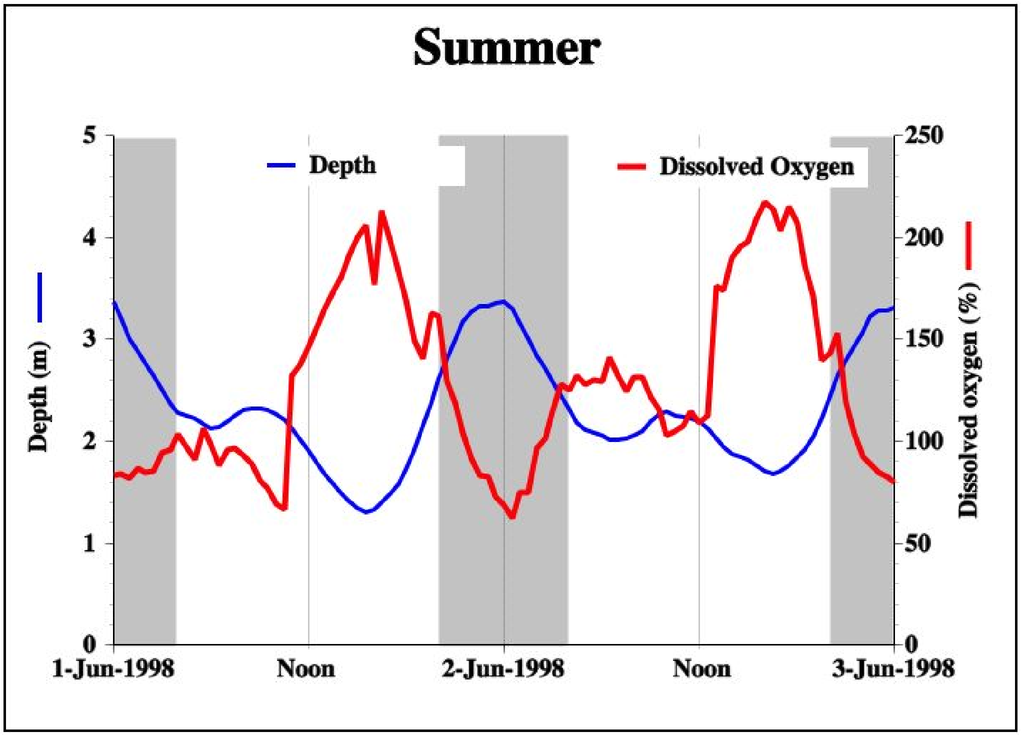


Figure 39. Dissolved oxygen (percent saturation) measured at the Bayview Channel water quality site from 1996 to 2005. Measurements taken every 30 minutes. Box plots show 90th percentile, median, and 10th percentile; whiskers show 99th percentile and 1 percentile of dissolved oxygen data recorded each month. Each monthly plot is a summary of more than 150,000 dissolved oxygen measurements taken over 10 years. (From Cottrell, Margerum, and Bulthuis unpublished data.)



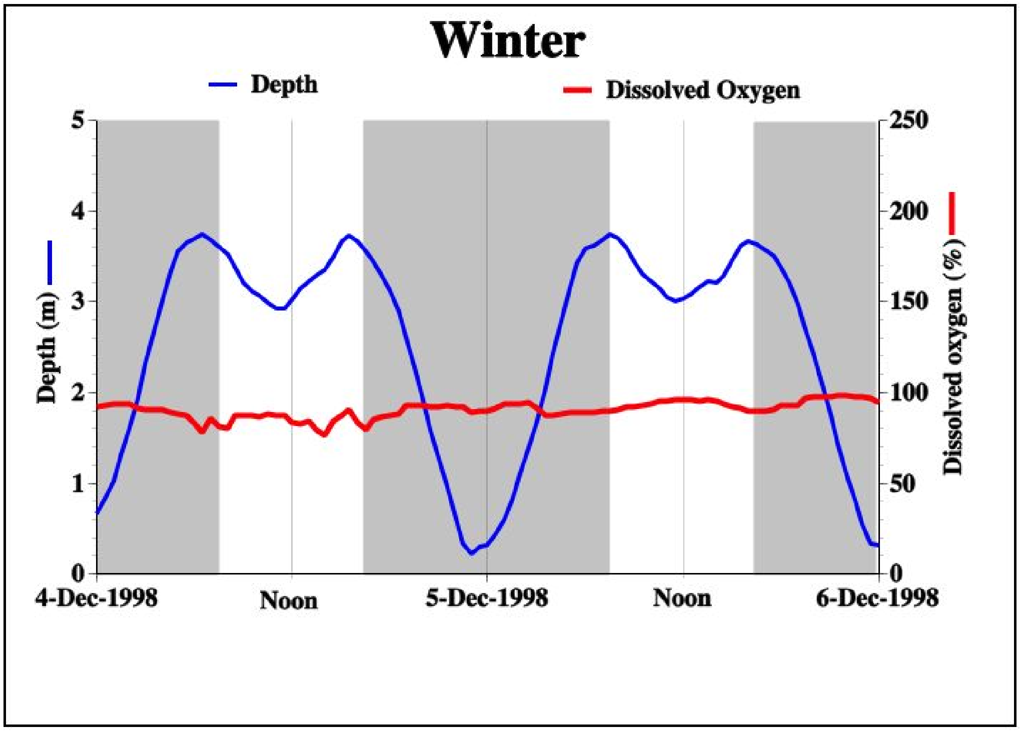


Figure 40. Dissolved oxygen and water depth at Bay View Channel site in Padilla Bay June 1-2 and December 4-5, 1998. Dissolved oxygen and temperature were measured every 30 minutes with a multi-parameter datasonde. Shaded areas indicate time between sunset and sunrise. (From Bulthuis and Cottrell 1999.)

between the 10th percentile and 90th percentile of measurements) (Fig. 39). In addition to the daily fluctuations in dissolved oxygen, dissolved oxygen fluctuates with spring and neap tides during summer. During neap tides less water is exchanged between Padilla Bay and the northwest straits, and the intertidal flats are not exposed or only exposed for a short period of time. When flats are exposed for only a short period of time, less water flows into the small channels off of the eelgrass covered flats than during spring tides when the flats are exposed up to six or more hours. Daily maxima in dissolved oxygen tend to be lower during and after neap tide than during and after spring tides (Fig. 41).

Sunlight is another factor controlling the daily fluctuation in dissolved oxygen during summer. During summer days the maximum dissolved oxygen is considerably lower on cloudy days compared to sunny days even when the tidal exchange is similar (Fig. 42). The difference between cloudy and sunny days, presumably, is due to difference in the productivity of the eelgrass community including eelgrass, epiphytes, macroalgae, and epipelic algae.

Seasonal differences in the concentration of dissolved oxygen are striking in Padilla Bay. During mid winter, the dissolved oxygen is much more stable with tidal and daily fluctuations of less than 20% (Fig 43, compare with Fig. 41). The trace of dissolved oxygen in a single winter day can be less than 20% even though the tidal exchange is similar to summer spring tides when the dissolved oxygen changed by more than 150% (Fig. 40). The lack of daily and tidal fluctuations in dissolved oxygen in winter is probably due to the low plant productivity of eelgrass and algae, and to the low rates of respiration and oxygen consumption by both plants and animals. Low plant productivity is probably due to low levels of light and low temperature in winter (cf. Figs. 11, 36, and 37. Low rates of respiration and oxygen consumption are probably due to low winter temperatures (cf. Figs. 36 and 37).

Hypoxia and low oxygen concentrations have caused problems in estuaries throughout the United States and the world (Likens 1972, Rabalais 1998, Wenner et al. 2004, Diaz and Rosenberg 2008). In the Salish Sea, low dissolved oxygen problems have been

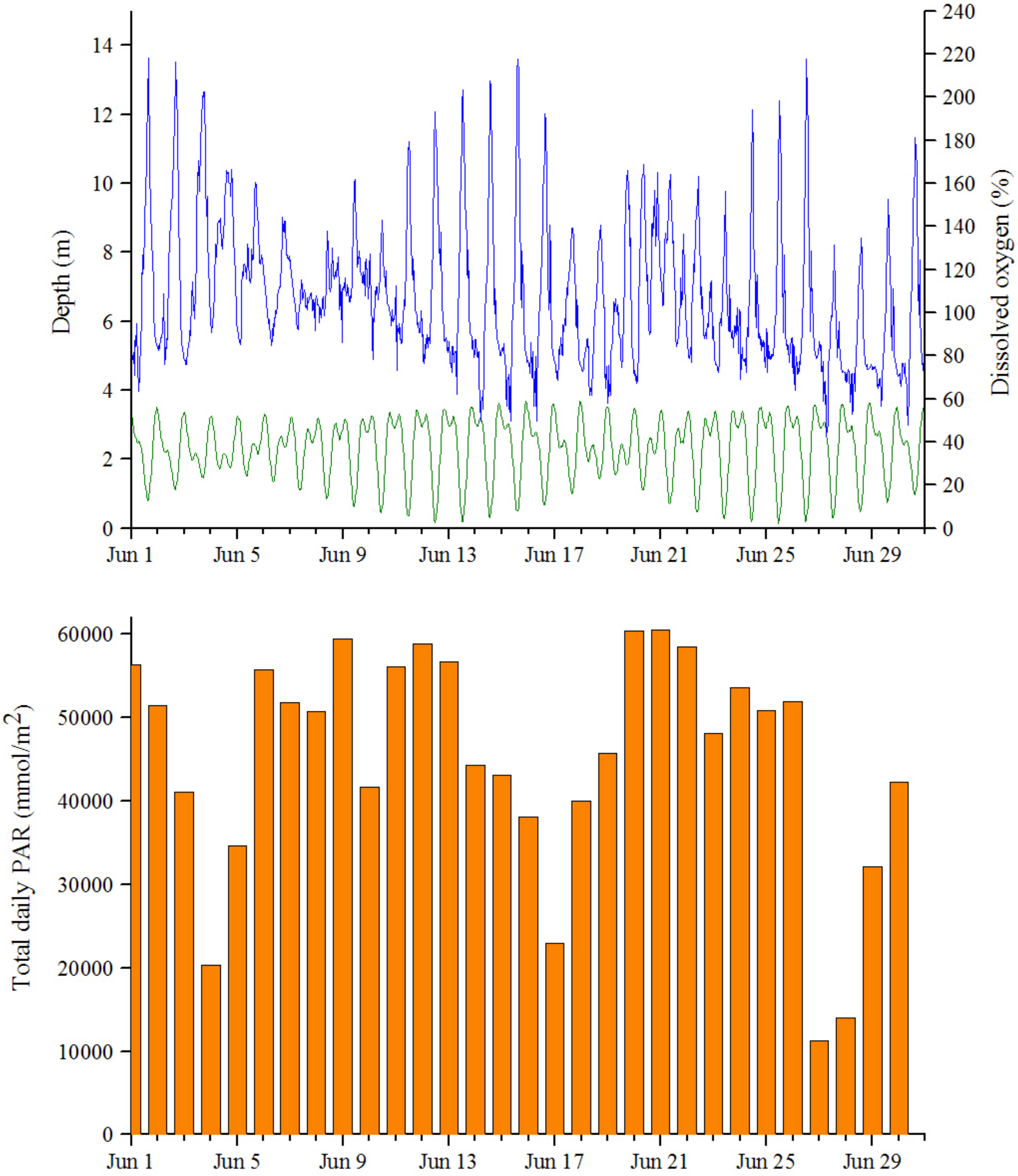


Figure 41. Depth (m) and dissolved oxygen (%) measured at the Bayview Channel water quality site, and total daily photosynthetically active radiation (PAR, mmol/m^2) measured at the Padilla Bay weather station from June 1-30, 2002. Depth is represented in green, dissolved oxygen in blue. Compare with Figure 43. (From Cottrell, Margerum, and Bulthuis unpublished data.)

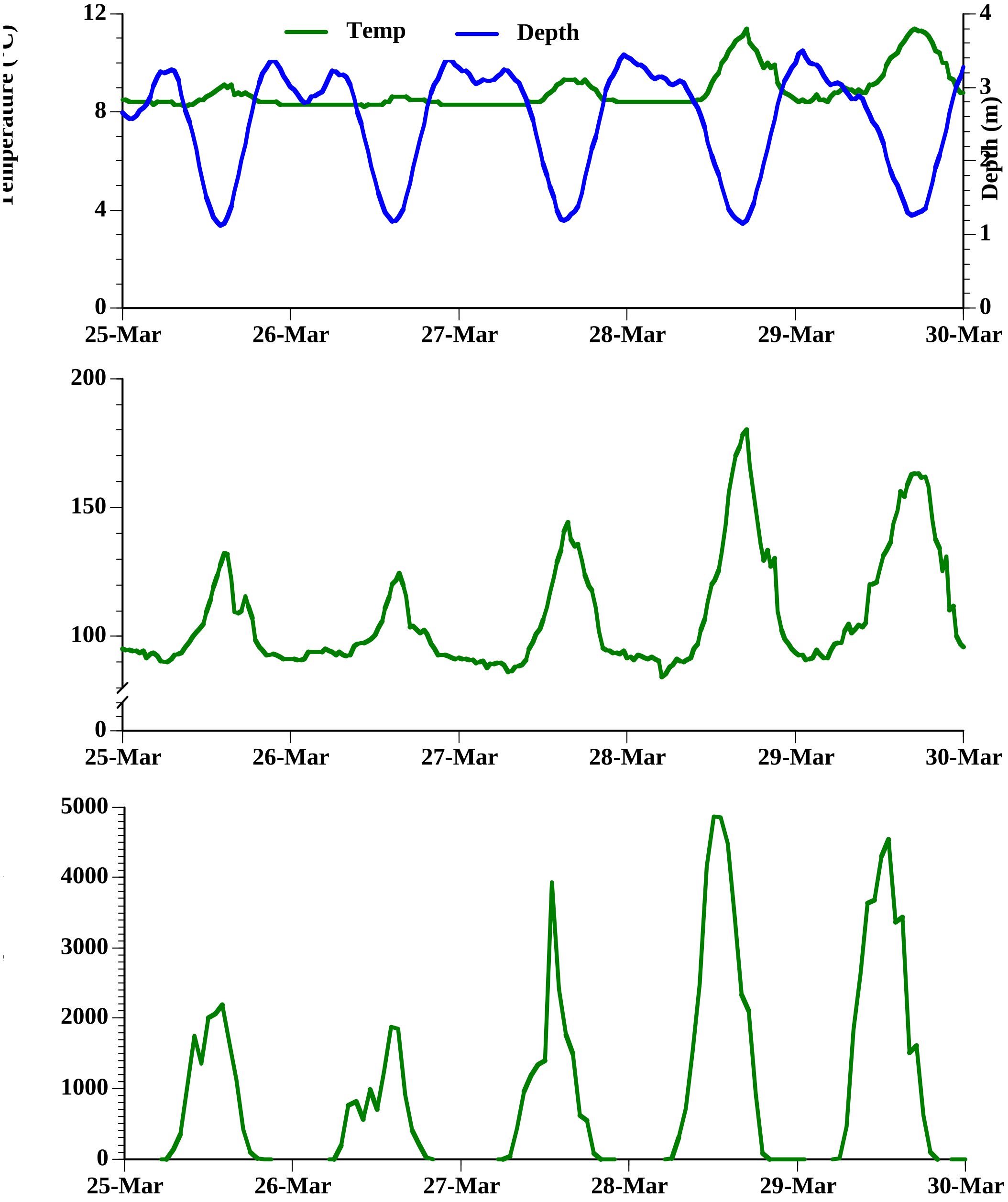


Figure 42. Dissolved oxygen, water depth, and temperature at Bay View Channel water quality site in Padilla Bay and photosynthetically active radiation (PAR) at the Padilla weather station near the southeast shore of Padilla Bay. Water quality parameters were measured every 30 minutes with a multiparameter datasonde. PAR was measured continuously with a LI-Cor sensor with hourly totals shown here. (From Cottrell et al. 2005)

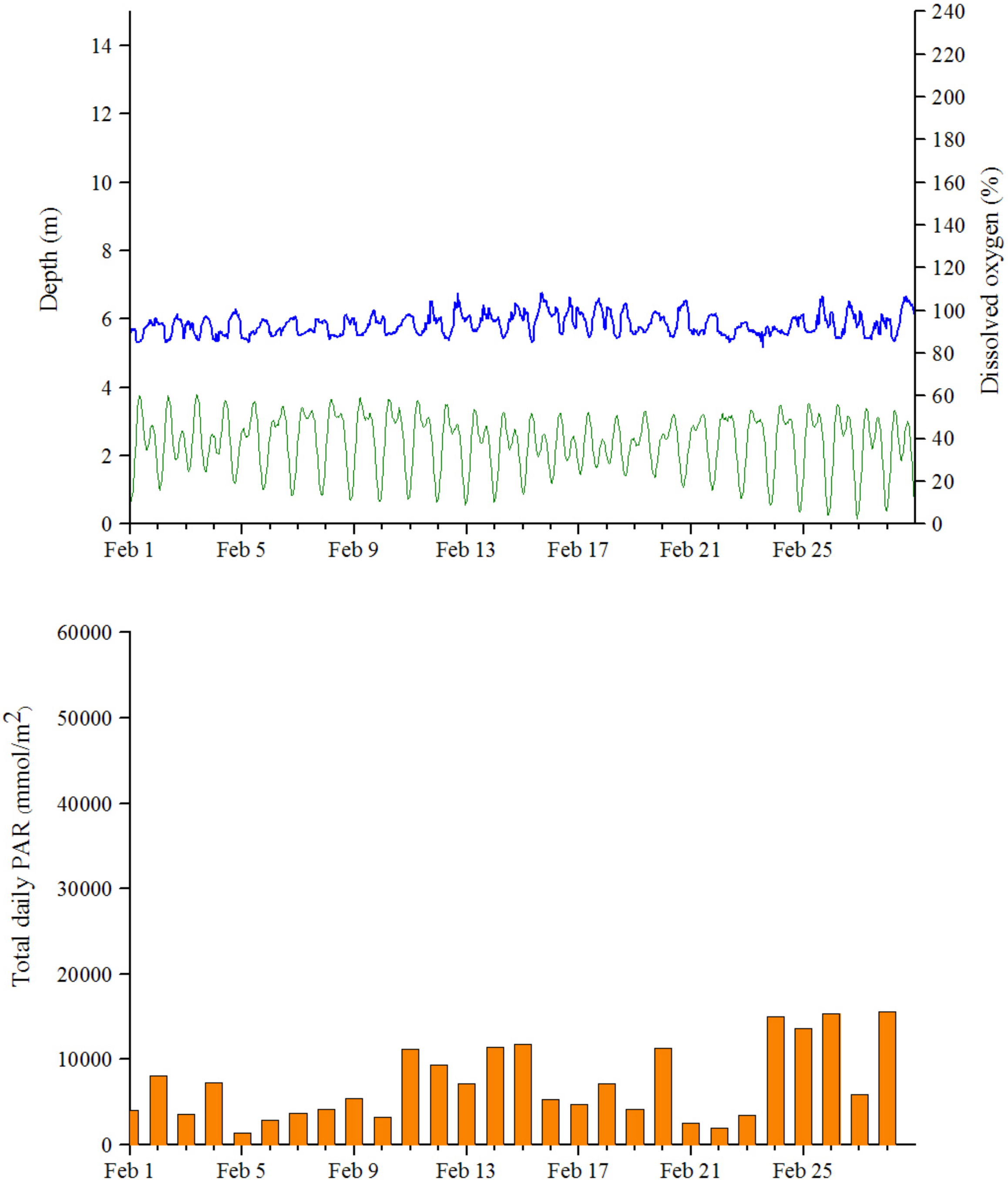


Figure 43. Depth (m) and dissolved oxygen (%) measured at the Bayview Channel water quality site, and total daily photosynthetically active radiation (PAR, mmol/m^2) measured at the Padilla Bay weather station from February 1-28, 2002. Depth is represented in green, dissolved oxygen in blue. Compare with Figure 41. (From Cottrell, Margerum, and Bulthuis unpublished data.)

recorded in Budd Inlet, Hood Canal, and other inlets and bays (Mackas and Harrison 1997, Newton et al. 2002). The dissolved oxygen data for Padilla Bay indicate that the concentration of dissolved oxygen is generally high and above the Washington State Water Quality standard of 6.0 mg/L and only rarely is a concentration below 2.0 mg/L (hypoxia) ever recorded. The daily tidal exchange with the northwest straits is an important factor in maintaining the dissolved oxygen in Padilla Bay. If water exchange were restricted, the high plant productivity could cause hypoxia and anoxia when it decays. An indication of the potential for such problems is provided by the daily dissolved oxygen data for Bayview Channel site (Figs. 39, 40, and 41). During summer months when the water is supersaturated during the day, the monthly minima and even the 10th percentile are below 5.0 mg/L because of nightly lows (Figs. 39, 40, and 41). These low concentrations occur even after super saturation during the day. If the community exerts that much oxygen demand on the water, then restricted water exchange could result in much lower concentrations. Bulthuis (1991) reported anoxia below floating algal mats that prevented water exchange below the mats with the overlying waters during high tide. However, hypoxia and anoxia are most often associated with deep areas that have limited oxygen exchange with the overlying water (e.g. Hood Canal, Budd Inlet, Sannich Inlet) and the shallow nature of Padilla Bay along with the high daily exchange of water with northwest straits make low dissolved oxygen and hypoxia very rare occurrences in Padilla Bay.

SUSPENDED SOLIDS AND TURBIDITY

Padilla Bay water is generally clear with low turbidity and low concentrations of suspended solids compared to many other estuaries. Turbidity at Bay View Channel was less than 25 NTU more than 95% of the time (readings every 30 minutes) over a two year period (Sanger et al. 2002). This placed Bay View Channel in the lowest 10% (lowest turbidity) of more than 50 sites in 22 National Estuarine Research Reserves around the nation in the summary of Sanger et al. (2002).

Turbidity at Bayview Channel in Padilla Bay ranged up to 143 during 2002 with monthly maxima of the 1440 turbidity measurements ranging from 10 to 143 and monthly means all below 10 NTU (Fig. 44). Turbidity is generally higher in winter months and lower in summer months, although this pattern is not always consistent.

Cassidy and McKeen (1986) reported highest turbidity in summer and lowest in spring over a 12 month study (Table 4). However, Bulthuis (1996c) did not see clear differences between summer and winter in either total suspended solids or turbidity (Fig. 46). In both of these studies surface samples were collected in Padilla Bay during high water when vessels could access central Padilla Bay. Thus, the water collected in both studies was that which had flowed into Padilla Bay from the northwest straits during the previous flooding tide. On the other hand, data collected from 1996 to 2005 with measurements of turbidity every 30 minutes indicated a clear seasonal trend with turbidity higher in winter and lower in summer (Fig. 47). In part these differences may reflect the episodic nature of turbidity peaks which measurements made every 30 minutes may include in the data record, while weekly or monthly sampling trips may miss these peaks. Thus, there are seasonal differences in turbidity in Padilla Bay with episodic high turbidities during winter and fewer such episodes and lower mean turbidity during spring and summer. The seasonal differences are probably due to a combination of stream and riverine input of suspended sediments during winter and spring, and wind generated suspended sediments during late fall and winter. Wind generated waves increase suspended solids and turbidity in Padilla Bay (Fig. 48). This may be particularly evident when water depth over the tidal flats is low. Tidal fluctuations also can cause changes in turbidity. During low water turbidity often increases (cf. Fig. 49). This increased turbidity during low water may be caused by tidal flow in the channels and/or by wind generated waves that re-suspend bottom sediments as depth over the flats decreases, and/or by organic and inorganic material ebbing from the eelgrass communities and into the channels.

NUTRIENTS

The nutrients, nitrogen and phosphorus, in the waters of Padilla Bay can best be understood in the context of the daily exchange of water with the northwest straits, the extensive intertidal flats in the bay, and the extensive eelgrass community. The total

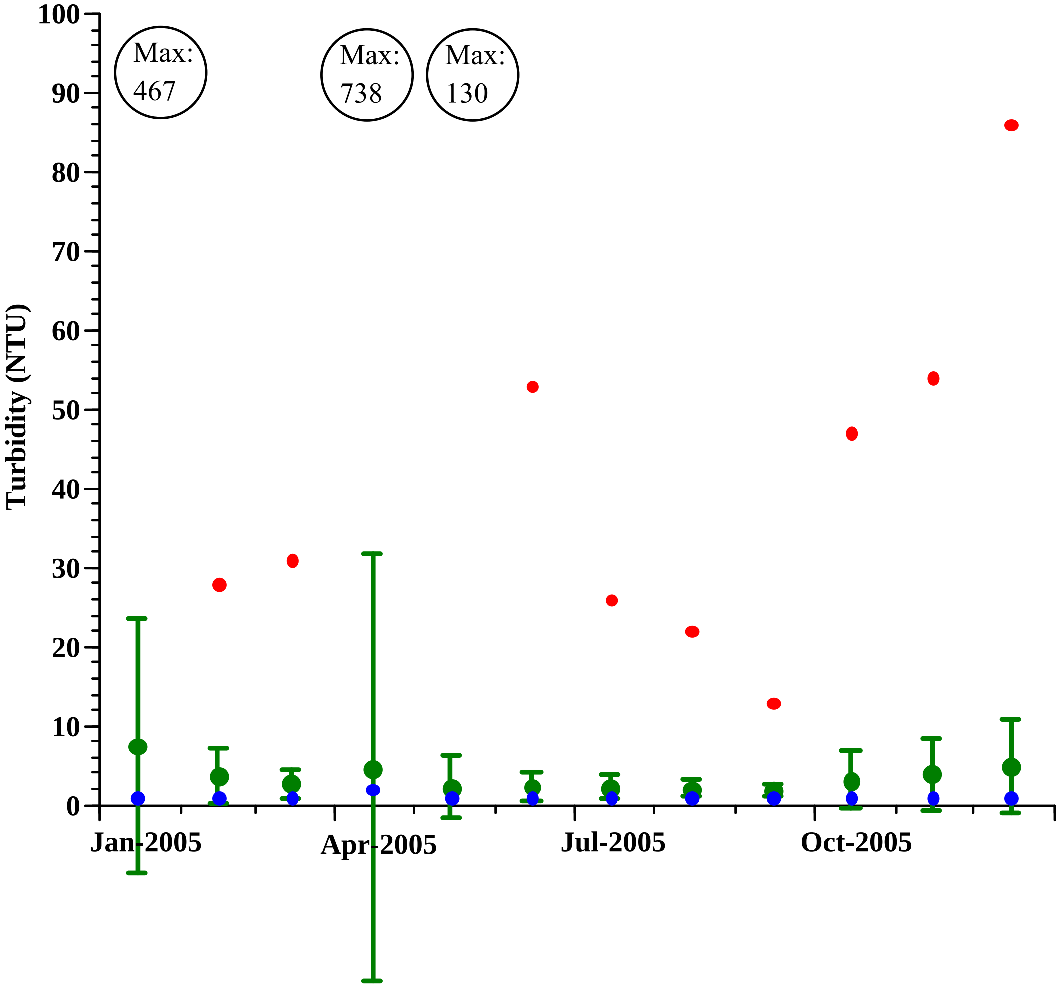


Figure 44. Mean (green circles), ± 1 standard deviation (green lines), maximum (red circles), and minimum (blue circles) turbidity (NTU) each month at Bayview Channel site in Padilla Bay during 2005. Monthly statistics are based on measurements taken every 30 minutes. (From Cottrell, Margerum, and Bulthuis unpublished data)

Table 4. *Mean seasonal turbidity (JTU) at six sites in Padilla Bay. Data from Cassidy and McKeen 1986. See Figure 45 for site locations.*

Site:	04	05	06	07	08	09
Summer	3.3	3.9	7.7	5.7	9.7	5.1
Fall	3.1	3.8	4.4	5.7	3.5	2.4
Winter	3.8	3.5	3.7	4.8	3.1	3.1
Spring	1.8	1.8	2.6	2.2	1.4	1.6

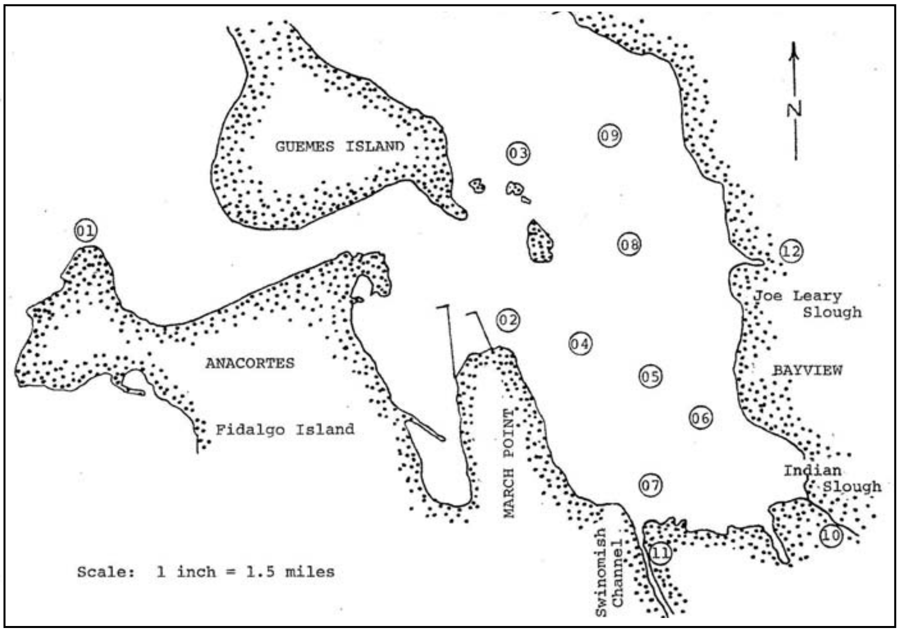


Figure 45. Location of sampling sites in Padilla Bay Baseline Water Quality Record by Cassidy and McKeen (1986).

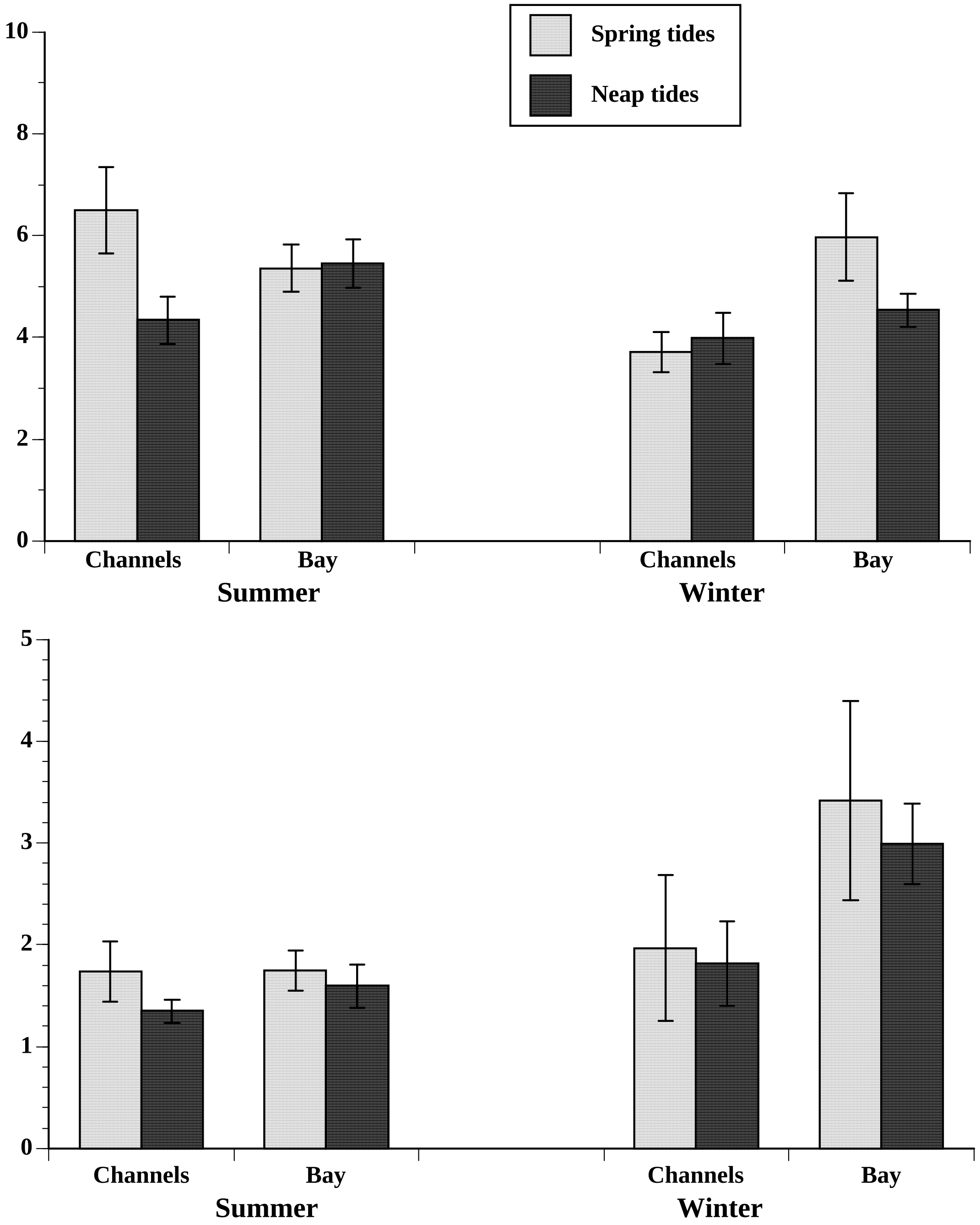


Figure 46. Total suspended solids and turbidity at two stations in the channels west of Padilla Bay and at four stations in the middle of Padilla Bay. Mean (± s.e.) of all stations within each category during four cruises during high tide in summer (July and August) and six in winter (December, January and February) during 1995-1996. (From Bulthuis 1996c)

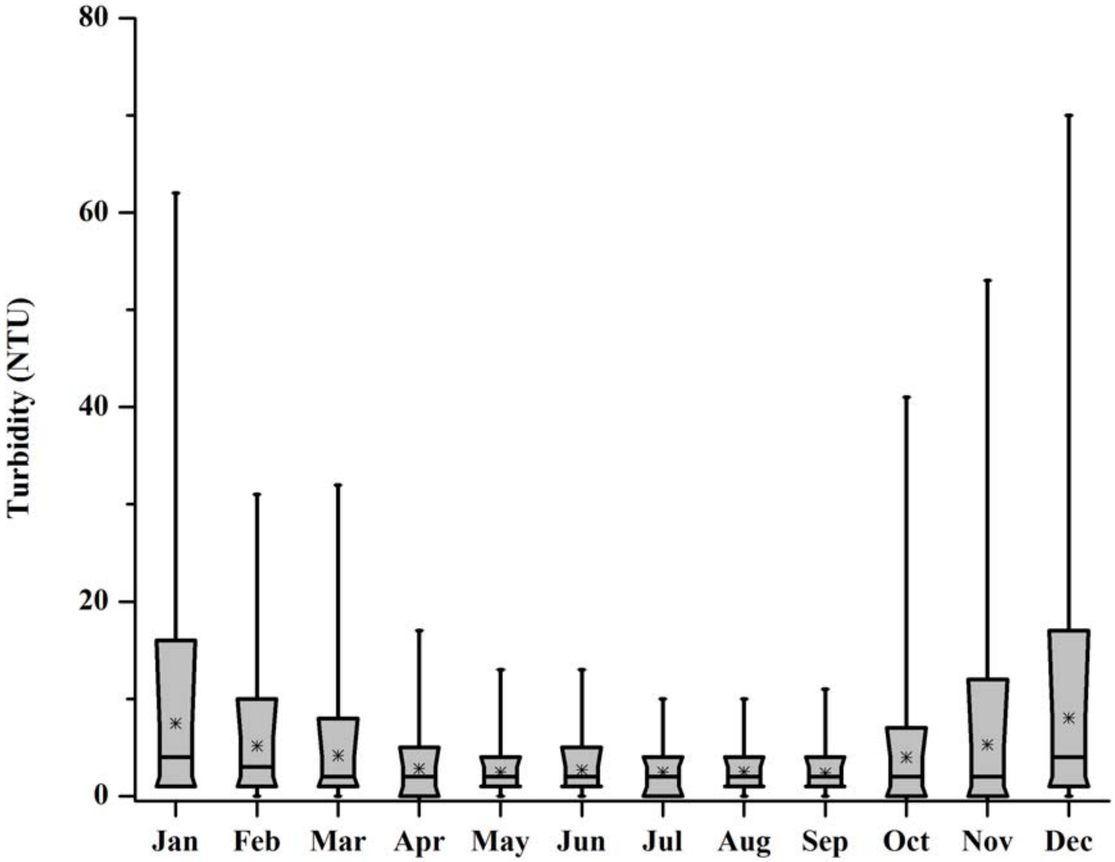


Figure 47. Turbidity at Bay View Channel water quality site over a 10 year period from 1996 through 2005. Mean (*), median (—), tenth and ninetieth percentiles (box) and one and ninety-nine percentiles (whiskers). Turbidity measured every 30 minutes with a multiparameter datasonde 0.5 m off the bottom in water depths ranging from 0.5 to 3.5 m. (From Cottrell, Margerum, and Bulthuis, unpublished data)

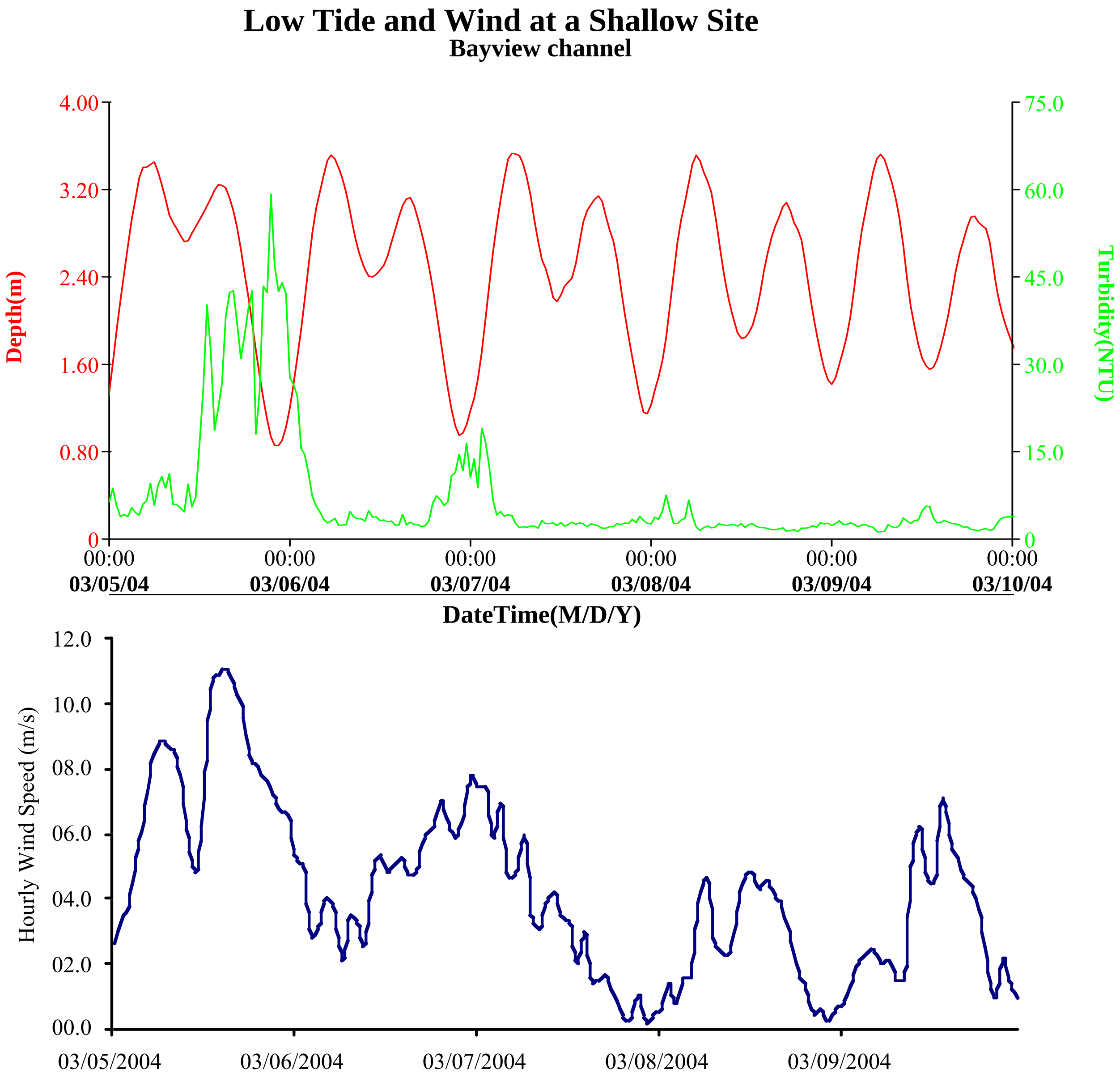


Figure 48. Turbidity (NTU) and water depth (m) at the Bayview Channel water quality site March 3-10, 2004. Turbidity and depth were measured every 30 minutes with a multi-parameter datasonde. Wind speed (hourly mean, m s^{-1}) was measured at the Padilla Demonstration Farm near the south east shore of Padilla Bay. (From Cottrell et al. 2005.)

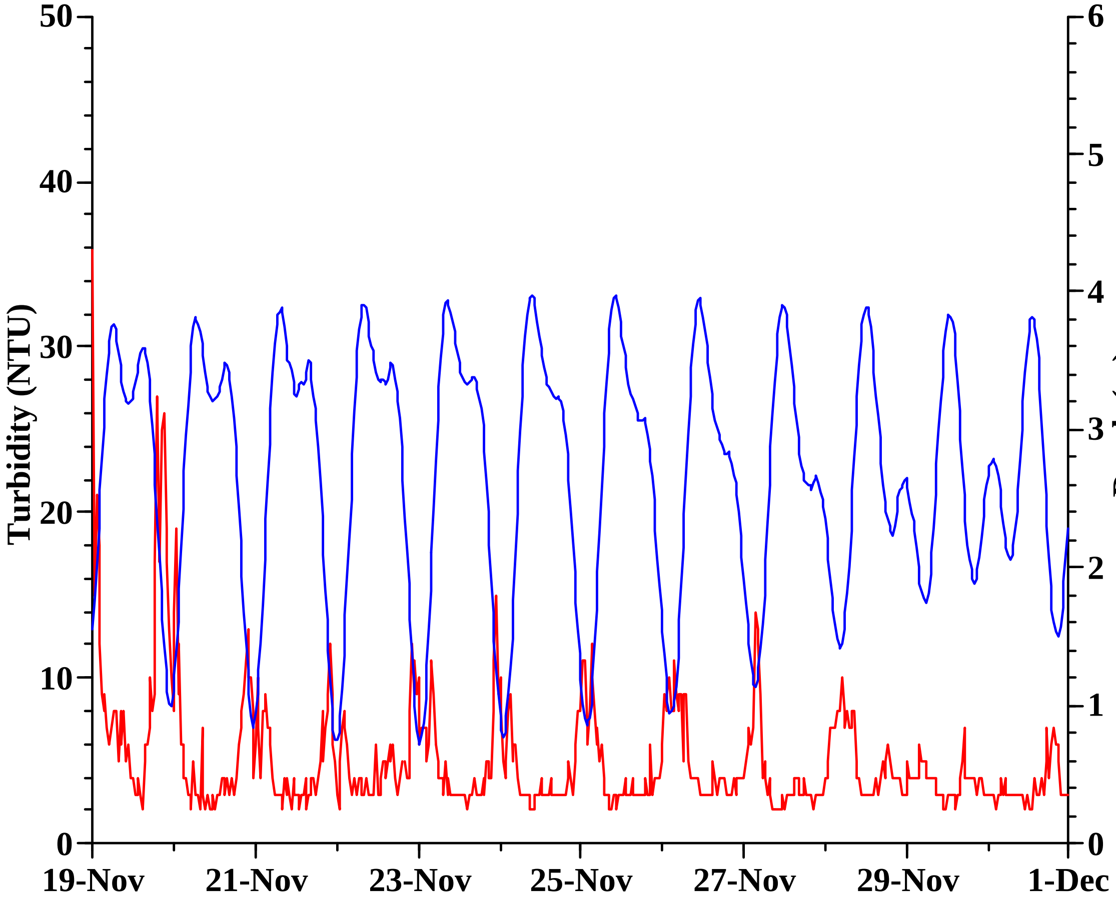


Figure 49. Turbidity (NTU) and water depth (m) at Ploeg Channel site November 19-30, 2002. Turbidity and depth were measured every 30 minutes with a multi-parameter datasonde. (From Cottrell, Margerum, and Bulthuis unpublished data)

nitrogen and phosphorus in the water can be divided into dissolved and particulate. The particulate fraction includes living phytoplankton, dead plant and animal material and inorganic suspended solids, all of which are often mixed in various combinations in a variety of particle sizes. It is the dissolved inorganic nitrogen and phosphorus that are the primary source of nutrients for plant growth, including phytoplankton, macro-algae, eelgrasses, and epiphytes of eelgrasses. Inorganic nitrogen in Padilla Bay is predominately nitrate, but ammonium is sometimes the major form of inorganic nitrogen when total dissolved inorganic nitrogen is very low (Table 5). Nitrite concentrations were always very low in the bay (Table 5).

Seasonal and tidal fluctuations in dissolved inorganic nutrients. Seasonal cycles of dissolved inorganic nitrogen (DIN: nitrate plus ammonium plus nitrite) were very strong in Padilla Bay (Bulthuis and Margerum 2005, Table 5). During 2002 and 2003, DIN fluctuated from highs near 30 µM in winter to below the detection limit, < 0.15 N µM, during summer (Fig. 50). Soluble reactive phosphate (SRP) was also higher in winter and decreased during summer (Fig. 50). However, soluble reactive phosphate only decreased to values of about one half of the winter peaks, from highs of about 2.5 µM to summer lows around 1 µM (Fig. 50). These seasonal fluctuations of DIN and SRP during 2002-2003 were similar to the seasonal fluctuations reported for Padilla Bay in Cassidy and McKeen (1986). They are also consistent with the seasonal pattern reported by Muller-Parker and Peele (1998). A variety of studies have measured nutrient concentrations in Padilla Bay as part of their data collection efforts usually as part of summer field studies (Bernhard and Peele 1997, Johnson 1993, Williams and Ruckelshaus 1993, and Brainard 1996). The data on dissolved inorganic nitrogen and soluble reactive phosphate from these studies was generally consistent with monthly means calculated from Bay View and Ploeg stations during 2002-2003.

The seasonal pattern of fluctuations of DIN and SRP in Padilla Bay is predominately a reflection of the seasonal pattern for north Puget Sound/Georgia Basin. Mackas and Harrison (1997) summarized data from many studies on nutrients in Georgia Basin. They stated, “Winter surface nitrate concentrations throughout the strait are similar to

Table 5. *Seasonal means (µM) of dissolved inorganic nitrogen at Ploeg Channel in Padilla Bay from March 2002 through February 2003. Each seasonal mean is based on duplicates collected on four to six dates. See Figure AR for location of sampling sites. (from Bulthuis, Cottrell, and Margerum, unpublished data)*

Season	Nitrate	Nitrite	Ammonium	Dissolved inorganic nitrogen
Spring (Mar-May)	8.47	0.15	1.64	10.27
Summer (Jun-Aug)	0.86	0.09	1.88	2.82
Autumn (Sep-Nov)	15.13	0.35	2.10	17.58
Winter (Dec-Feb)	26.19	0.28	1.30	27.77

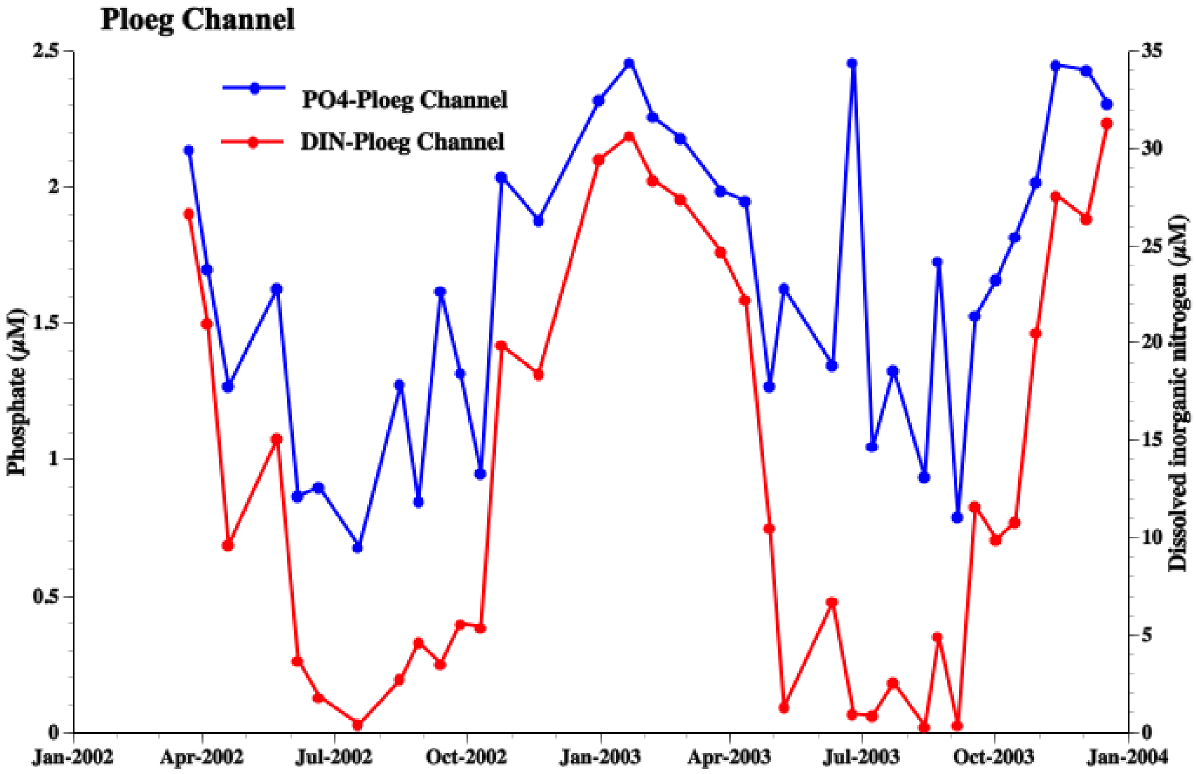


Figure 50. Dissolved inorganic nitrogen (DIN, nitrate plus nitrite plus ammonium) and soluble reactive phosphate (PO4) in water collected 0.5 m above the bottom in Ploeg Channel during 2002 and 2003. Mean of duplicate samples collected semi-monthly. (From Bulthuis and Margerum 2005)

concentrations in Strait of Georgia deep water (about 25 µM). Phytoplankton productivity and standing stock increase, and nitrate concentrations decline in March-June; the start of this seasonal progression is earliest in the vertically-stabilized Fraser River plume (Parsons et al. 1980, Clark and Drinnan 1980, Stockner et al. 1980). The annual nitrate minimum is June through August. This is the season in which potential impacts of eutrophication are greatest. Concentrations return to near their winter maximum by October." (Mackas and Harrison 1997, p 7). This description of the seasonal nitrate trends (which is the predominate form of DIN in the Strait of Georgia) for the Strait of Georgia applies also to the seasonal DIN trends for Padilla Bay (cf. Fig. 50).

The question of the effect of the eelgrass community on the concentrations of DIN and SRP in the water that flows into the bay from the channels and surrounding straits was addressed by consideration of diurnal fluctuations in Padilla Bay (Bulthuis and Margerum 2005). During a 26 hour sampling series on May 19-20, 2003, the higher low tide and lower high tide in Padilla Bay were very similar in height (Fig. 51). On these days, water flowed into Padilla Bay from the straits and channels east of the bay, flooded over the eelgrass flats and remained in the bay for about twelve hours. As water flooded into the bay past the Bay View Channel site, the concentration of DIN increased from about 3 µM to 9 and then 14 µM (Fig. 51). These data indicate that DIN concentrations in the straits and channels east of Padilla Bay were higher than the residual water in the bay at low tide. As the water remained in the bay over the next twelve hours, the concentration of DIN decreased (Fig. 51). It is suggested that this decrease is due to the biological activity of the eelgrass community. The low concentrations of chlorophyll in this water indicate that phytoplankton were unlikely to be the community responsible for the decreasing DIN. In contrast, the concentrations of soluble reactive phosphate remained similar throughout the tidal cycle (Fig. 51). It is suggested that, although there may have been exchange between the eelgrass community and the soluble reactive phosphate (SRP) in the water, the eelgrass community did not have a measurable net effect on the concentration of SRP in the overlying bay water.

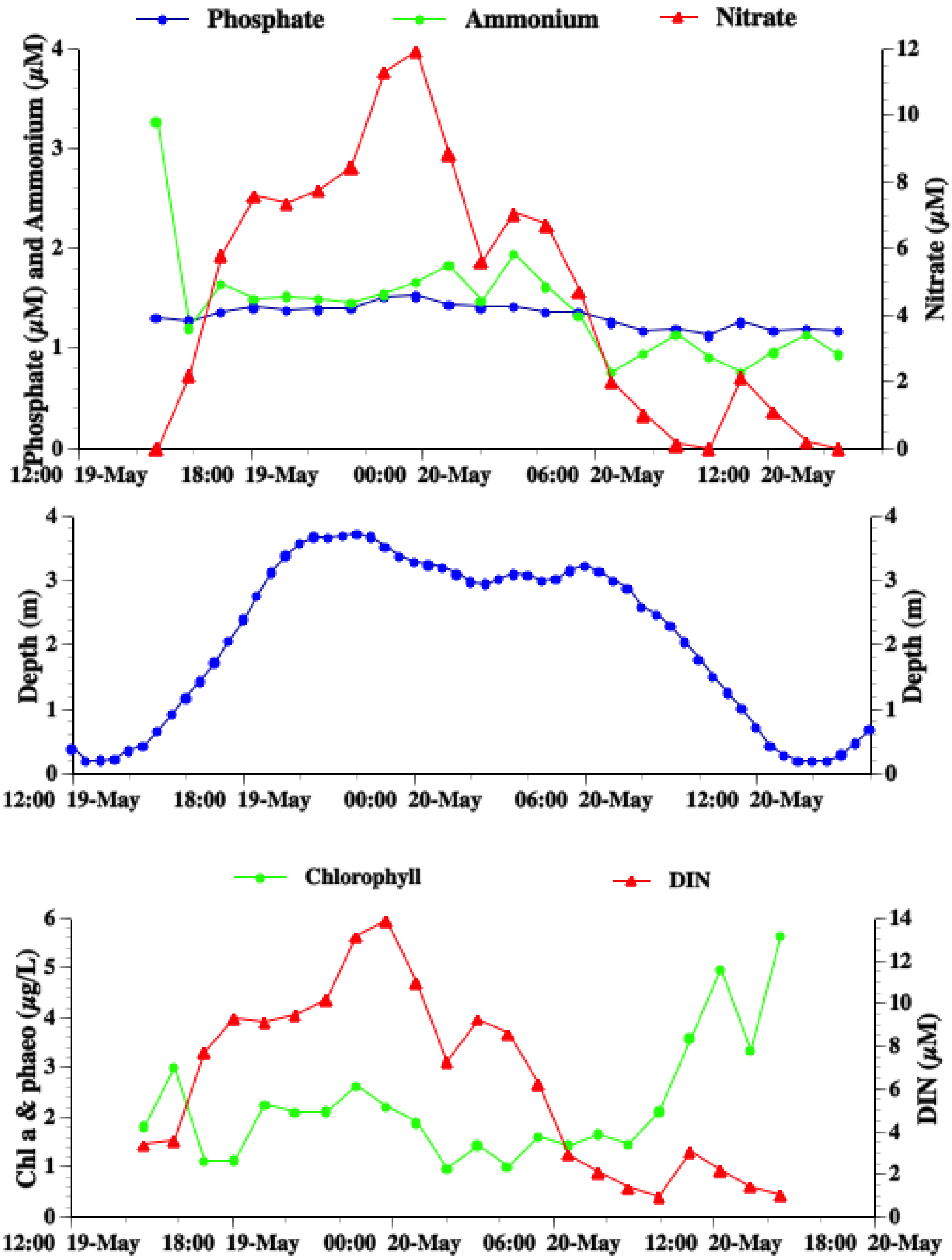


Figure 51. Nitrate, ammonium, dissolved inorganic nitrogen (DIN), phosphate, and chlorophyll *a* concentrations, and water depth, at 0.5m from the surface in Bay View Channel in samples collected every 68 minutes for 26 hours May 19-20, 2003. (From Bulthuis and Margerum 2005)

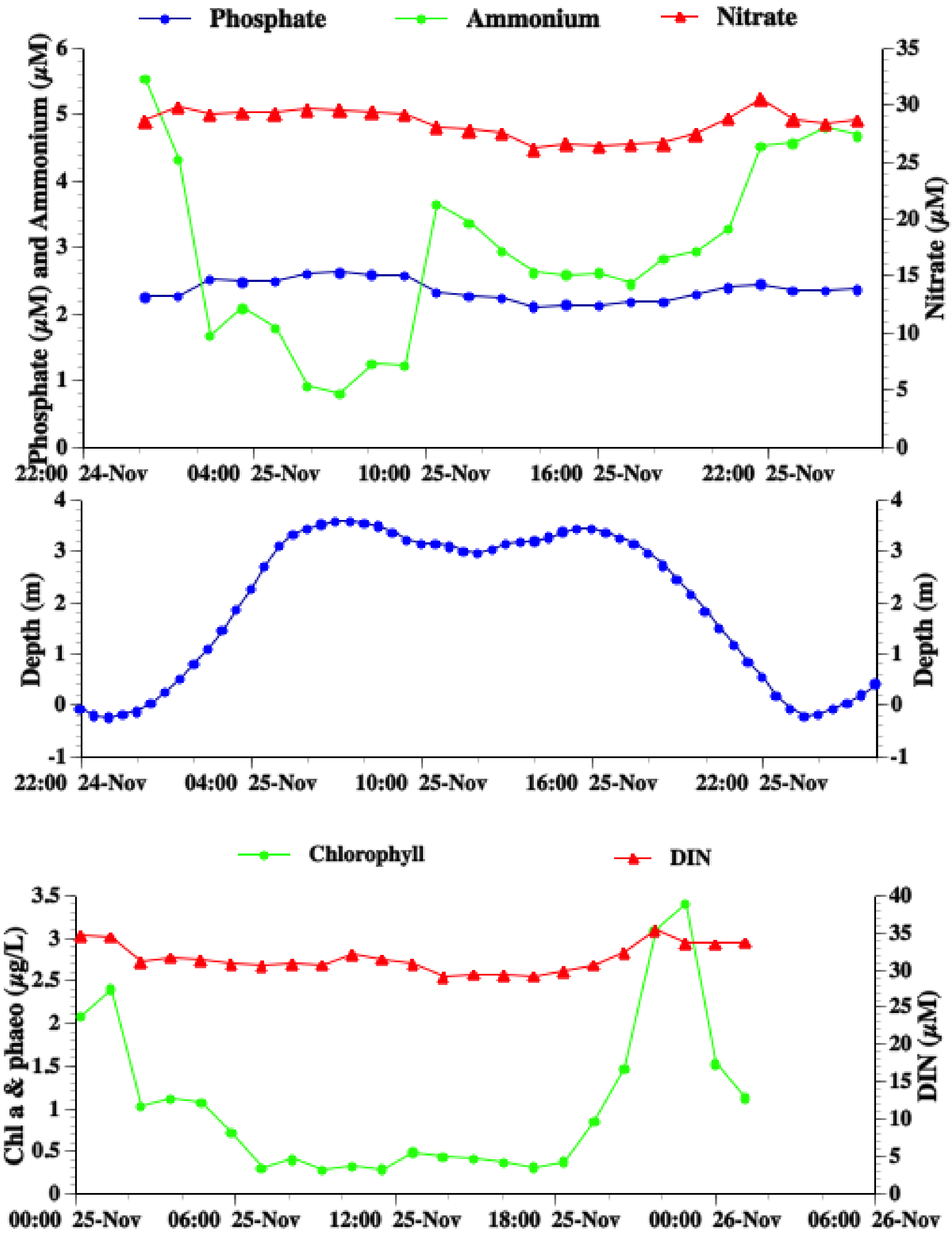


Figure 52. Nitrate, ammonium, dissolved inorganic nitrogen (DIN), phosphate, and chlorophyll *a* concentrations, and water depth, at 0.5m from the surface in Bay View Channel in samples collected every 68 minutes for 26 hours November 25-26, 2003. (From Bulthuis and Margerum 2005)

In contrast to the pattern seen in May, both DIN and soluble reactive phosphate during a 26 hour sampling series in November did not change during the tidal cycle (Fig. 52). DIN concentrations in November were more than twice the highest concentrations that were measured in May (cf. Figs. 51 and 52). Soluble reactive phosphate concentrations were similar throughout the tidal cycle in November and were about one and a half times the concentrations measured in May (cf. Figs. 51 and 52). It is suggested that the lack of change in the concentrations of both DIN and SRP indicate that the eelgrass community was not having a net effect on the concentration of dissolved inorganic nutrients in the water because of low rates of biological activity during November.

These diurnal patterns indicate that the eelgrass community (including eelgrass; epiphytes on the leaves; intermixed macroalgae and microalgae; the fauna in, on, and among the eelgrass plants; and the sediment and associated bacteria and fungi) in Padilla Bay absorbs dissolved inorganic nitrogen during spring and summer from the northwest straits waters that flood over the eelgrass community each day (Bulthuis and Margerum 2005). These spring and summer diurnal patterns also indicate that the nitrogen demand of the eelgrass community is being partially met by the northwest straits rather than from watershed nutrient inputs. On the other hand, during winter, these patterns indicate little impact of the eelgrass community on northwest straits waters.

This hypothesis (of absorption of dissolved inorganic nitrogen [DIN] from northwest straits waters in summer, but not during winter) is supported by spatial differences reported in 3 studies. Bulthuis (1996c) found that, during summer, DIN in the channels west of Padilla Bay had the higher concentrations than did mid-bay stations or stations close to the mouths of the major sloughs flowing into Padilla Bay (Fig. 53). Data from Cassidy and McKeen (1986) indicate mean concentrations of DIN in the bay less than half the means in the channels west of Padilla Bay in summer (Table 6). In contrast, DIN concentrations were similar in both locations in winter (Table 6). Data from the NERRS System-Wide Monitoring Program at Padilla Bay (Bulthuis unpublished data) indicate mean concentrations of DIN at a station inside the bay (Ploeg Channel 1.7 µM) is less than one third the concentration at a paired station outside Padilla Bay

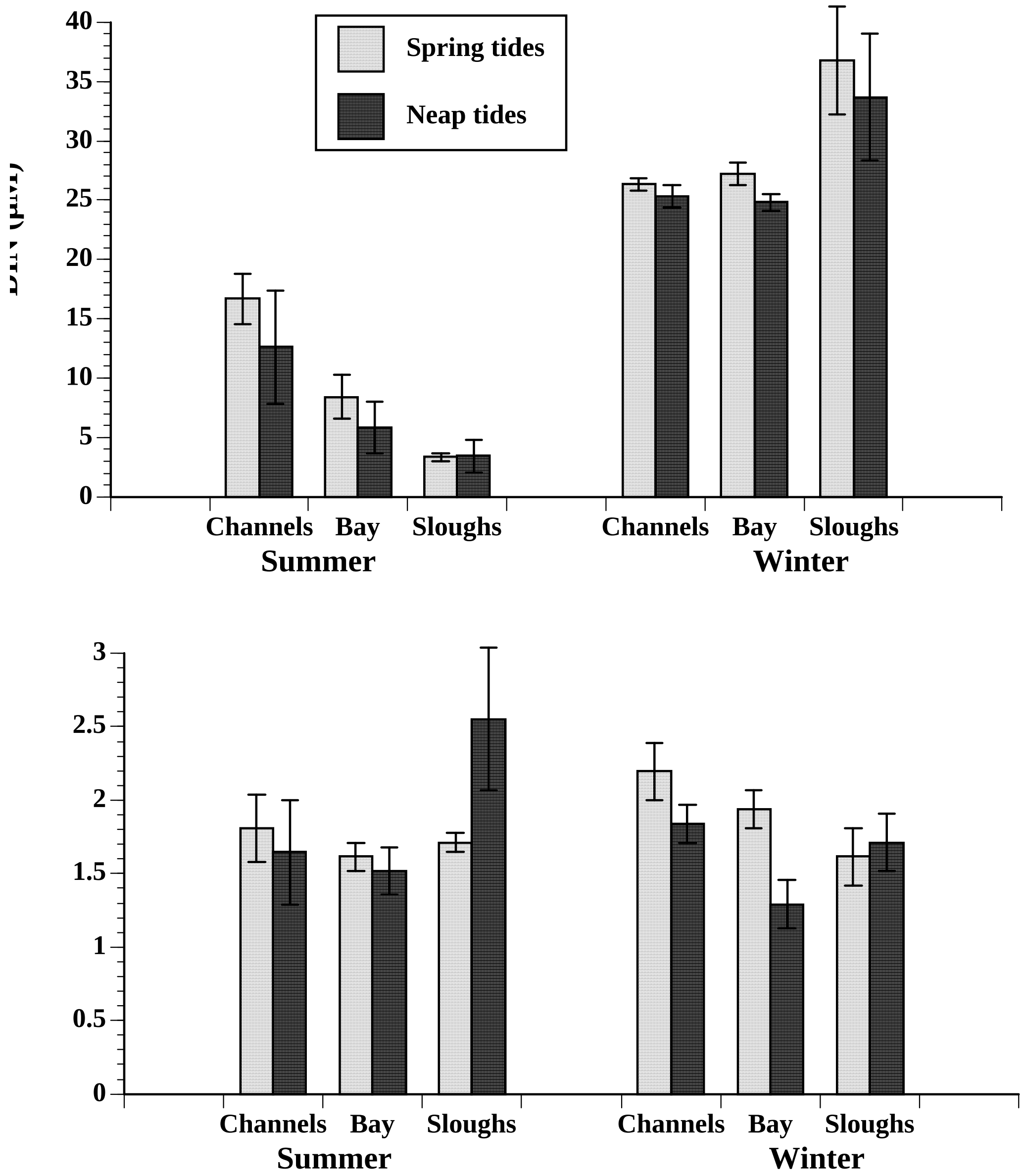


Figure 53. Dissolved inorganic nitrogen (DIN: nitrate, nitrite, and ammonium) and dissolved orthophosphate at two stations in the channels west of Padilla Bay, at four stations in the middle of Padilla Bay, and at two stations in Padilla Bay near the mouths of sloughs. Mean (± s.e. of the mean) of all stations within each category during four cruises during high tide in summer (July and August) and six in winter (December, January and February) during 1995-1996. (From Bulthuis 1996c)

Table 6. *Concentrations of dissolved inorganic nitrogen (DIN: nitrate plus ammonium plus nitrite) and soluble reactive phosphate in mid-Padilla Bay (means of five stations: 5, 6, 7, 8, and 9) and the channels west of Padilla Bay (means of three stations: 2, 3, and 4) during summer (June to August) and winter (December to February) during 1985-86. (See Figure 45 for location of sampling stations.) Calculated from data presented in Cassidy and McKeen (1986).*

Location	Dissolved inorganic nitrogen (µM)		Soluble reactive phosphate (µM)	
	Summer	Winter	Summer	Winter
Mid-Padilla Bay	4.7	30.2	1.3	2.3
Western Channels	10.3	30.7	1.1	2.4

Table 7. *Seasonal means (µM) of dissolved inorganic nitrogen (DIN) at the Ploeg Channel site in Padilla Bay and at the Gong site just west of the Padilla Bay tide flats from June 2003 through May 2004. Each seasonal mean is based on duplicates collected on four to six dates. See Figure 33 for location of sampling sites. (from Bulthuis, Cottrell, and Margerum, unpublished data)*

Site	Summer	Autumn	Winter	Spring
Ploeg Channel	1.7	17.8	29.2	6.17
Gong	5.3	20.0	28.9	13.9

(Gong, 5.3 µM) during summer (Table 7). During winter DIN concentrations inside and outside the bay were very similar (Table 7). Similarly, Muller-Parker and Peele (1998) measured DIN and SRP at two stations inside Padilla Bay and one station between Hat and Saddlebag Islands on 12 occasions over 18 months. During summer DIN at the channel site (Station 3) was about twice as high as the samples in Padilla Bay.

Interannual variation in dissolved inorganic nutrients. There are limited data for Padilla Bay to indicate either interannual variation or long-term trends. Limited comparisons with nutrient data collected in a variety of studies indicate a similar seasonal pattern for DIN and SRP in studies conducted in 1985-86, 1995-96 and 2002-03 (Cassidy and McKeen 1986, Bulthuis 1996c, Bulthuis and Margerum 2005). The lack of seasonal trend in SRP in 1995-96 may be due to the limited temporal distribution of samples collected in that study compared with Cassidy and McKeen (1986) and Bulthuis and Margerum (2005). The somewhat higher concentrations of DIN in winter in the 2002-03 study may indicate a trend of increased nitrogen inputs to the northwest straits in recent years or increased inputs to Padilla Bay from the sloughs that flow into the bay during winter. However, future monitoring is required to indicate whether this represents a trend, or whether 2002-03 was an anomalous year.

Total nitrogen and phosphorus. Total nitrogen and total phosphorus concentrations in the water in Padilla Bay indicate a weak seasonal pattern of slightly higher concentrations in winter and slightly lower concentrations in summer (Fig. 54). The dissolved fractions (DIN and SRP) comprise more than half and up to 85% of the total nitrogen and total phosphorus during winter, but less than half and at times less than 10% of the total nitrogen and phosphorus in summer (Fig. 55).

Chlorophyll *a*. Chlorophyll *a* in the water column in Padilla Bay is generally low. During October 2002 to April 2003 chlorophyll *a* was less than 2 µg/L in samples collected biweekly at two sites (Fig. 56). During late spring and summer, concentrations ranged up to 12 µg/L in both 2002 and 2003 (Fig. 56). The chlorophyll *a* measured in the

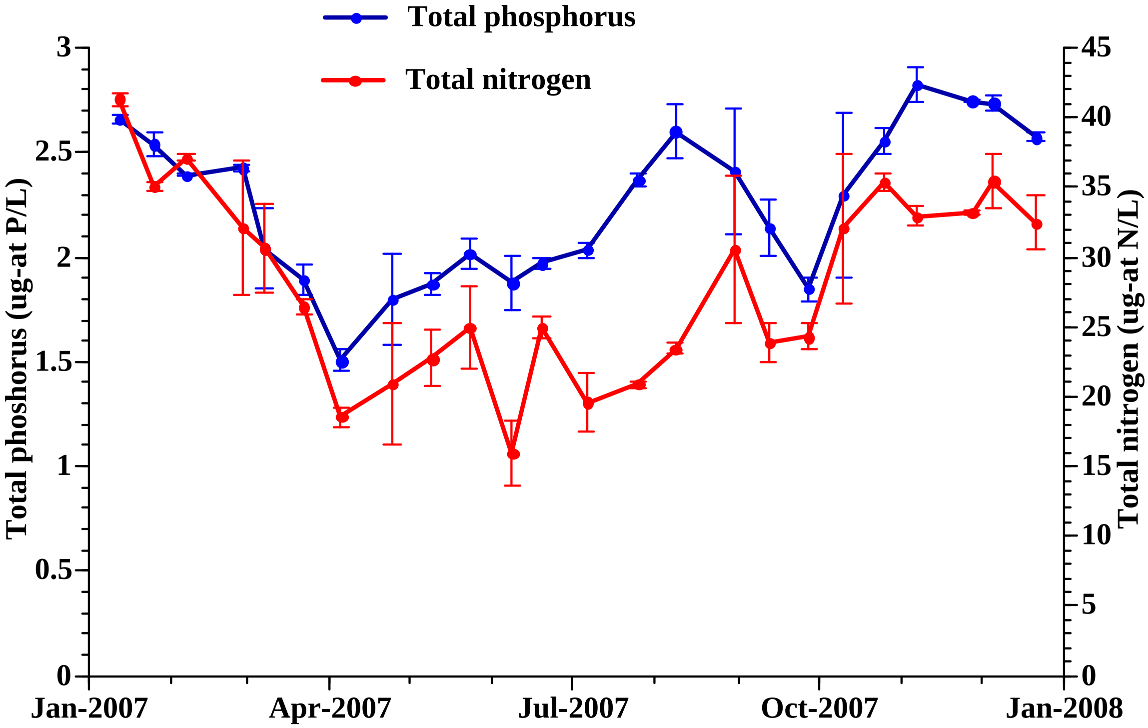


Figure 54. Total phosphorus and total nitrogen in Padilla Bay during 2007. Means (± standard error of the mean) of two sites in mid-bay (Bay View Channel and Ploeg Channel) at which duplicate samples were collected semi-monthly about 0.5 m above the bottom. (From Margerum, Burnett, and Bulthuis, unpublished data).

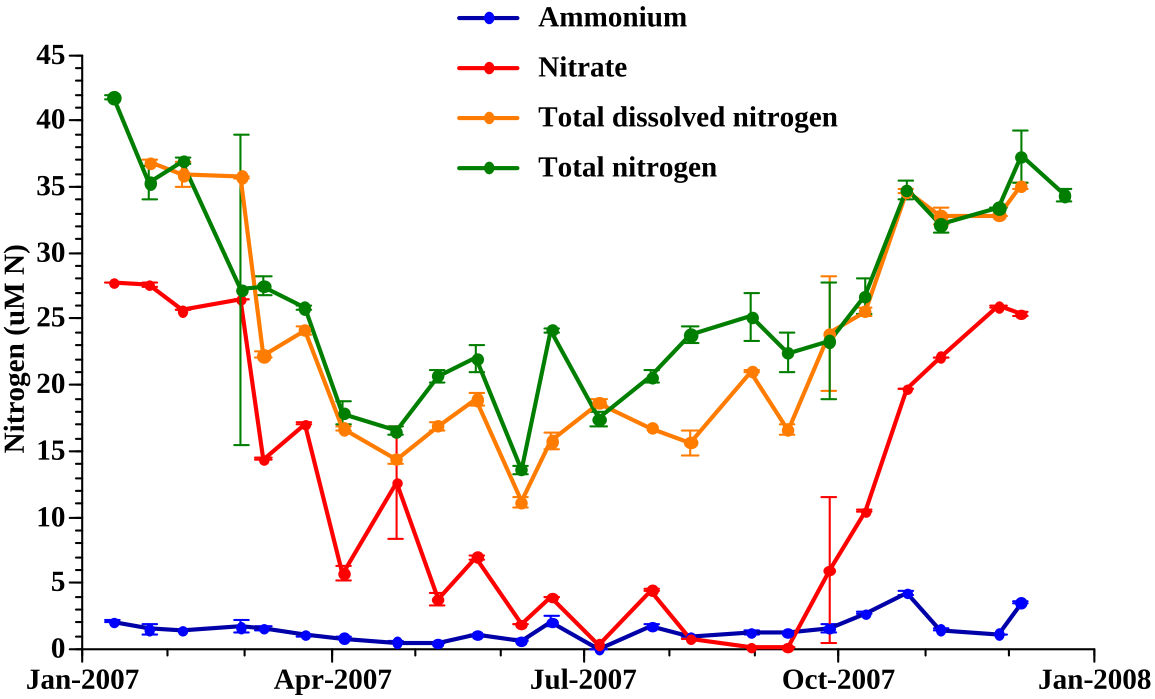


Figure. 55. Mean (± standard error of the mean, n=2) nitrogen concentrations in Padilla Bay at the Ploeg Channel site during 2007. Duplicate samples were collected twice a month. All concentrations reported as ug-at of N which is equivalent to uM for nitrate and ammonium. (From Margerum, Burnett, and Bulthuis, unpublished data)

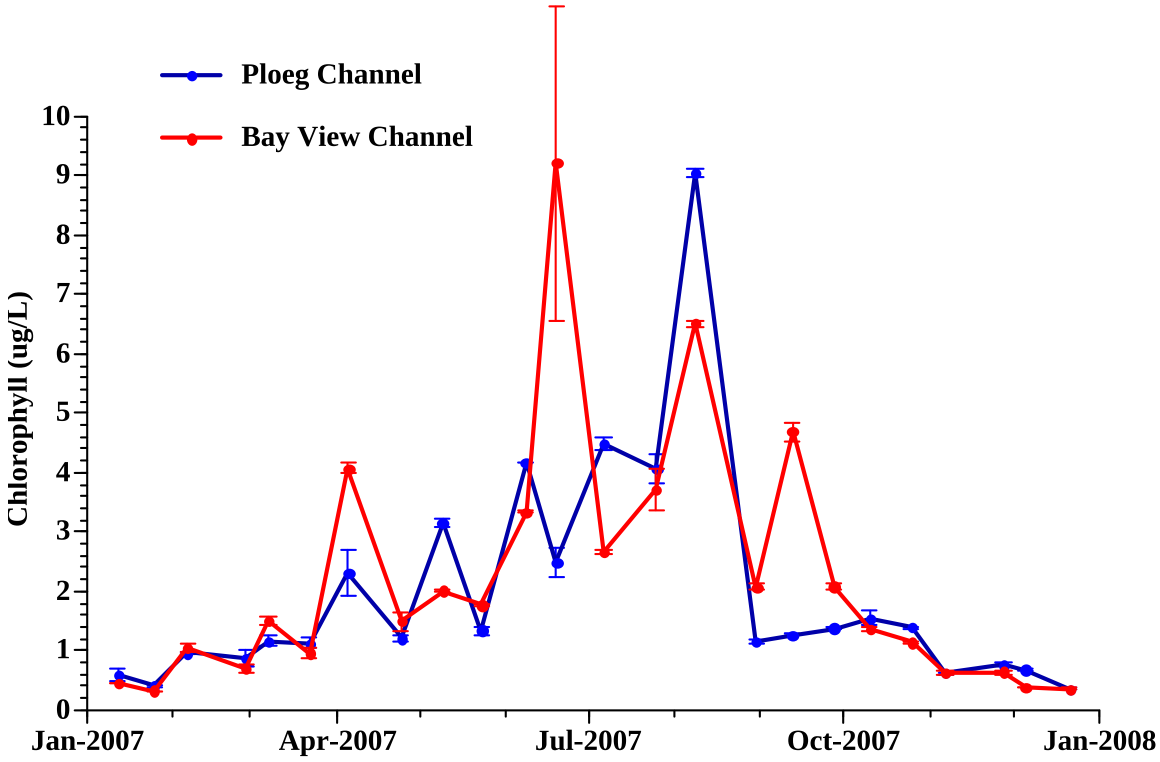


Figure 56. Chlorophyll *a* concentration (micrograms L-1) in Padilla Bay during 2007. Means (± standard error of the mean) at two sites in mid-bay (Bay View Channel and Ploeg Channel) at which duplicate samples were collected semi-monthly about 0.5 m above the bottom. (From Burnett, Margerum, and Bulthuis, unpublished data)

water column in Padilla Bay probably includes epiphytic algae that has become detached from the eelgrass leaves and epipelic algae that have been suspended from bottom sediments.

Sources of nutrients to Padilla Bay. Nutrient inputs from the Joe Leary Slough, the largest freshwater input to the bay from Padilla Bay watershed were estimated for a one year period based on weekly concentration data and flow measurements (Bulthuis 1996c). Most of the DIN and SRP entered Padilla Bay during the rainy months of November through February (Fig. 57). Nutrient inputs from the watershed were low during the summer (Fig. 57). These watershed nutrient inputs may be locally very important near the mouths of the sloughs. However, on a bay wide basis, the tidal exchange with the northwest straits brings in far more nutrients to the bay. A nitrogen budget for Padilla Bay has not been attempted. However, assuming a neap tide of 2 m (6 ft) and a total DIN concentration of 5 μM (cf. Fig 50), a single tide would bring 9.3 metric tons of DIN, more than the highest weekly total of 8.4 metric tons DIN from Joe Leary Slough (cf. Fig. 57).

Limiting nutrients to plants in Padilla Bay. The concentrations of DIN and SRP provide an indication that nitrogen may be the limiting nutrient rather than phosphorus for plants dependent on water column nutrients. The Redfield N:P ratio of 16:1 provides an indication of which nutrient will be in short supply (Ryther and Dunstan 1971). When ratios are below 16:1, nitrogen is likely to be limiting. Over a two year period, 2002-03, ratios were always below 16:1 in mid-Padilla Bay, and less than 5:1 during summer, the time of most active growth (Fig. 58).

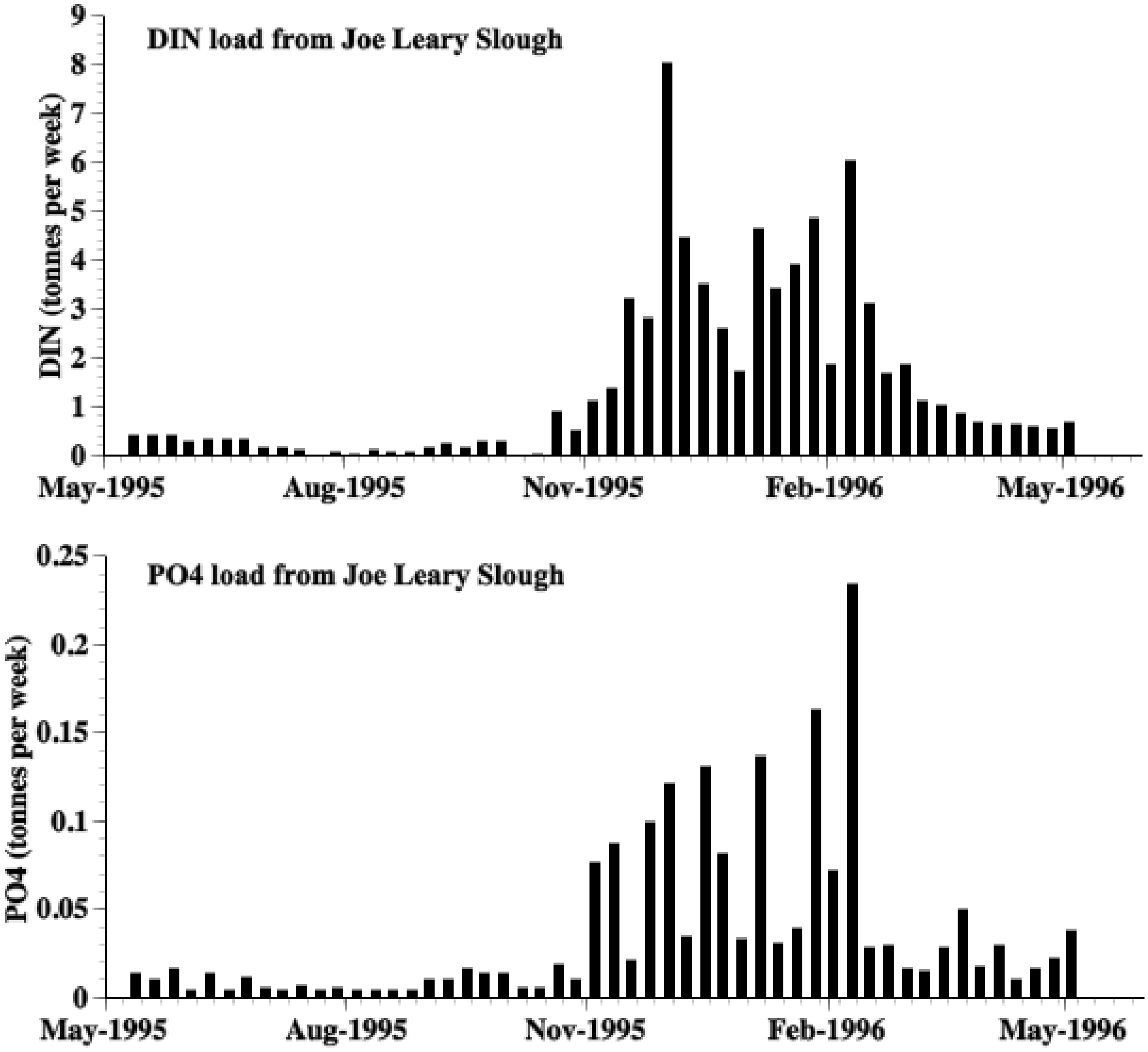


Figure 57. Export of dissolved nutrients to Padilla Bay from Joe Leary Slough during 1995-96. Flow was measured every 15 minutes to estimate weekly flow and dissolved inorganic nitrogen (DIN: ammonium, nitrate, and nitrite) and soluble reactive phosphate measured weekly for 13 months. (From Bulthuis 1996c)

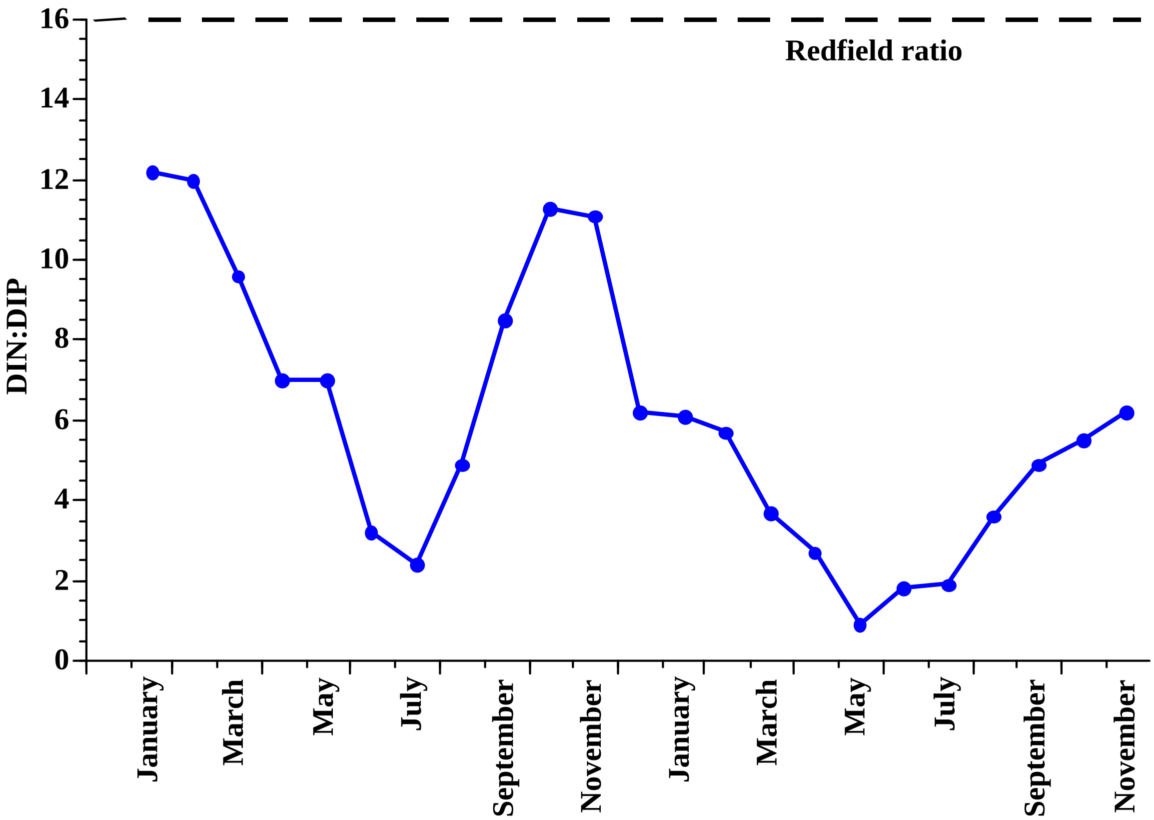


Figure 58. The ratio of dissolved inorganic nitrogen (DIN: ammonium plus nitrate plus nitrite) to soluble reactive phosphate (DIP) in Padilla Bay, Washington during 2002-2003. The Redfield ratio of 16:1 is indicative of ratios below which nitrogen is often limiting to plant growth and above which phosphorus is often limiting to plant growth. Monthly means of duplicate samples taken twice a month at two sites in mid-bay (Bay View Channel and Ploeg Channel). (From Bulthuis and Margerum 2005)

CONTAMINANTS IN PADILLA BAY

Contaminants may enter Padilla Bay in surface water flow from the watershed, groundwater flow, tidal flow from north Puget Sound, and via the atmosphere. Concern for toxicants or contaminants in Padilla Bay have been the impetuous for a variety of studies. The first reports on water quality in Padilla Bay were concerned with complaints that sulfite waste pollution from the pulp and paper mill in Anacortes was affecting oysters in Padilla Bay. Oyster growers reported that there was high mortality of oysters and that oyster "condition" was poor. Orlob et al. (1950) and Neale (1952) concluded that sulfite water liquor was not the cause for the decline in oysters. However, Sylvester and Clogston (1958) reported low measurable levels of spent sulfite liquor in the water in Padilla Bay.

Contaminants often adsorb to particulate matter and are deposited in the sediments. Therefore, most studies of contaminants in Padilla Bay have focused on the sediments. Long et al. (1999) sampled sediments in Padilla Bay as part of a widespread survey of sediment quality in Puget Sound. Sediments in Padilla Bay indicated significant results above background for both the sediment chemistry and toxicity for one of three sites in the bay (Long et al. 1999). Fitzpatrick (1999) surmised that Padilla Bay had equal or better sediment quality than average non-urban bays in Puget Sound based on toxicity tests and sediment chemistry. Barrick (1987) ranked Padilla Bay sediments as having an intermediate level of toxic chemical contamination. Gardiner (1992) concluded that Padilla Bay was intermediate in sediment surface toxicity compared to two other bays in Puget Sound. Thus, Padilla Bay sediments are generally neither pristine nor heavily contaminated.

Hydrocarbons. Barrick and colleagues extensively analyzed the hydrocarbon content of sediment cores throughout Puget Sound (Barrick et al. 1980, Barrick and Hedges 1981, Barrick and Prahl 1987). The concentration of combustion-derived polycyclic aromatic hydrocarbons in one Padilla Bay core was among the highest found in their study, and the calculated surface accumulation rate of these compounds was the highest reported for

Puget Sound. A second core from Padilla Bay indicated average concentrations of these compounds. On the other hand, Long et al. (1999) found that none of the Padilla Bay stations exceeded numerical guidelines for polycyclic aromatic hydrocarbons. The U.S. Fish and Wildlife Service (1994) reported polycyclic aromatic hydrocarbon concentrations above the "biological effects criteria" at one of about 12 sites in Padilla Bay. "Biological effects" were defined by the National Status and Trends Program as concentrations in the sediment at which the contaminant may affect sediment associated organisms. Fitzpatrick (1999) found slightly elevated total PAH concentrations in 20 of 27 samples throughout Padilla Bay, with the highest concentrations on the western side of the bay. Sites with the highest PAH concentrations had the highest amphipod mortalities in toxicity tests. These limited data indicate some hydrocarbon contamination in Padilla Bay but not high levels of contamination throughout the bay.

Trace metals. Trace metals in Padilla Bay sediments were in low concentrations in studies reported by Antrim (1985) and Long et al. (1999). However, U.S. Fish and Wildlife Service (1994) reported a few sites that exceeded "biological effects" levels for nickel, chromium, and zinc. The concentrations were based on reviews of numerous studies where the contaminant concentrations were related to biological effects (Long and Morgan 1991). Although some trace metals exceeded biological effects concentrations, the authors concluded that elevated contaminant residues in Padilla Bay were few and localized (U.S. Fish and Wildlife Service 1994). Johnson (2000) reported low concentrations of lead, cadmium, selenium, and mercury in crabs, clams, and oysters. Arsenic concentrations were at the "human health screening level" but similar to concentrations throughout Puget Sound. "Human health screening levels" were developed by Patrick (2000) using the approach outlined by EPA (U.S. Environmental Protection Agency 1995). The screening values reflect a daily chemical intake level which is unlikely to result in any adverse human health impacts over an individual's lifetime exposure.

Herbicides and pesticides. Herbicides and pesticides may be accumulated in sediments or some pesticide may enter the food chain and may accumulate in tissue or affect higher level predators. Mayer and Elkins (1990) reported only trace amounts of dicamba and 2, 4-D in sediments of Padilla Bay and did not detect any of fourteen herbicides that had been used that spring on crops in the watershed. Butler (1968) detected only trace amounts or no detectable concentrations of DDT, DDD, and DDE in oysters from Padilla Bay. Norman (1991) measured breast and liver tissue of nestlings and eggs of Great Blue Herons from the Samish Island colony. The concentrations were below the levels indicating acute toxic effects. U.S. Fish and Wildlife Service (1994) reported that organochlorines were not detected in bivalve samples and only traces of p', p' DDE in two of about 12 samples in the bay. Johnson (2000) reported low but detectable concentrations of DDT and other pesticides in oysters and crab muscle in Padilla Bay. He stated that these concentration likely reflect present day background levels (Johnson 2000). Fitzpatrick (1999) detected low concentrations of organophosphate pesticides in sediments at sites scattered throughout Padilla Bay. These limited studies indicate the presence of herbicides and pesticides at scattered locations in Padilla Bay sediments and biota. However, the concentrations are low and near background levels for non-urbanized bays and estuaries.

Toxicity of sediments and sea surface microlayer. Bioassays of sediments in Padilla Bay consistently report a low level of toxicity at a variety of sites in the bay, but without a clear source of the toxicity. These bioassays are standardized tests that are used to indicate the presence or absence of contaminants that might affect the biota in an estuary. Sediments and sea surface microlayers that show some level of toxicity in these tests may be affecting sensitive species in the community and thus altering community and food web dynamics. When these tests indicate high toxicity, further studies are needed to determine the ecological consequences of the toxicity. One approach to setting the toxicity tests into context is the triad approach in which toxicity, concentration of potential contaminants, and community composition are determined in sediments from one place and time (Long and Chapman 1985). This triad approach was used on sediments in Padilla Bay in a study by Long et al. (1999). The ecological and food web consequences of sediments and sea surface microlayer with moderate or high toxicity is often not known and has not been studied in Padilla Bay. DeWitt et al. (1989) reported no toxicity in an amphipod test at one site in the bay. Bulthuis and Shaw (1992) reported mean survival of 14 to 92 percent of the amphipod *Rhepoxinius abronius* at 16 sites in Padilla Bay, indicating slight toxicity to the amphipod throughout the bay. Gardiner (1992) compared sea surface film and surface deposit onto intertidal flats in Commencement Bay (near Tacoma), Padilla Bay, and Discovery Bay on the Olympic Peninsula. Using three toxicity tests, Padilla Bay was intermediate in toxicity compared to the other two bays. These results indicate that contaminants in the sea surface film and deposited on the sediments cause some toxicity to marine life in Padilla Bay. Long et al.(1999) reported significant toxicity in the sediments at one of three sites in Padilla Bay. Fitzpatrick (1999) reported that about 30% of sediment samples collected throughout Padilla Bay were toxic to the marine amphipod *Rhepoxinius abronius*. Most of the toxicity was correlated to the influence of grain size because *R. abronius* does not do well in very fine grain size sediments. However, toxicity in about 10% of the sites was not correlated with physical factors and was presumably due to anthropogenic contaminants (Fitzpatrick 1999).

Several toxicity studies have indicated high toxicity in the marine sediments near the Whitmarsh Landfill, also called the March Point Landfill, in the southwest corner of Padilla Bay. Milham (1986) reported slight and inconsistent concentrations of contaminants in sediments near the landfill, particularly of fluoranthene and toluene. Johnson (1989) reported moderately elevated levels of phenols. Bulthuis and Shaw (1992) reported survival rates of only 7% to 40% for the marine amphipod *Rhepoxinius abronius* in the upper 20 mm of sediments near the landfill. Wiggins (1992) reported very high toxicity (up to 100% mortality to amphipods in the top 20 mm of sediment near the landfill. However, Wiggins also found that the top 2 mm of sediment were not toxic to *R. abronius*, indicating that sedimentation is "capping" contaminated sediments at this site (Wiggins 1992).

These limited studies on contaminants and sediment toxicity indicate that in Padilla Bay most contaminants are either not detected or reported at very low concentrations similar to non-urbanized bays and estuaries. One exception is hydrocarbon contamination which is present at scattered locations throughout the bay, with some indication of higher concentrations on the western side of the bay. Sediment toxicity also is present at scattered locations throughout the bay, with highly toxic sediments near the Whitmarsh landfill in the southwest corner of the bay.

CHAPTER 4

ECOLOGICAL COMMUNITIES OF PADILLA BAY

Padilla Bay contains a wide diversity of estuarine plants and animals that live in a variety of habitats with various levels of inter-dependence and interaction. Some organisms move freely among the habitats; others occupy different habitats during different life stages, still others are generally found in only one or two of the habitats in Padilla Bay. In this chapter, Padilla Bay has been divided into several habitats or communities such as the eelgrass communities that include eelgrasses, macroalgae, epiphytes, infauna, epifauna, plankton, and nekton; salt marshes; rocky habitats; and estuarine channels. A summary is made in this chapter of what is known about the communities and organisms within each of these habitats based on studies conducted in Padilla Bay and/or nearby areas.

EELGRASS COMMUNITES

Intertidal eelgrass (*Zostera marina* and *Z. japonica*) is the most extensive habitat in Padilla Bay and the most important of the habitats in terms of defining the habitat value of the bay as a whole. For the last couple of decades Padilla Bay has been considered a valuable estuarine embayment requiring protection primarily because of the extensive eelgrass beds and the associated fish, shellfish and birds (Jeffrey 1976, Jeffrey *et al*. 1977, Sylvester and Clogston 1958, Koons and Cardwell 1981). Preservation of the intertidal eelgrass habitat and the connected fauna was a major impetus behind the nomination and designation of Padilla Bay as a National Estuarine Research Reserve (National Oceanic and Atmospheric Administration and Washington State Department of Ecology 1980).

AERIAL EXTENT OF EELGRASSES

Padilla Bay contains one the largest contiguous stands of eelgrasses along the Pacific Coast of North America (Bulthuis 1995). Webber et al. (1987) and Morton (1988) made the first estimates and distribution maps of eelgrasses in Padilla Bay in the mid 1980's. Based on satellite imagery, they distinguished four classes of seagrass cover: very sparse (less than 10% cover), sparse (approximately 40% cover), and high intertidal and low intertidal/subtidal (both with 100% cover). Excluding the area of very sparse coverage, Webber *et al*. (1987) estimated 3097 hectares of eelgrass in Padilla Bay with an additional 823 hectares around March Point (Table 8). Bulthuis (1991) used color aerial photography to map the distribution and area of habitats in Padilla Bay (Table 9). Six classes of seagrass cover were distinguished based on dominate species (*Zostera marina*, *Z. japonica*) percent cover (5-20%, 21-50%, 51-100%) and elevation (subtidal, intertidal). Total area of eelgrass in Padilla Bay east of Swinomish Channel (within Padilla Bay boundaries and comparable to Padilla Bay as defined by Webber *et al*. 1987) was about 3018 hectares. Shull (2000) used hybrid-classification techniques on Compact Airborne Spectrographic Imager data to delineate eelgrasses and other vegetation in Padilla Bay. Within the Padilla Bay NERR boundaries, Shull estimated 2824 hectares of intertidal and subtidal *Zostera* spp. in 1996. In 2000 Bulthuis and Shull (2002) estimated 3867 hectares of cover by *Zostera* spp. based on on-screen digitizing of color aerial photographs. Using similar methods, Bulthuis and Shull (2006) delineated 3800 hectares of eelgrass in Padilla Bay in 2004. Porter et al. (2006) also obtained imagery in 2004. They estimated 4046 hectares of eelgrass in Padilla Bay. These six studies, conducted over 18 years from 1986 to 2004, indicate an extensive area of some 3800-4000 hectares of intertidal and shallow subtidal seagrasses with moderate to dense cover of the eelgrasses *Zostera marina* and Z. *japonica* (Table 10).

DISTRIBUTION WITHIN PADILLA BAY

Two species of eelgrass grow on the intertidal and subtidal flats in Padilla Bay. *Zostera marina* is a "native" eelgrass that is widely distributed on the west coast of North America. *Z. marina* has a worldwide distribution that includes eastern North America and Europe. *Zostera japonica* apparently was introduced to the Pacific Northwest in the early 1900's (Harrison and Bigley 1982), and is now common on the Washington coast,

Table 8. *Area of eelgrass in Padilla Bay in 1986 as estimated by Webber et al. (1987) from satellite imagery. Webber et al. did not consider the very sparse seagrass/algae category as "seagrass" covered habitat.*

Cover category	Area (hectares)
(very sparse seagrass/algae)	(463)
Sparse seagrass cover	717
Complete seagrass cover - high intertidal	495
Complete seagrass cover-low intertidal, subtidal	1885
Total seagrass in Padilla Bay east of Swinomish Channel	3097

Table 9. *Area of eelgrass in Padilla Bay in 1989 based on color aerial photography and ground truth observations. The first five categories are intertidal. (From Bulthuis 1995)*

Cover category	Area (hectares)	
Zostera japonica	236	
Zostera japonica with *Z. marina*	81	
Zostera marina 5-20% cover	297	
Zostera marina 21-50% cover	839	
Zostera marina 50-100% cover	1326	
Subtotal intertidal *Zostera* spp. in Padilla Bay	2779	2779
Zostera marina subtidal		239
Total *Zostera* spp. in Padilla Bay east of Swinomish Channel		3018

Table 10. *Total area of submerged and emergent vegetation in Padilla Bay in 2000 (Bulthuis and Shull 2002) and 2004 (Bulthuis and Shull 2006) and the gains or losses for each classification category.*

Classification category	**Area (hectares) 2000**	**Area (hectares) 2004**	**Area (hectares) Gain or Loss**
Zostera marina intertidal 51-100%	2779	2448	-331
Zostera marina intertidal 11-50%	50	194	144
Zostera marina subtidal	217	471	254
Zostera marina/Algae Mixed intertidal 51-100%	-	17	
Zostera marina/Algae Mixed intertidal 11-50%	-	1	
Total *Zostera marina*	**3046**	**3131**	**85**
Zostera japonica intertidal 51-100%	722	417	-305
Zostera japonica intertidal 11-50%	114	53	-61
Zostera japonica/Zostera marina Mixed intertidal 51-100%	-	155	
Zostera japonica/Zostera marina Mixed intertidal 11-50%	-	20	
Zj/Zm/Algae Mixed intertidal 51-100%		15	
Zj/Zm/Algae Mixed intertidal 11-50%	-	9	
Total *Zostera japonica*	**836**	**669**	**-167**
Total *Zostera*	**3882**	**3800**	**-82**
Macroalgae 51-100%	124	263	139
Macroalgae 11-50%	80	88	8
Total Macroalgae	**204**	**351**	**147**
Salt marsh	47	58	11
Total Vegetation	**4133**	**4209**	**76**
Intertidal bare	1145	1156	11
Subtidal bare	926	836	-90

northern Puget Sound, and southern Strait of Georgia. Harrison and Bigley suggest that *Z. japonica* spread to the Pacific Northwest via introduction of the Japanese oysters, *Crassostrea gigas* Thunberg. The first introduction of Japanese oysters were made in 1902 to Samish Bay, immediately north of Padilla Bay. Japanese oysters were widely planted in Padilla Bay in the 1930's (Dinnel 2000). Thus, Samish Bay and Padilla Bay may be the sites of some of the first introductions of *Z. japonica* to the Pacific Northwest.

Zostera japonica is generally distributed higher in the intertidal than *Z. marina* in Padilla Bay (Figs. 3 and 59, Thom 1990, Bulthuis 1995, Bulthuis and Shull 2006). In addition, *Z. japonica* is widely distributed in small patches throughout Padilla Bay, particularly on channel berms and hummocks along channel edges (Hahn 2003, Bulthuis personal observation). The two species grow intermixed near the upper distribution of *Z. marina* and the lower distribution of *Z. japonica* (Bulthuis 1991, Bulthuis and Shull 2006). Harrison (1982a, 1982b, 1993) and Nomme and Harrison (1991a, 1991b) have shown evidence from field measurements and laboratory studies in Georgia Basin/Puget Sound that distribution of *Z marina* in the higher intertidal region is likely to be limited by physical factors of desiccation and temperature. When both species were grown together in the laboratory, *Z marina* grew taller and above *Z. japonica* and out competed *Z. japonica* for light (Harrison 1982a). In its native distribution in Asia, *Z. japonica* grows in subtidal as well as intertidal conditions (DenHartog 1970). Thus, the lower limit of distribution of *Z. japonica* may be limited by biological competition with *Z marina* (Harrison 1982a, 1993). However, both of these explanations (desiccation tolerance and biological competition) have been challenged by studies in Padilla Bay. Shafer et. al. (2007) found that *Z. japonica* was more severely affected by desiccation than *Z marina*. As for biological competition, Hahn (2003) transplanted *Z. marina* and *Z. japonica* in Padilla Bay in areas dominated by each species and in areas where the two species were intermixed. After 18 months *Z. japonica* persisted both in monoculture and in mixed beds across all zones to which it was transplanted. Hahn (2003) reported that there were differences among sites within Padilla Bay. He suggested that *Z. marina* may be dominating in areas where it is already established, but that Z. *japonica* may continue to

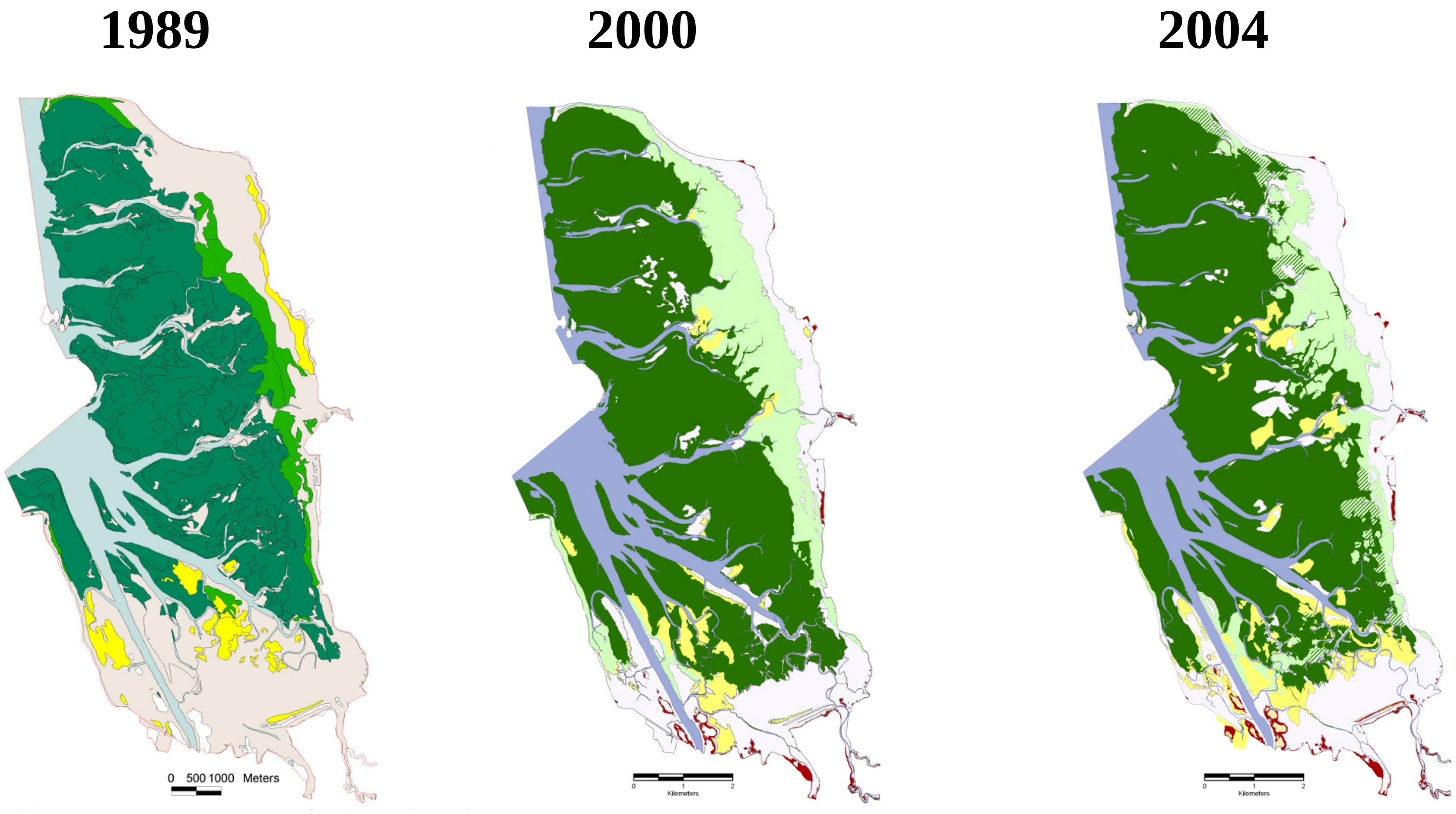


Figure 59. Distribution of *Zostera marina* (dark green) *Z. japonica* (light green) and macroalgal mats (yellow) in Padilla Bay in 1989, 2000, and 2004. (From Bulthuis 1991, 1995, Shull and Bulthuis 2002, Bulthuis and Shull 2002, 2006)

extend its range in Padilla Bay into areas that were dominated by *Z. marina* in the recent past.

Increased distribution of *Zostera japonica* in Padilla Bay has been documented over the last 15 years. Delineation of the boundary between *Z. marina* and Z. *japonica* depends on ground reference data. The two Z*ostera* species in Padilla Bay could not be distinguished only by characteristics seen on aerial photos (Shull and Bulthuis 2002, Bulthuis and Shull, 2006). Nonetheless, based on ground reference data and apparent boundaries on aerial photos taken in 1989, 2000, and 2004 specific areas fluctuated between *Z. marina* and *Z. japonica*. Over the 15 years from 1989 to 2004, the area covered by *Z. japonica* in Padilla Bay has increased (Bulthuis and Shull 2002, 2006, 2007, Figure 59, Table 10).

Zostera marina is a clonal plant spreading via rhizome growth. Gene flow between clones is possible vegetatively by rhizomes or fragmentation of clones or by seed dispersal. Laushman (1993) reported allozyme variation in populations of *Z. marina* from Padilla Bay as well as False Bay, San Juan Island, Washington and Massachusetts. He reported that the *Z. marina* population in Padilla Bay was multiclonal and did not appear to be genetically isolated. Gene flow in *Z. marina* was comparable to many terrestrial species of plants.

INTERANNUAL VARIATION

The distribution of *Zostera marina* and *Z. japonica* in Padilla Bay varies from year to year for unknown reasons (Bulthuis and Shull 2002, 2006, 2007). The broad outlines of distribution -- extensive areas of the lower intertidal flats and upper subtidal covered with *Z. marina* and large areas of the mid intertidal covered with *Z. japonica* -- are similar each year. However, in the mid to upper intertidal region there appear to be large changes from one year to the next at any one location. Few studies have attempted to consistently document the year to year variations in distribution of eelgrass (But see Orth and Moore 1986, 1987, Orth and Nowak 1990, Orth *et al*. 1990, and Dowty et al. 2005). Only a few years of data (1989, 2000, 2004) have been collected and documented in

Padilla Bay. In Padilla Bay, eelgrass distribution has been mapped from color aerial photos and ground reference data in 1989, 2000 and 2004 (Bulthuis 1991, Bulthuis and Shull 2002, 2006). However, color aerial photos taken in intervening years indicate high variability in the upper intertidal areas of eelgrass coverage. Bulthuis and Shull (2002) documented considerable interannual changes in the northeast corner of Padilla Bay including both *Z. marina* and *Z. japonica* (Bulthuis and Shull 2002, Fig 60, Table 11). These data indicate the importance of not relying on a single survey taken in one year to estimate the areas covered by eelgrass. The boundaries and area covered by eelgrasses are not fixed, but fluctuate from year to year.

Table 11. *Area of eelgrasses* (Zostera marina and Z. japonica) *in the northeast study area (see Fig. 60) 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. (From Bulthuis and Shull 2002)*

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

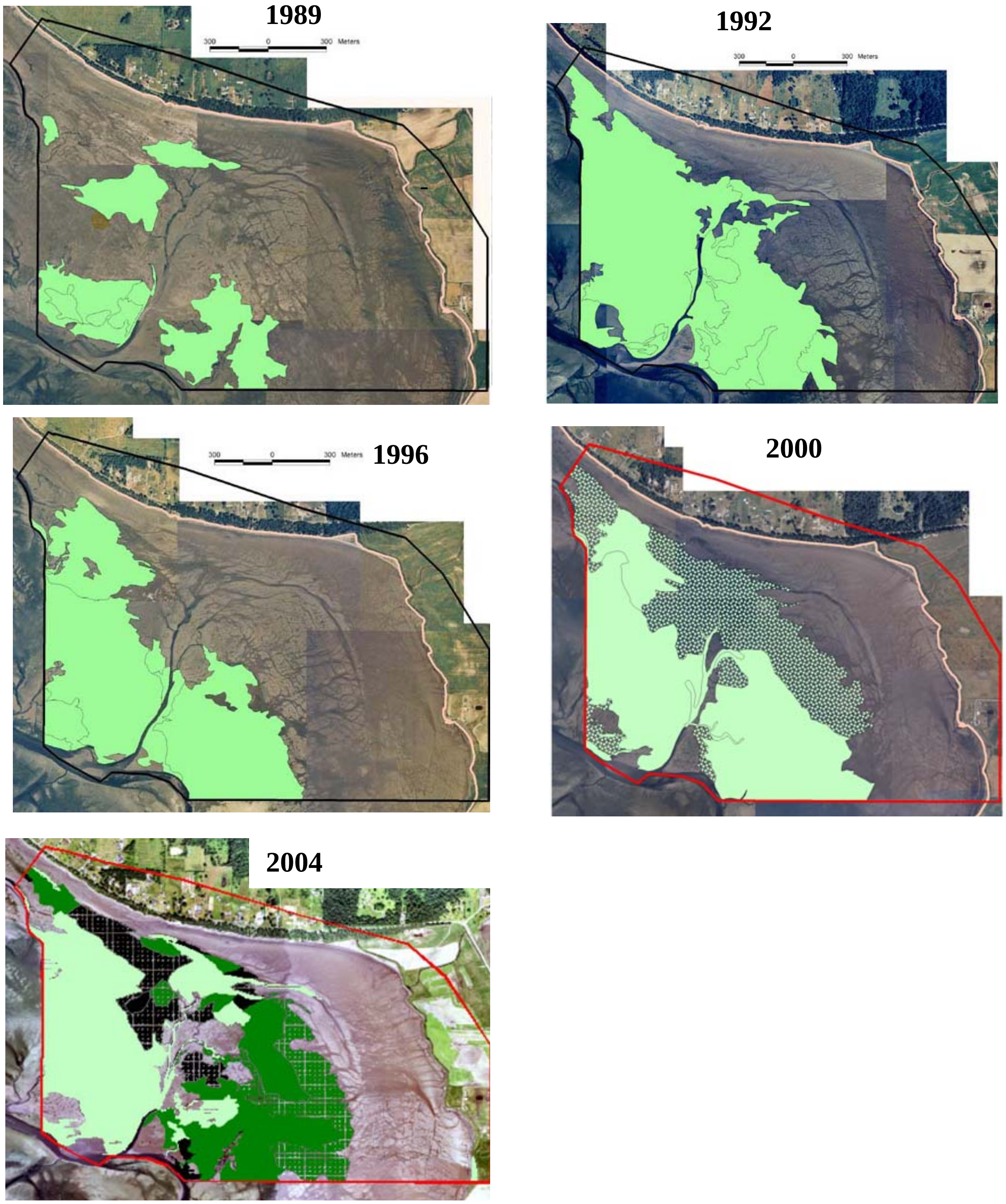


Figure 60. Distribution of eelgrasses, *Zostera marina* and *Z. japonica* combined, in the northeast corner of Padilla Bay as delineated from color aerial photographs every three to four years from 1989 to 2004. See Table 11 for hectares of eelgrass cover in 1989 through 2000. (From Bulthuis 1991, Shull and Bulthuis 2002, Bulthuis and Shull 2002, 2006)

EELGRASS BIOMASS AND DENSITY

The density and biomass of *Zostera marina* and *Zostera japonica* have been measured by several authors at various sites in Padilla Bay, sometimes as ancillary data to describe site characteristics. The density and biomass of both species of eelgrass from samples taken during summer in these studies are listed in Table 12. The data indicate the range of density and biomass, but are not necessarily representative of Padilla Bay as a whole. Several of the studies were conducted in locations where access from the shore was important in deciding placement of the sample sites. Thus, populations close to shore are better represented in Table 12 than sites farther from shore. The main intertidal beds of *Z. marina* in Padilla Bay occur in the lower intertidal, but few sites were sampled in those beds. However, the table does indicate the range of biomass and density of *Z. marina* and *Z. japonica* that occur in Padilla Bay including high intertidal sites and subtidal sites. The dry weight and density measurements for *Z. marina* are within the range reported for *Z. marina* populations in other parts of the world in the reviews by McRoy and McMillan (1977) and Zieman and Wetzel (1980) and similar to seasonal maxima reported for *Z. marina* in Puget Sound (Phillips 1972, Thom and Albright 1990, Nelson and Waaland 1997, Thom et al. 2003). Similarly, the density and shoot biomass of *Z. japonica* is in the same range as other reports for *Z. japonica* in the Pacific Northwest (Harrison 1982b, Bigley and Harrison 1986, Baldwin and Lovvorn 1994a).

SEASONAL FLUCTUATIONS IN EELGRASS

Zostera marina biomass and density fluctuate seasonally in Padilla Bay with maxima in spring or summer and minima in winter. Winter densities of *Z. marina* were about 50 - 100 and 400 - 500 at a lower intertidal site (-0.4 m) and a mid intertidal site (+0.1 m) in Padilla Bay (Thom 1990, Thom et al. 1995.). Density of Z. *marina* approximately doubled at these two sites in the spring and summer (Thom 1990) with peak densities occurring as early as April and apparently as late as November (Thom 1990, Thom et al.1995). At an intertidal site Bulthuis (1996b) reported lows of about 100 in October and November but increasing density in January to maxima over 400 in March and April before declining during June to September to winter lows of about 200 (Bulthuis 1996b,

Table 12. *Above ground dry weight and density of eelgrass and algae during summer at various locations in Padilla Bay in eight different studies. Peak biomass or density is reported when several measurements were made during the summer.*

Author site #	Above-ground dry weight (g m^{-2})			Density (no. m^{-2})	
	Z. marina	*Z. japonica*	algae	*Z. marina*	*Z. japonica*
Smith & Webber 1978[1,3]					
	+1 foot	140		5	
	+2 foot	90		4	
	+3 foot	70		3	
	+4 foot	160		5	
Riggs 1983		163			
Webber et al. 1987					
	1	60	100		200
	3500				
	2	110	1		770 13
	3	150		45	280
	4	140			85
	5	90			40
Thom 1990					
0.6 foot		140	<5[2]		3200
0.1 foot	180		270[2]	800	
-0.4 foot	180		80[2]	300	
Thom et al. 1991					
ZJ		130	10[2]		
ZM1	90		9[2]		
ZM4	200		25[2]		
Bulthuis 1991					
1	100		180	250	
2	100		150	230	
3	60		130	440	
4	60		130	160	
5	30		40	180	
6	20		190	60	
7	12		40	160	
8[3]		29	8		390
9		31	<1		1100
10	<1		530	6	
Bulthuis & Shaw 1993					
1-1992		130			3900
1-1993		40			2000
2-1992[3]	140			1600	
2-1993[3]	180			1300	
3-1992	160-340			190	

1: Wet weight converted to dry weight assuming ratio of 8:1. Annual mean reported.

2: Dry weight of algae is for epiphytes.

3: *Z. marina* and *Z. japonica* combined.

Fig. 61). At a subtidal site near the lower limit of distribution in Padilla Bay, density was 50-70 shoots m^{-2} during December through May and then increased to 100 - 140 during July to August (Bulthuis 1996b, Fig 62). Gwozdz (2006) reported minimum density of about 150 shoots m^{-2} in November and a high of 375 in July for a site at -0.25 MLLW.

Several generalizations may be made from these seasonal studies on density in Padilla Bay:

- *Zostera marina* shoots are present throughout the year in Padilla Bay at intertidal and subtidal sites.
- Density of shoots are lower in winter than in summer.
- The magnitude of the seasonal differences vary from less than a doubling of density up to almost a quadrupling of density.
- The month of the peak density can vary widely among sites and years. For example, at least one of the study sites of Thom et al. the maximum density occurred in November whereas Gwozdz found that minimum density occurred in November (Thom et al. 1995. Gwozdz 2006).

Similar generalizations regarding the seasonal pattern of above-ground standing crop were evident. But the magnitude of seasonal fluctuation in above ground biomass was generally greater than for density (Thom 1990, Bulthuis 1996b, Gwozdz 2006).

Seasonal fluctuations in density and biomass were greater in *Z. japonica* than in *Z. marina*. For example, Thom (1990) reported *Z. japonica* density fluctuating from less than 100 up to 3200 shoots per m^2 and Gwozdz (2006) from less than 1000 up to more than 3500. All studies of seasonal fluctuations in Padilla Bay have reported above ground over wintering biomass of *Z. japonica* (Thom 1990, Hahn 2003, Gwozdz 2006).

PRIMARY PRODUCTIVITY

The primary productivity of the eelgrass community (including epiphytic algae and benthic algae) was measured at several sites in Padilla Bay by Thom (1990) and total productivity in Padilla Bay estimated. Annual net primary productivity for the eelgrass

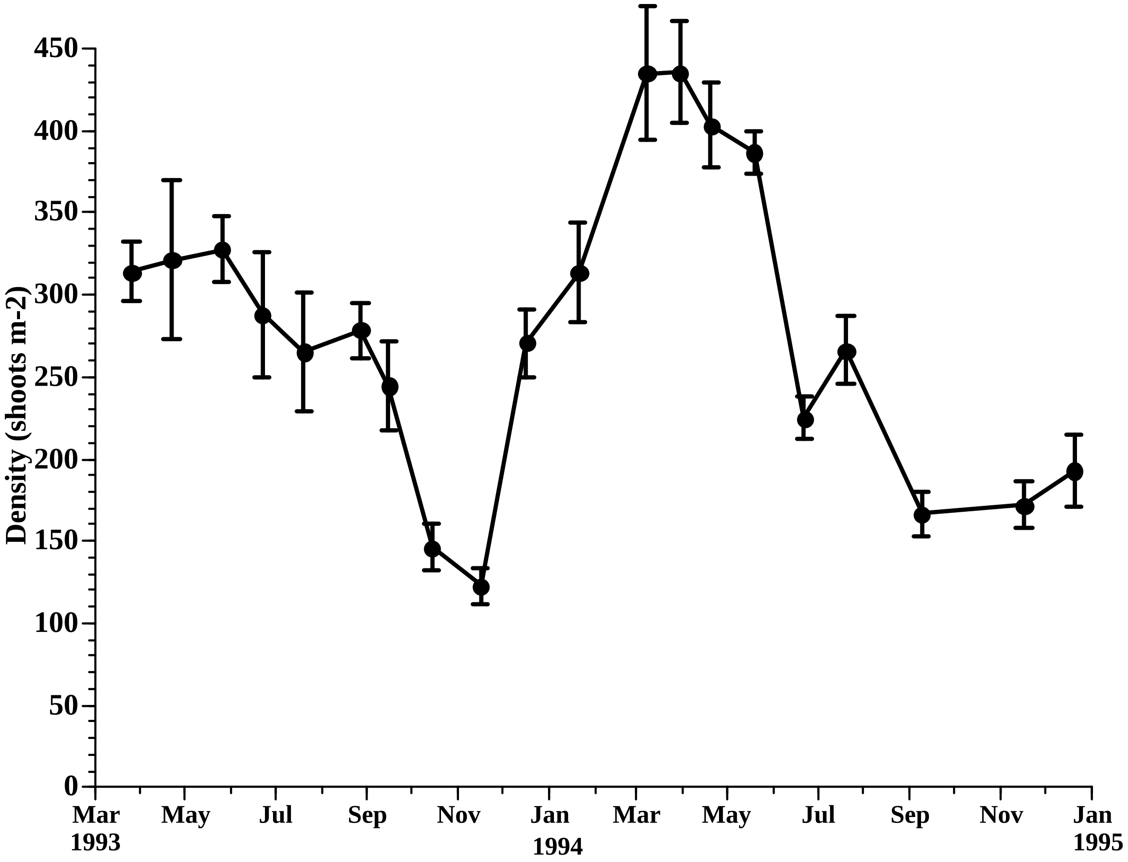


Figure 61. Density of *Zostera marina* in control plots at an intertidal experimental site in mid Padilla Bay from March 1993 to December 1994. Mean ± s.e. (n=3 plots in March 1993 increasing up to 12 plots by March 1994 and thereafter) (From Bulthuis 1996b)

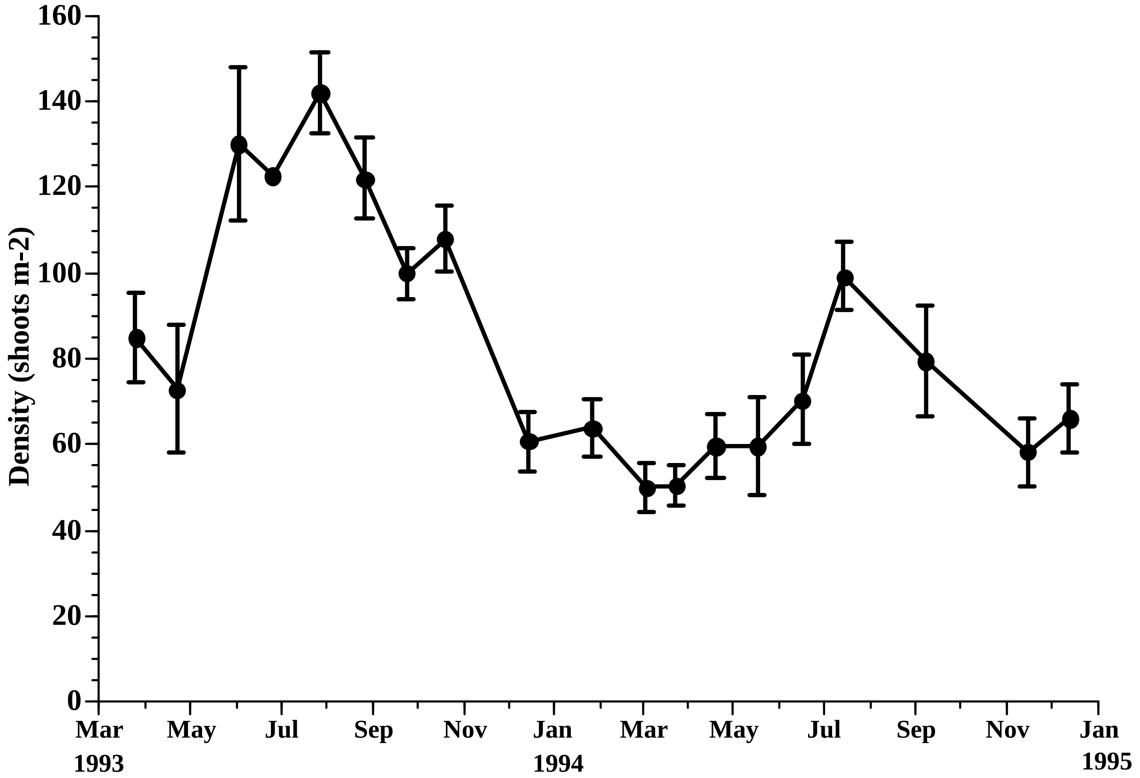


Figure 62. Density of *Zostera marina* in control plots at a subtidal experimental site in Padilla Bay from March 1993 to December 1994. Mean ± s.e. (n=3 plots in March 1993 increasing up to 12 plots by March 1994 and thereafter). (From Bulthuis 1996b)

system was estimated at 351 g C m^{-2} with *Z. japonica* contributing 2%, *Z. marina* 48%, and epiphytic algae 50% of the annual production. These rates indicate somewhat lower productivity of eelgrasses in Padilla Bay than for published values for elsewhere (McRoy and McMillan 1977). Thom (1990) notes, for several reasons, that the estimates for Padilla Bay may be underestimates and suggests that actual eelgrass productivity may be three times greater than estimated in his study. Gwozdz (2006) measured above ground productivity of eelgrass at one intertidal site and estimated about 0.7 to 1.0 g dry weight of eelgrass growth per m^{-2} per day during spring and summer. These estimates were comparable to the annual average daily estimates of Thom (1990). However, Gwozdz (2006) also stated that his measurements may be underestimates.

NUTRIENT SOURCES FOR EELGRASS

As rooted vascular plants, eelgrasses are able to absorb nutrients for growth and productivity both from the sediments via their roots (McRoy and Barsdate 1970, McRoy and Goering 1974) and from the water column through their leaves (Thursby and Harlin 1982). Williams and Ruckelshaus (1993) studied effects of nutrient enrichment of the water column and of the sediments on eelgrasses and epiphytes in Padilla Bay. Their studies indicated that eelgrass in Padilla Bay is nitrogen limited and that during times of peak growth, the eelgrass are taking up nutrients from the sediments in Padilla Bay. Eelgrasses and the eelgrass community including epiphytes, macroalgae, bacteria, etc. also take up nutrients from the water column. This can be very striking during spring and summer when the concentration of nutrients in the water column is reduced by the eelgrass community. As water flows into Padilla Bay from the deeper waters of North Puget Sound surrounding Padilla Bay, nitrogen is removed from the water by the eelgrass community. The effect of this nitrogen removal can be seen in bulk water nutrient concentrations taken about hourly during a spring or summer tidal cycle. During a 26 hour sampling series on May 20-21, 2003, water flowing into the bay on the rising tide had a much higher concentration than the residual water in Padilla Bay during low tide (Fig. 51). Dissolved inorganic nitrogen concentrations increased from 3 µM to 9 and then 14 µM (Fig. 51). As the water remained in the bay over the next twelve hours, the concentration of dissolved inorganic nitrogen decreased. It is suggested that this decrease is due to the biological activity of the eelgrass community. The low concentrations of chlorophyll in this water (Fig. 51) are a measure of the phytoplankton biomass in North Puget Sound water surrounding Padilla Bay. These phytoplankton were living in the nutrient milieu of north Puget Sound water that had higher nutrient concentrations of the incoming water. Thus, the north Puget Sound phytoplankton are unlikely to be the community responsible for the decreasing dissolved inorganic nitrogen within Padilla Bay. The low ratios of dissolved inorganic nitrogen to dissolved phosphate relative to the Redfield ratio in Padilla Bay provide further evidence that eelgrasses and the eelgrass community are nitrogen limited (Fig. 58). Thus, eelgrasses and the eelgrass community in Padilla Bay are apparently nitrogen limited during spring and summer, and absorb nutrients from the sediments and the water column to maintain this growth and productivity (Williams and Ruckelshaus 1993, Bulthuis and Margerum 2005).

EELGRASSES AND HERBICIDES

Eelgrasses in estuaries may be threatened by a variety of pollutants and sources including herbicides and pesticides that are used for control of other plant species. Two studies conducted in Padilla Bay addressed the threat of herbicides to eelgrasses. Mayer and Elkins (1990) evaluated the threat to eelgrasses in Padilla Bay from herbicides and other pesticides applied to agricultural fields in the Padilla Bay watershed. For two consecutive years during the spring and early summer, the concentrations of the herbicides that were being applied that year were measured in the water and sediments in the freshwater sloughs draining the fields, and in the water and sediments in Padilla Bay near the mouth of the sloughs. Only two herbicides, 2, 4-D and Dicamba, were detected in any of the samples, and the concentrations of these two herbicides were so low in the water (< 200 mg L^{-1} Dicamba and < 2mg L^{-1} 2, 4-D) and sediments (< 20 mg g^{-1} Dicamba) that Mayer and Elkins concluded that, "no ecologically significant levels of any of the fourteen pesticides studied were found in the water or sediments associated with Padilla Bay sloughs or the bay itself during this two-year investigation."

Bulthuis and Shaw (1993), and Bulthuis and Hartman (1994) evaluated the effects of the herbicide, glyphosate, mixed with a spreader, X-77, on eelgrass in Padilla Bay because of the anticipated use of glyphosate to control the non-native (to the Pacific Northwest) cordgrass, *Spartina alterniflora*. Bulthuis and Shaw reported that glyphosate had no consistent effect on *Zostera marina* or *Z. japonica* when sprayed directly onto eelgrasses in both an intertidal site and a subtidal site as measured by density, biomass, percent cover, dead leaves, or chlorophyll *a*. Similarly, Bulthuis and Hartman (1994) reported no effect on the epiphytes of *Z. marina* or *Z. japonica* as measured by dry weight of epiphytes and by concentration of chlorophyll. Bulthuis and Shaw (1993) and Bulthuis and Hartman (1994) suggested that the glyphosate did not have any measurable effect because water retained on the leaf surface reduced absorption of the herbicide and because of the short time of exposure to the herbicide (three hours or less) before the flooding tide.

EELGRASSES AND EPIPHYTES

Epiphytes begin growing on eelgrass leaves shortly after they emerge from the leaf sheath (Bulthuis and Woelkerling 1983). The first to colonize the leaf surface are often diatoms (Sieburth and Thomas 1973). This diatomaceous layer is then colonized by a wide variety of epiphytes and microorganisms (Borowitzka et al. 2006). The total biomass of epiphytes may become quite large and be over 50% of the plant standing stock in some seagrass meadows (Borowitzka et al. 2006). In Padilla Bay, Thom (1990) reported that epiphytes accounted for 1% to 18 % of the plant biomass at eight sites varying in elevation from 0.8 to -0.4 m relative to chart datum (MLLW). This was 0.2 g m^{-2} to 21 g m^{-2} with the lowest biomass per unit area on *Zostera japonica* at the highest tidal elevation, and the highest biomass on *Z. marina* at mid tidal elevations (MLLW) and lower (Thom 1990). Epiphyte biomass varied seasonally with the highest biomass in spring and summer and the lowest biomass in winter. Peak epiphyte biomass per unit area was in June (50-250 g dry weight m^{-2}) and the lowest in January and February (< 5 g m^{-2}; Thom 1990). Peak biomass per shoot was 40–70 mg $shoot^{-1}$ in April to August in a study covering 3 seasons and minima of <5 mg dry weight $shoot^{-1}$ in November and March (Williams and Ruckelshaus 1993). During July and August epiphyte dry weight was 1.8 to 7.7 g m^{-2} of leaf surface on *Zostera japonica* at one site (Bulthuis and Hartman

1994), 4.7 to 10.2 g m^{-2} on *Z. marina* at two sites (Bulthuis and Hartman 1994, Fig. 63), and 4 to 62 g m^{-2} on *Z. marina* at five sites (Portinga 2002).

Dry weight of epiphytes per unit area from April through September fluctuated from about 0.5 to 4.1 g m^{-2} of *Z. marina* leaf area at three sites (DeLorenzo 1999). The highest biomass of epiphytes occurred in July and August (DeLorenzo 1999). Similarly Shaw (1994) reported highest epiphyte biomass in July of 8.9 g dry weight m^{-2} of *Z. marina* leaf area and decreasing during the next two months with a low of 2.8 g m^{-2}. On the other hand, Simenstad et al. (1995) reported increasing density of epiphytes throughout March through September with a maximum of 8.28 g dry weight m^{-2} on their last sampling, September 11, 1989.

When water column nutrient concentrations are high, epiphyte growth increases and the resulting high biomass of epiphytes can shade leaves of eelgrass and reduce growth (Bulthuis and Woelkerling 1983, Neckles et al. 1994, Nelson and Waaland 1997). In Padilla Bay, Portinga (2002) demonstrated that epiphytes on the leaves were reducing growth of *Z. marina*. At March Point sites, leaf growth rate was significantly higher in Z. *marina* shoots whose leaves were kept clear of epiphytes for 30 days compared to plants with epiphyte growth and biomass undisturbed (Portinga 2002, Figure 64). This higher epiphyte biomass may have been the result of higher nutrient loading to the site, or reduced grazing on epiphytes, or some combination of these and other factors. Portinga (2002) found no difference between leaf growth rates of treatment and control at a site on the east side of Padilla Bay, indicating that epiphytes were not negatively impacting eelgrass growth at that site.

Grazers reduce epiphyte biomass, thereby increasing light reaching the leaf surface of seagrasses and enhancing growth and survival of the eelgrass (Bulthuis and Woelkerling 1983, Borowitzka et al. 2006). Williams and Ruckelshaus (1993) found in Padilla Bay that the isopod, *Idotea resecata* reduced epiphyte biomass by one-third, and thus prevented negative effects of epiphyte biomass on growth of eelgrass. Shaw (1994) studied temporal, diel, and vertical distribution of four grazers, the isopod *I. resecata*, the amphipod *Caprella californica* (and other caprellids), the sea hare, *Phyllaplasia taylori*,

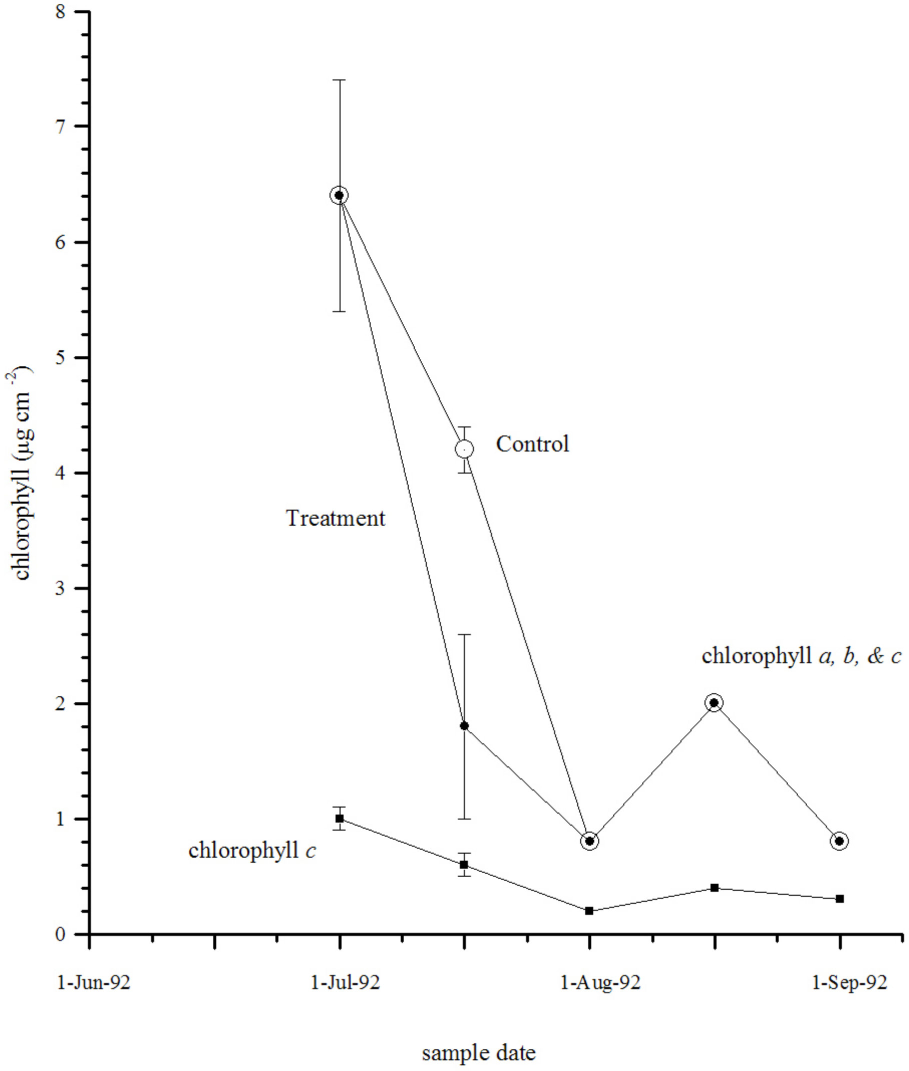


Figure 63. Concentration of chlorophylls *a, b, & c* and chlorophyll *c* in epiphytes of *Zostera marina* at an experimental site in mid Padilla Bay from June 30 to Aug 28, 1992. Mean ± standard error, n=3 to 18 plots (depending on date) with 3 leaves sampled per plot. On the 14th of July there was a significant difference in the total chlorophyll (*a, b, & c*) between treatment (glyphosate applied) and control plots. Therefore, chlorophyll *a, b, & c* are plotted separately for that date. On the remaining dates, the concentrations from treatment and control plots were combined. (From Bulthuis and Hartman 1994)

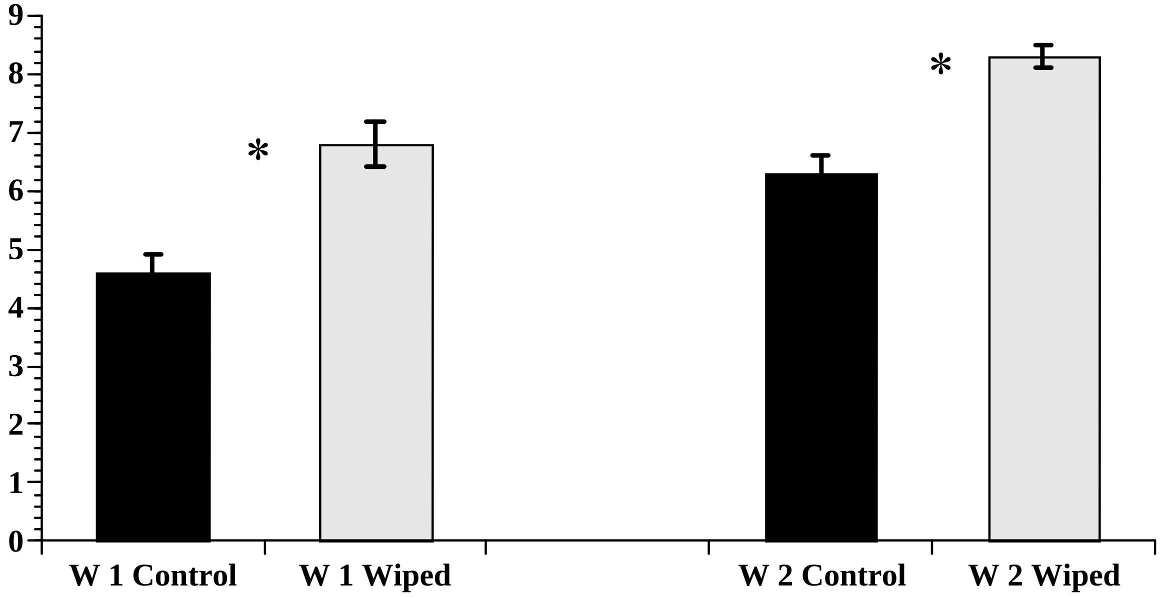


Figure 64. Mean shoot growth (the sum of the growth of all leaves on a shoot) of *Zostera marina* at two experimental sites on the west side of Padilla Bay in cm shoot^{-1} day^{-1} ± se (n=20). Treatment consisted of wiping epiphytes off the leaves of *Z. marina* every 3-4 days for one month. The asterisk indicates a significant difference between the control and wiped treatment at alpha = 0.05 at both sites. (From Portinga 2002)

and the bubble shell snail, *Haminoea vesicula*. The times of greatest abundance varied among the four grazers. *I. resecata*, *C. californica*, and *P. taylori* migrated vertically moving up toward the apex of the eelgrass leaves during the night. The epiphyte resource was thus partitioned among the four grazers temporally (diel and seasonal) and spatially along the eelgrass leaf (Shaw 1994). *P. taylori* is an abundant grazer on *Z. marina* in Padilla Bay. In laboratory preference studies DeLorenzo (1999) demonstrated a strong preference for color and green was preferred by the greatest number of *P. taylori*. *P. taylori* also showed a preference for the top portion of the leaf. The abundance of *P. taylori* from March to September varied with maximum numbers in July and August (DeLorenzo 1999).

INFAUNA OF EELGRASS COMMUNITIES

The infauna species of Padilla Bay have been characterized by an extensive study by Ray (1997) who sampled in 9 habitats throughout the bay: five intertidal habitats and four subtidal habitats based on vegetative communities mapped by Bulthuis (1991, 1995, Fig. 3). In addition, other researchers have sampled infauna in selected sites or habitats within Padilla Bay (Smith and Webber 1978, Riggs 1983, and Hahn 2003). Ray reported 127 species plus 21 species identified to genus, and 16 other taxonomic categories. More than 75 polychaete species were identified by Ray in Padilla Bay. The ten most abundant species in the three intertidal eelgrass habitats included six polychaetes and three amphipods (Ray 1997, Table 13). The polychaete, *Exogene molesta,* the amphipod *Corophium acherusicum,* and the tanaid *Leptochelia savigni* were all in the top five most abundant species in all three of the intertidal eelgrass habitats (Ray 1997, Table 13).

Taxon richness in habitats increased with increasing depth of the habitats to a maximum in the shallow unvegetated subtidal habitat (Ray 1997, Fig. 65). The five intertidal habitats had higher abundance of infauna than the four subtidal habitats and the highest abundance of infauna were in the two intertidal *Zostera marina* habitats (Fig. 66). Biomass among the intertidal habitats was higher in eelgrass habitats than those without eelgrass (Fig. 67). Ray reported that two types of species assemblages dominated in Padilla Bay habitats, a single widely distributed assemblage and several habitat specific

Table 13. *Top ten taxa by numerical dominance in four eelgrass habitats in Padilla Bay: 1 = greatest, 10 = tenth greatest, + = present but not in top 10; Z.j.* = Zostera japonica, *Z.m.* = Zostera marina, *low = percent cover of eelgrass 5-50%, high = percent cover of eelgrass 50-100%. (From Ray 1997*)

Taxa	Habitat			
	Intertidal			Subtidal
	Z.j.	Z.m. Low	Z.m. High	Zmar
Polychaete				
Barantolla americana	+	8	+	+
Malacoceros glutaeus	+	5	9	+
Dipolydora quadrilobata	9	+	+	+
Prionospio steenstrupi				5
Axiothella rubrocincta	+	6	10	+
Owenia fusiformis	+	+		4
Fabricia sabella	10	+		
Exogene molesta	4	2	2	3
Oligochaete				
Tubificoides foliatus	+	3	3	2
Grania paucispina		9	5	6
Bivalve				
Mysella tumida		+	8	7
Transenella tantilla	3	+	+	+
Isopod				
Corophium acherusicum	1	4	4	+
Amphipod				
Ericthonius hunteri	6	+	+	10
Eobrolgus spinosus	+	10	6	9
Caprella laeviscula	+	+	+	8
Cumacean				
Leptocuma spp.	7	+	7	+
Leucon sp.	5	+	+	+
Tanaid				
Leptochelia savigni	2	1	1	1
Pancolus californiensis	8	7	+	+
Echinoderm				
Leptosynapta clarki	+	10	+	+

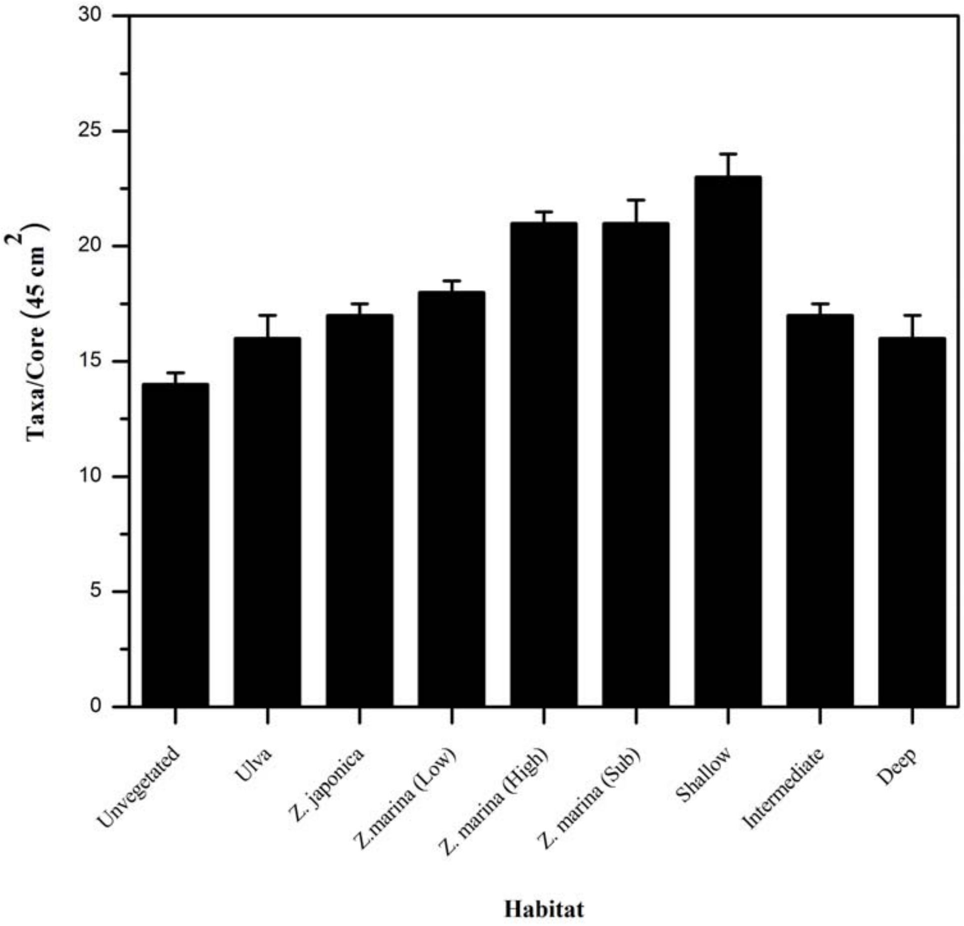


Figure 65. Taxon richness (taxa per 45 cm core) of infauna in nine habitats in Padilla Bay (mean ± standard error, n = 15 stations per habitat with 1 to 5 cores collected at each station). "Unvegetated" are stations on unvegetated intertidal flats; "*Z. marina* (Low)" are stations on intertidal flats with low density (<50% cover) of *Zostera marina*; "*Z. marina* (High*)*" are stations on intertidal flats with high density (> 50% cover) of *Z. marina*; "*Z. marina* (sub)" are stations from subtidal sites with *Z. marina*; "Shallow", "Intermediate", and "Deep" are stations from unvegetated subtidal sandy habitat at depths of < 5m, 5-20m, and > 20m. (From Ray 1997)

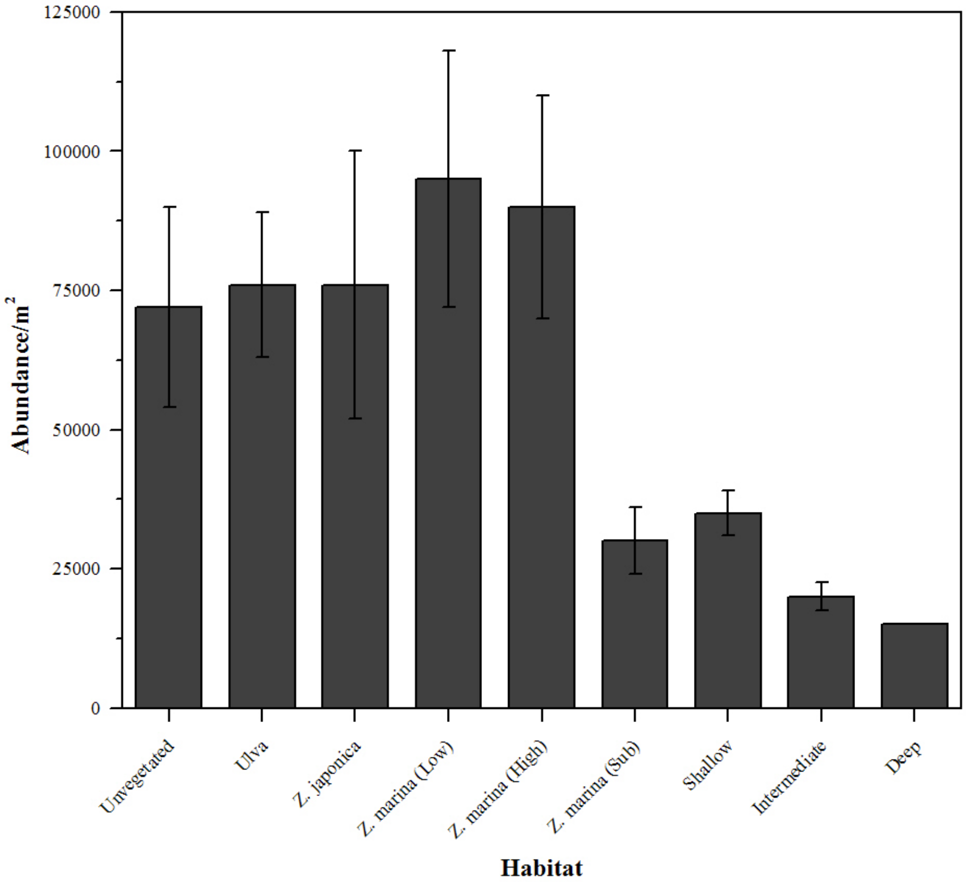


Figure 66. Abundance (number m^{-2}) of infauna in nine habitats in Padilla Bay (mean ± standard error, n = 15 stations per habitat with 1 to 5 cores collected at each station). See Figure 65 for definitions of the habitat types. (From Ray 1997)

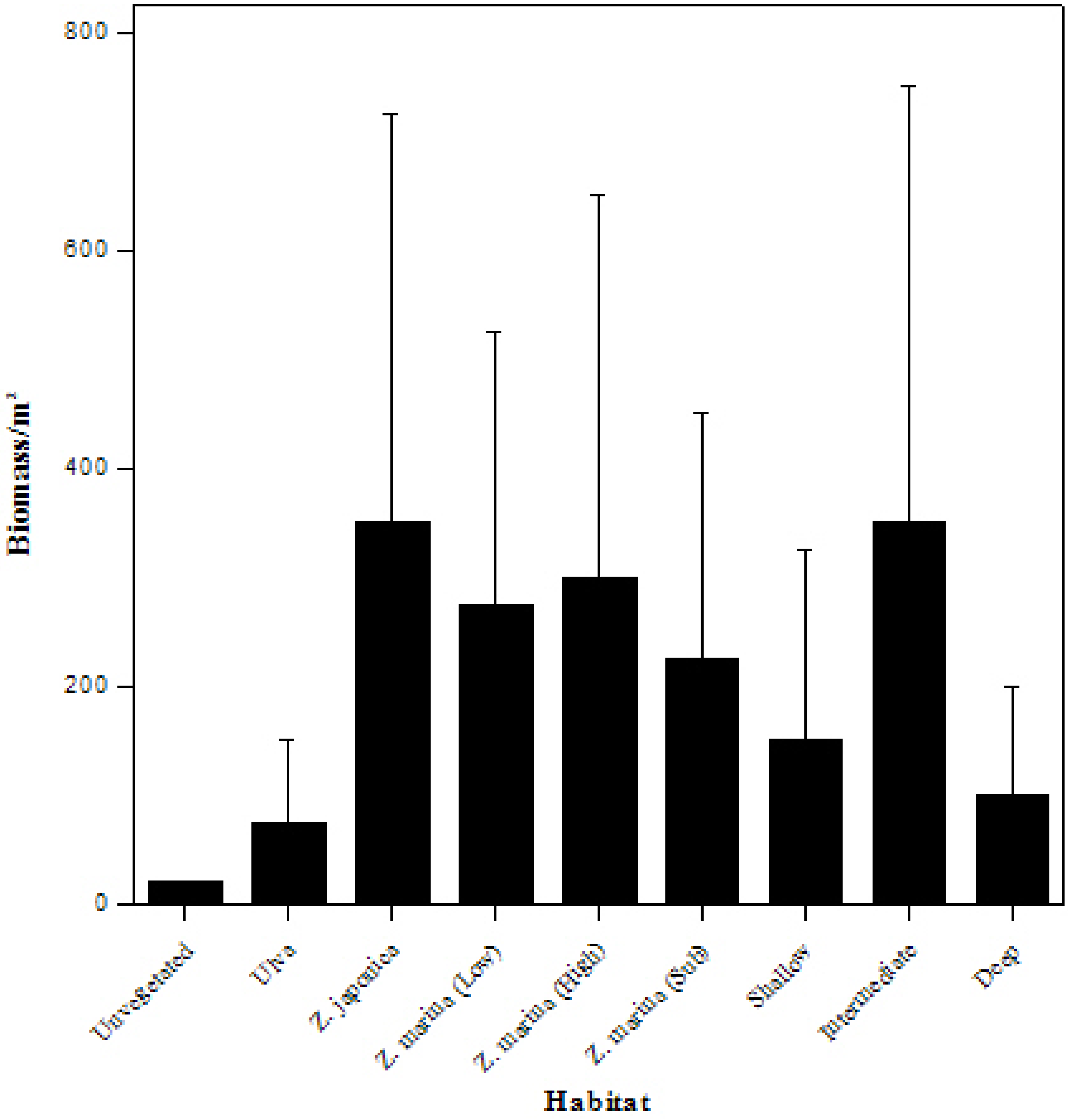


Figure 67. Biomass (g m^{-2}) of infauna in nine habitats in Padilla Bay (mean ± standard error, n = 15 stations per habitat with 1 to 5 cores collected at each station). See Figure 65 for definitions of the habitat types. (From Ray 1997)

assemblages. The wide-ranging assemblage included *Barantolla americana, Mediomastus* sp., *Exogene molesta, Tubificoides foliatus, Transenella tantilla, Mysella tumida, Corophium acheriuscium,* and *Amphioda occidentalis*. Common taxa in the eelgrass habitat were *Lacuna variegata, Haminoea vesicula, Idotea resecata,* and *Caprella laeviscula*.

In *Z. japonica* habitat, mollusks made up most of the biomass of infauna (Ray 1997, Fig. 68). On the other hand, in *Z. marina* habitat, polychaetes, mollusks, and crustaceans were all major components of the biomass (Fig. 68). The top two centimeters contained most of the biomass, the greatest abundance, and the greatest number of taxa in all eelgrass habitats (Ray 1997, Fig. 69). The one exception was the biomass in the high density *Z. marina* habitat where the greatest biomass was at 6-8 cm depth (Fig. 69). The vertical distribution is particularly striking in the *Z. japonica* habitat where the upper two cm contains such a high percentage of taxa, abundance, and biomass (Fig. 69).

Whereas Ray (1997) reported differences between the infauna in *Z. japonica* habitats and *Z. marina* habitats, Hahn (2003) reports that "the assemblages associated with *Z. japonica* do not differ from the native eelgrass in any of the community measures used in this study." There may be several reasons for these differences between the studies. Ray (1997) sampled randomly throughout Padilla Bay within broad habitat categories whereas Hahn monitored communities in reciprocal transplants between the two species at various tidal elevations. Ray also identified taxa to species level for most of the taxa. Thus, Ray's study indicates the infaunal communities in the *Z. japonica* habitats are different from those in the *Z. marina* habitats including factors such as tidal height, length of exposure during low tide, and sediment grain size (Ray 1997). Hahn's study indicates that if one keeps all of these factors consistent but only the species of eelgrass are different (*Z. japonica* vs. *Z. marina*), then the communities, while diverse, are not different in terms of abundance, richness, or diversity in broad taxonomic categories (Hahn 2003).

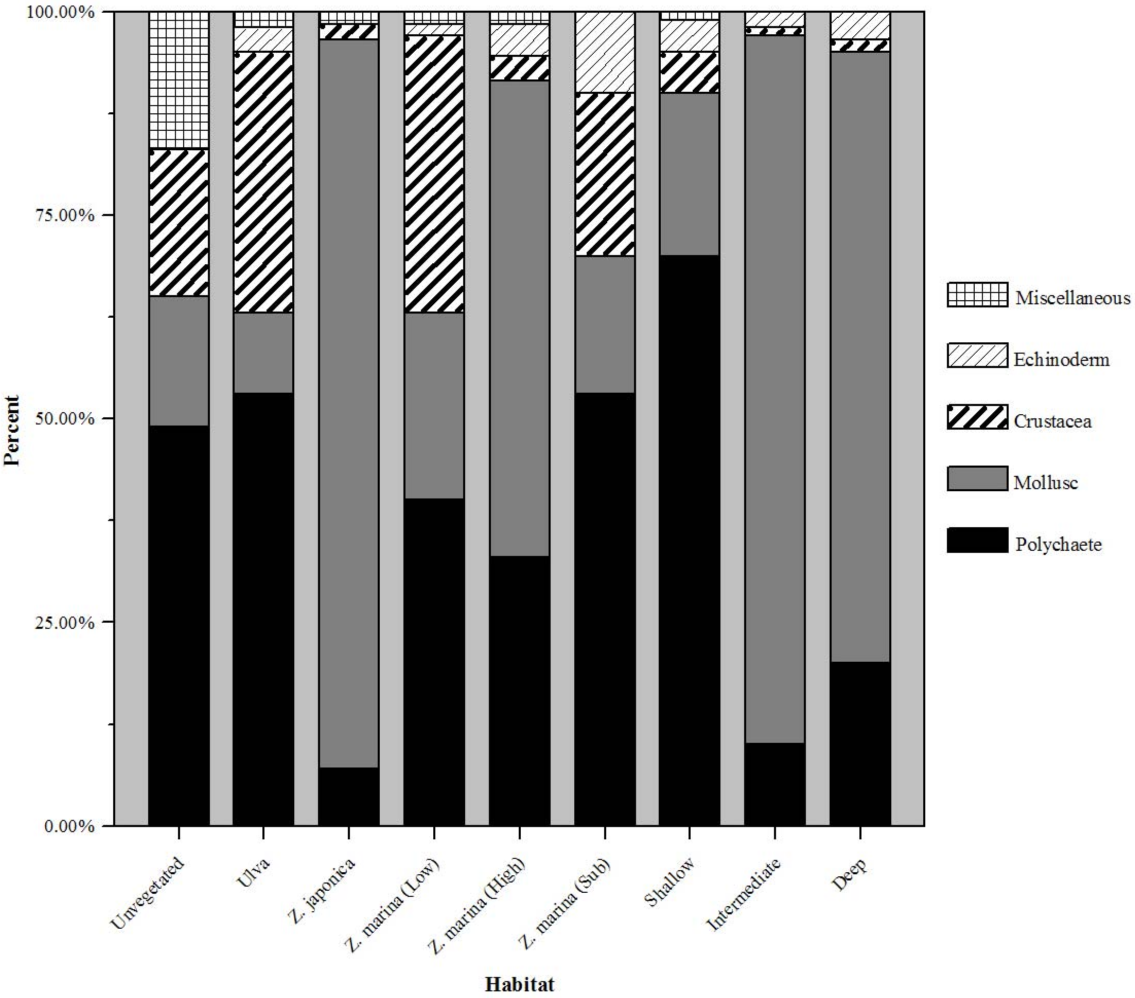


Figure 68. Taxonomic distribution of biomass of infauna in nine habitats in Padilla Bay (15 stations per habitat with 1 to 5 cores collected at each station). See Figure 65 for definitions of the habitat types. (From Ray 1997)

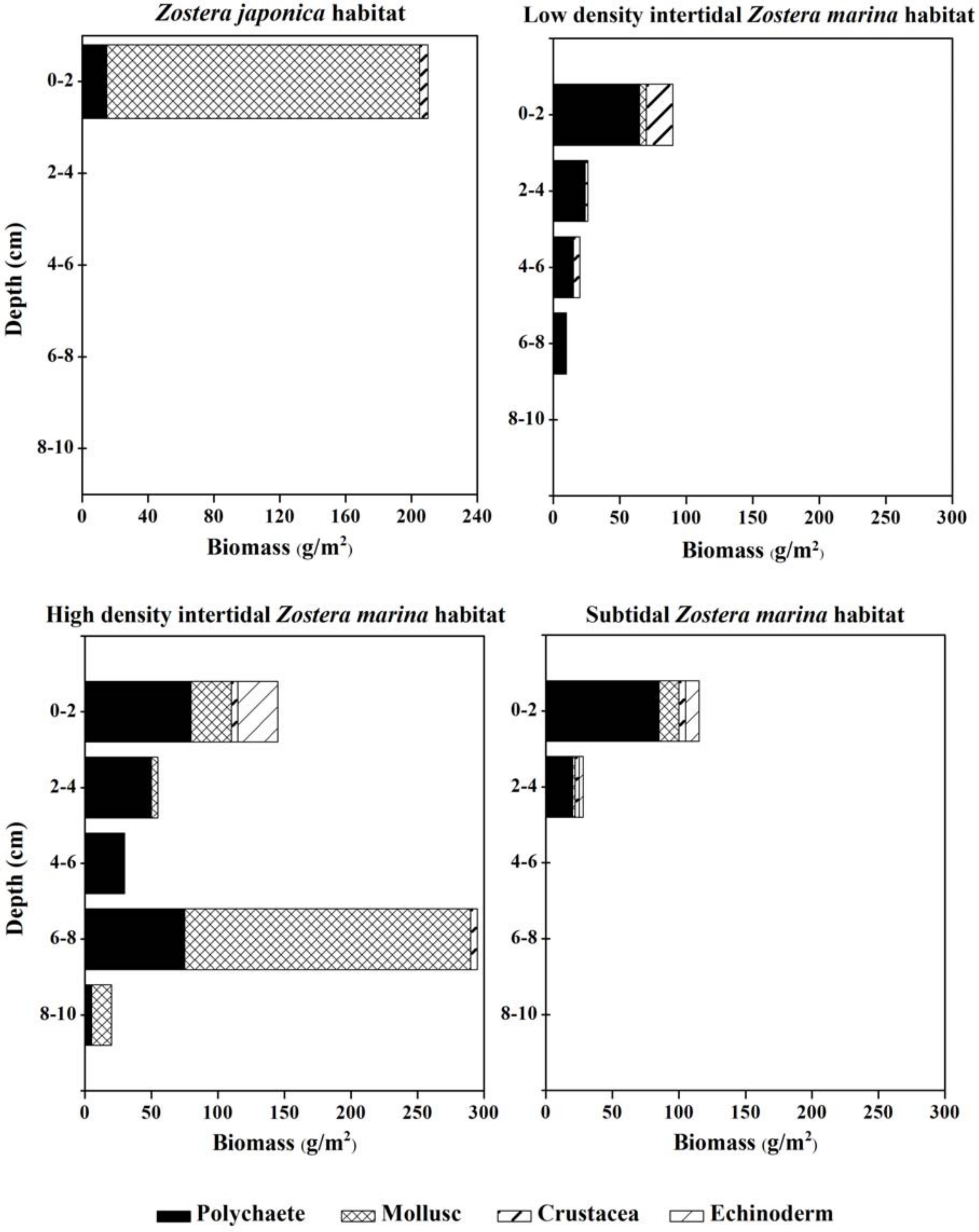


Figure 69. Vertical distribution of biomass (g m^{-2}) of four taxa of infauna in four eelgrass habitats in Padilla Bay (5 stations per habitat). See Figure 65 for definitions of the habitat types. (From Ray 1997)

Smith and Webber (1978) sampled infauna in Padilla Bay as part of the North Puget Sound Baseline Study Program. Their transect in Padilla Bay indicated that both *Zostera marina* and *Z. japonica* were present, so the infauna data probably represent fauna from intertidal eelgrass habitat. Bivalves were the major group of invertebrates reported by Smith and Webber, making up more than 50% of the biomass at all elevations sampled. The most common bivalve was the clam *Mya arenaria* which was found both in the eelgrass and in the sandy habitat. *Macoma nasuta* was also very common and the distribution data indicated that *M. nasuta* may be even more prevalent in the eelgrass areas than *M. arenaria*, occurring in densities up to 60 individuals m^{-2} with annual means of 3-15 at three sites. *Macoma balthica* and *Transennella tantilla* were also common in the tidal heights where eelgrass was prevalent. Common polychaetes included *Capitella capitata*, *Polydora* sp., *Polydora kempi-japonica*, *Abarenicola* sp., *Notomastus tenuis*, *Armandia brevis* and *Glycinde picta*.

Riggs (1983) reported infauna sampled in June from a *Zostera japonica* community near Bay View State Park in Padilla Bay. Common species included the polychaetes *Cirriformia spirabranchia* and *Pseudopolydora kempi*, the amphipods *Allorchestes angusta*, *Corophium spinicorne* (mean of 32 per 0.0625 m^2 sample quadrat, n=6), *Paraphoxus obtusidens*, the Tanaidacead *Pancolus californiensis*, the bivalve *Macoma nasuta*, and the gastropods *Nassarius fraticularis*, *Haminoea vesicula* and *Batillaria attramentaria*.

EPIFAUNA OF EELGRASS COMMUNITIES

The epifauna of the intertidal eelgrass habitat in Padilla Bay has been studied by more authors than the infauna. The eelgrass epifauna are diverse, abundant, and have a critical role in the food web. Simenstad, *et al*. (1988) and Cordell and Simenstad (1988) studied the assemblage of epibenthic organisms in four habitats at three tidal stages during May, 1986. Two were eelgrass habitats: intertidal *Zostera marina* and intertidal *Z. japonica*. Numerically abundant taxa were Nematoda, Harpacticoida, and Polychaeta in both habitats during tidal exposure. Total density of epibenthos at the benthic boundary layer was 2-3 orders of magnitude less during tidal submergence than densities collected during tidal inundation or tidal exposure (Simenstad, *et al*. 1988). During all three tidal stages the Harpacticoid copepods were the most abundant taxa in both *Z. marina* and *Z. japonica* except for tidal exposure in the *Z. japonica* when Nematoda were more abundant than Harpacticoida. Harpacticoid genera that were abundant on leaves of *Z. marina* included *Zaus*, *Harpacticus*, and *Tisbe* (Simenstad *et al*. 1988). Density of Harpacticoids increased along *Z. marina* leaf blades from the distal end and toward the rhizome end, with up to 23 species of harpacticoid copepods and densities greater than 2000 per 100 cm^2 in the section of the leaf blade closest to the rhizome.

An important component of the eelgrass habitat is the epiphyte community on the leaves of the eelgrass. Simenstad *et al*. (1988) reported a range of 3-57 different taxa per 100 cm^2 of leaf area, mean standing crops of epibenthos up to 10,000 mg per 100 cm^2 and mean density more than 140,000 per 100 cm^2 of leaf area. Nematoda and Harpacticoida were particularly abundant. Caine (1991) measured abundance of the epiphytic amphipod *Caprella laeviuscula* in three months during spring. Density of *C. laeviuscula* averaged about 95 individuals per 625 cm^2 quadrats during March and April and then declined to about 1 per 625 cm^2 by mid June. Caine suggested that reproductive migrations of shiner perch, *Cymatogaster aggregata*, that move into the seagrass beds may selectively prey on caprellids and may be responsible for the sharp drop in caprellid abundance. Shaw (1995) studied the interaction of a common caprellid, *Caprella californica* and one of its predators, the shiner perch, *Cymatogaster aggregata* over 8 weeks and over diurnal cycles. Shiner perch fed on *C. californica* both during the day and at night. Caprellid densities were greater near the base of *Z. marina* leaves and densities on the apical regions of the leaves decreased throughout the period that shiner perch were observed within the eelgrass meadow (Shaw 1995).

Common epifauna reported by Smith and Webber (1978) at tidal heights that included eelgrass were the snail *Batillaria attramentaria* and amphipods including *Anisogammarus confervicolus*, *Parallorchestes orchotensis* and *Corophium* sp. Riggs (1983) also reported *Batillaria attramentaria* from a *Zostera japonica* site, but very few other species were found in the leaf samples whereas many species were reported in leaf samples of *Z. marina* from Anacortes. Williams and Ruckelshaus (1993) reported high densities of the isopod, *Idotea resecata*, as well as the presence of *Lacuna* sp., *Phyllaplysia taylori* and *Haminoea* spp. Thom *et al*. (1991) reported that the primary invertebrate grazers on the epiphyte community in the eelgrass habitat were *Idotea resecata*, *Caprella laeviuscula* and *Lacuna variegata*. Abundance of these three grazers was monitored from October 1989 to July 1990 at three eelgrass sites. The variance was high when mean population density peaked, but both *Idotea resecata* and *Caprella laeviuscula* increased sharply in July compared to the rest of the year at two of the three sites while density of *Lacuna variegata* decreased (Thom *et al*. 1991). At the third site a similar seasonal pattern in density was evident, except that in addition to the observed peak in abundance in July, *Idotea resecata* had high population numbers in December and *Caprella laeviuscula* had high numbers in July. Shaw (1994) studied the temporal (diurnal and weekly during July to September) and vertical (on the eelgrass leaf) distribution of *Idotea resecata, Caprella californica, Phyllaplysia taylori,* and *Haminoea vesicula,* all of which were common on leaves of *Z. marina* at the study site in Padilla Bay. The first three of the above grazers exhibited a vertical diurnal migration during at least part of the study period. For example, *C. californica* was much more abundant during the last three weeks of July on the upper part of the *Z. marina* leaf than during the day (Shaw 1994. Fig. 70). *C. californica* declined when *P. taylori* was increasing during the 3 months of Shaw's study (Fig. 71, Shaw 1994). With either temporal or vertical variation, the four most abundant epiphyte grazers on eelgrass leaves reflected niche separation (Shaw 1994). DeLorenzo (1999) also found that *P. taylori* increased sharply in August at March Point (Fig. 72, DeLorenzo 1999). However, at Bay View peak abundance of *P. taylori* was in July and *P. taylori* never became abundant at Kirby Beach (Fig. 72, DeLorenzo 1999). The increase in *P. taylori* at March Point correlated with an increase in epiphyte biomass and was negatively correlated with abundance of *Lacuna variegata, Isolchyrocerus anguipes,* and *Caprella californica* (DeLorenzo 1999).

Thom et al. (1995) also reported that the three most abundant grazers of epiphytes on eelgrass leaves were *Idotea resecata, Caprella* spp., and *Lacuna variegata.* Sampling seven times over a 12 month period, they found *I. resecata* fluctuated over three orders of

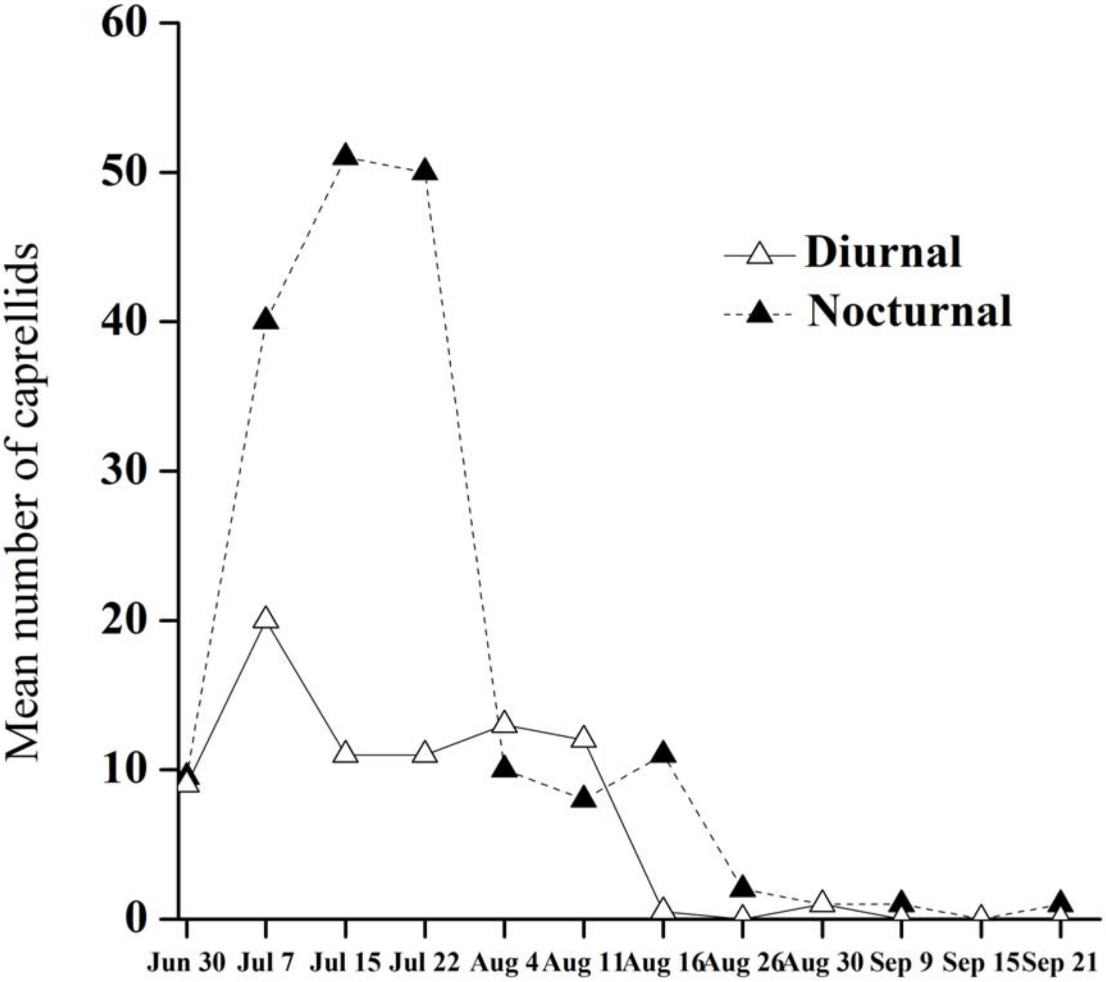


Figure 70. Abundance of caprellid amphipods on apical fractions of eelgrass leaves during the day and at night from June through September 1993. (From Shaw 1994)

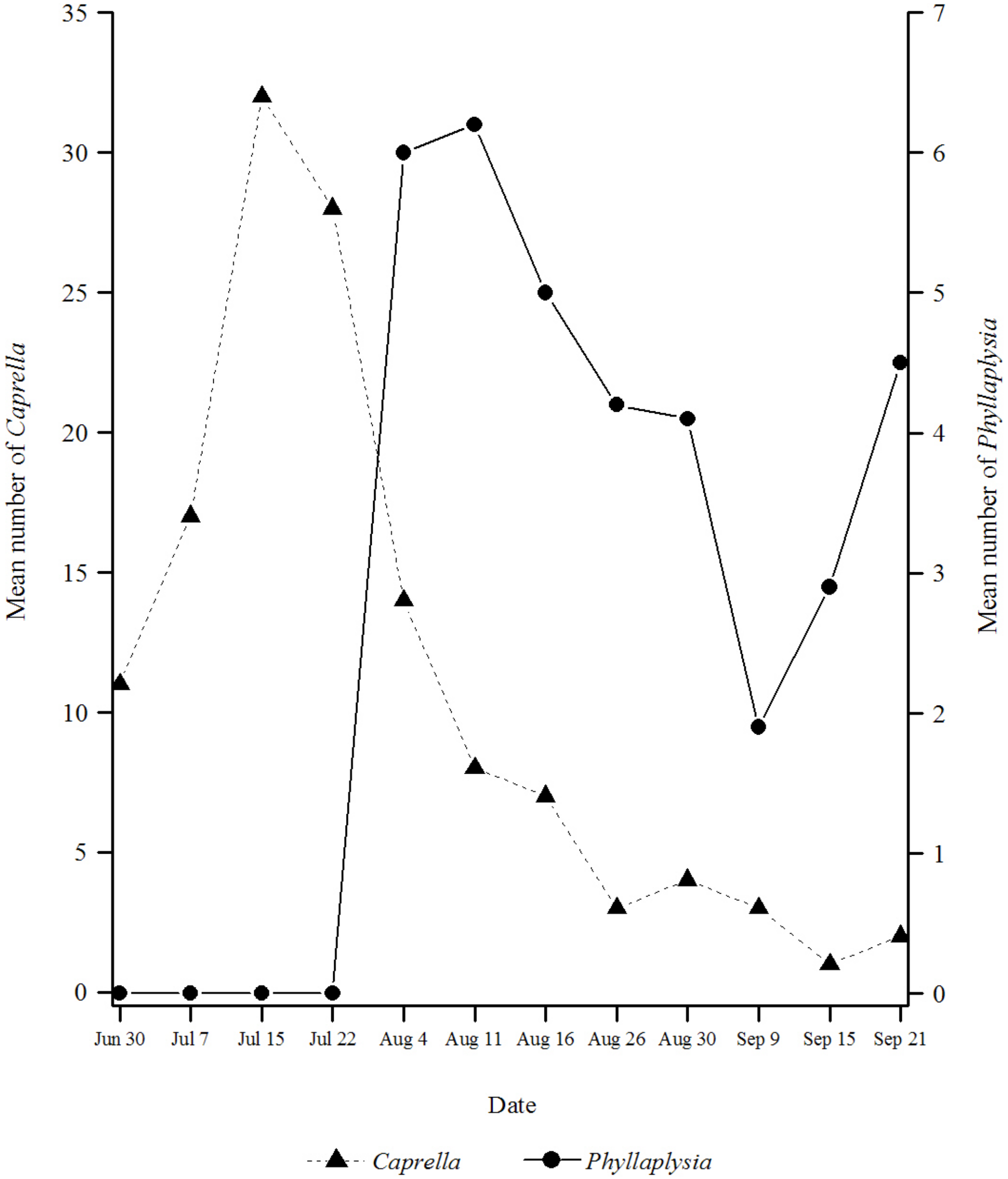


Figure 71. Abundance of *Caprella californica* and *Phyllaplysia taylori* on *Zostera marina* leaves from June through September 1993. (From Shaw 1994)

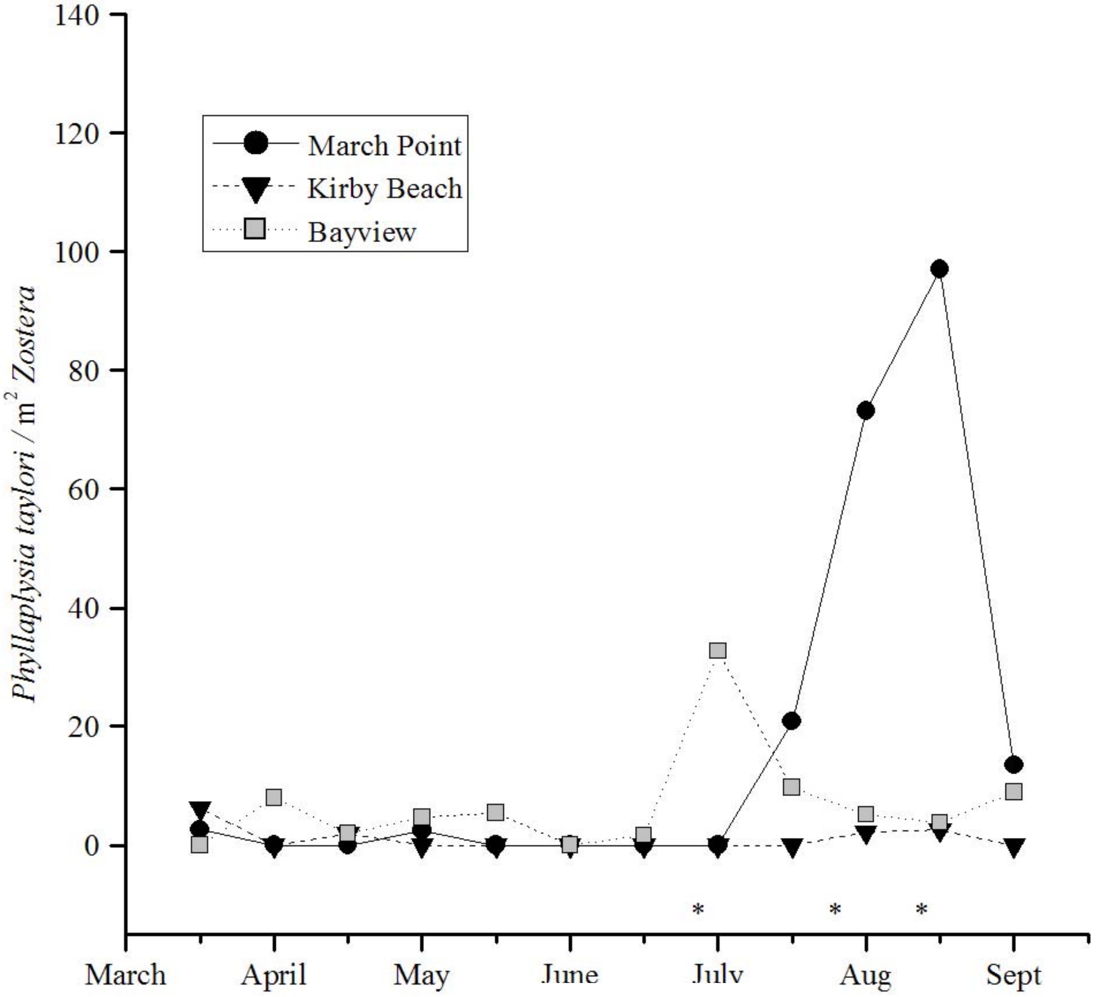


Figure 72. Mean density (number m^{-2} of eelgrass leaf) of *Phyllaplysia taylori* on *Zostera marina* leaves collected at 3 sites in Padilla Bay on twelve sampling dates from mid-March to early September 1998. An asterisk above the x-axis indicates a significant difference among sites on that sampling date. (From Delorenzo 1999)

magnitude with a maximum in July. *L. variegata* abundance was generally lower than *I. resecata* with lowest densities in April and May. Caprellid density fluctuated over almost 4 orders of magnitude with highest densities in July (Thom et al. 1995).

The crab, *Cancer magister*, is another important component of the epibenthos community in eelgrasses in Padilla Bay. After megalopae of *C. magister* molt into juveniles (April - August in Washington and British Columbia, Pauley *et al*. 1986) they are found in shallow coastal waters including Padilla Bay. Juveniles settling in Padilla Bay may come both from oceanic cohorts and Puget Sound cohorts with about half coming from each cohort during 1988 (Dinnel *et al*. 1993, McMillan et al. 1995, Fig. 73). The early instars are found primarily in intertidal eelgrass habitat or intertidal gravel and algae habitat (Dinnel *et al*. 1986, McMillan et al. 1995). The eelgrass habitat apparently provides protection, substrate and food organisms for the early instars (Pauley *et al*. 1986, McMillan 1991). The 1+ age class of juveniles prefer the shallow channels and subtidal eelgrass habitat rather than the intertidal habitat (Dinnel *et al*. 1986, McMillan 1991, McMillan et al. 1995).

FISH

The fish community of the intertidal eelgrass habitat is generally transient with diurnal movement of fish onto and off of the intertidal flats with the movement of tides, seasonal changes in the abundance of various species (Fresh 1979) and movements into and out of eelgrass habitats at different stages of life cycle and growth (Fresh 1979, Simenstad *et al*. 1988, Caine 1991). In summarizing a two year study of fish assemblages at 15 sites grouped into five different habitat types in nearshore waters of northern Puget Sound, Fresh (1979) found that "the dominant nearshore pelagic species were present throughout the various nearshore habitats [including eelgrass habitat] of northern Puget Sound with little evidence of distinct assemblages in different habitats. However, even though the dominant species exploit the entire nearshore spectrum of habitats, there were preferred habitats and areas." Thus, there does not appear to be a distinct eelgrass habitat assemblage of fish, although many of the dominant species utilize the eelgrass habitat. One of the sample sites used by Fresh (1979) was an eelgrass habitat site in Padilla Bay.

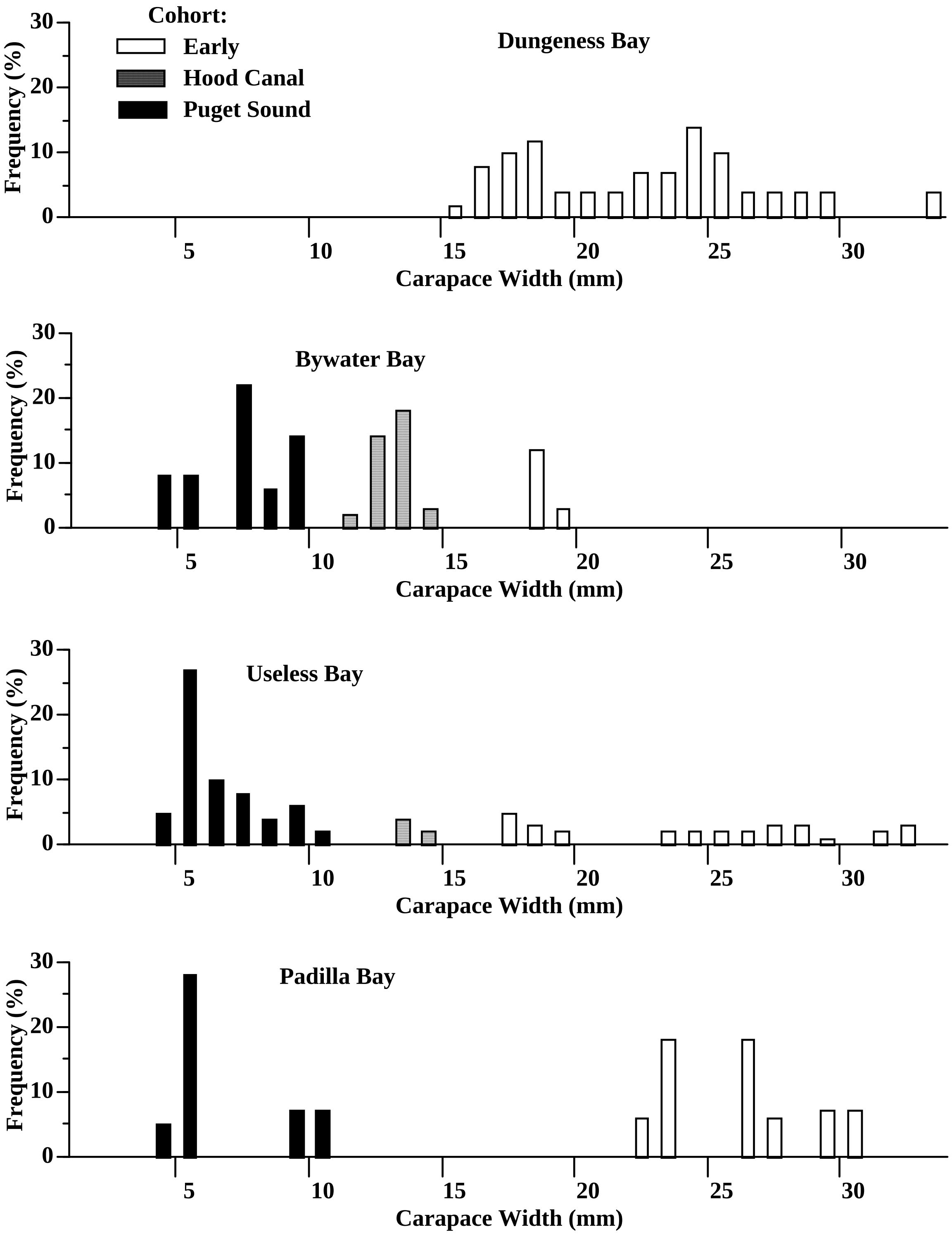


Figure 73. Size-frequency distributions of the 1988 year-class crabs, *Cancer magister*, sampled intertidally in late August 1988 in Dungeness Bay, Bywater Bay (Hood Canal), Useless Bay, and Padilla Bay. The presumed source of the cohorts is indicated by shading of the histograms. (After Dinnel et al. 1993)

Biologically important species in Padilla Bay included Pacific Herring, Threespine Stickleback, Pacific Sand Lance, Surf Smelt, Longfin Smelt, Soft Sculpin, Chinook Salmon, and Staghorn Sculpin.

Dinnel *et al*. (1990) caught fish in Padilla Bay in the intertidal eelgrass, subtidal eelgrass and subtidal channel habitats. Fish species with abundances greater than 100 per hectare in the intertidal eelgrass included Staghorn Sculpin, Snake Prickleback, Silver-spotted Sculpin, Shiner Perch, Saddleback Gunnel, Three-spined Stickleback and Bay Pipefish. All of these species, except for the first two, were found almost exclusively in the two eelgrass habitats and only in very low numbers in the channel habitat (Fig. 74). The Staghorn Sculpin, the most abundant of the fish sampled in this study, fed about equally on amphipods, crabs, unidentified crustaceans and isopods in the intertidal eelgrass habitat (Dinnel *et al*. 1990).

Beamer et al. (2007) reported monthly catch records from May to November of fish from beach seine, fyke trap, and surface trawl sets in five habitats in Padilla Bay: shallow intertidal flats, blind channels, subtidal fringe of flats, subtidal fringe of beaches, and off-shore surface waters. Many of the species that were reported were similar to those reported by Dinnel et al. (1990). Most abundant species (based on relative abundance over all months) included Three-spined Stickleback, Staghorn Sculpin, Shiner Perch, Starry Flounder, Surf Smelt, Pacific Herring, Gunnels, and Snake Prickleback. English Sole and Starry Flounder were abundant on shallow intertidal flats and subtidal fringes of those flats. Smelt and Three-spined Stickleback were abundant in all habitats; Shiner Perch and Staghorn Sculpin were abundant in all habitats except off-shore surface waters. Pacific Herring were common in the two subtidal fringe habitats and abundant in the off-shore waters (Beamer et al. 2007). In all Padilla Bay habitats (except blind channel habitat) out migrating Chinook Salmon and/or Chum Salmon were common during at least one of the monthly sets.

Pacific Herring are abundant throughout Puget Sound and were abundant in tow net samples in Padilla Bay (Fresh 1979, Miller *et al*. 1977, Beamer et al. 2007). Herring lay

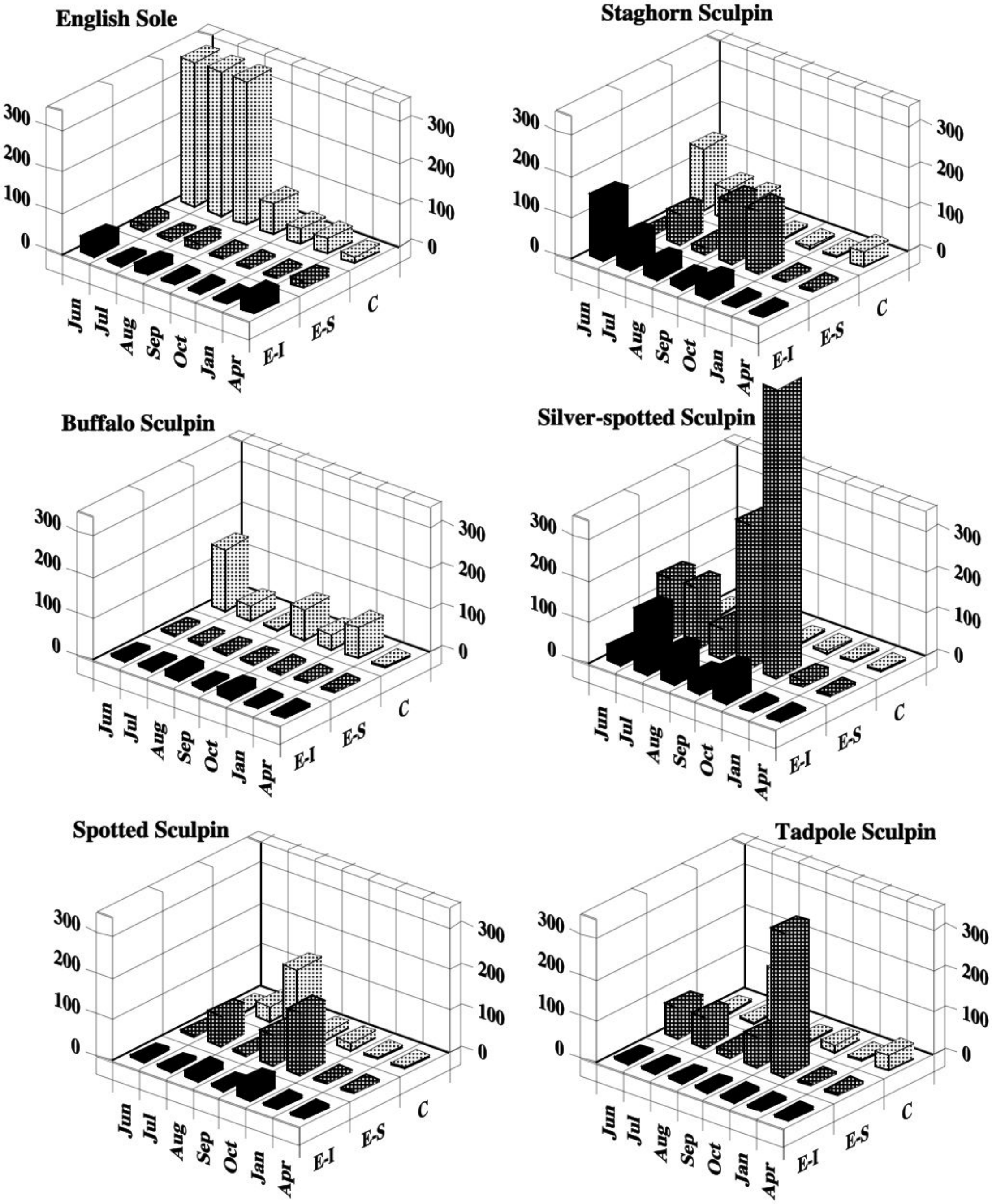
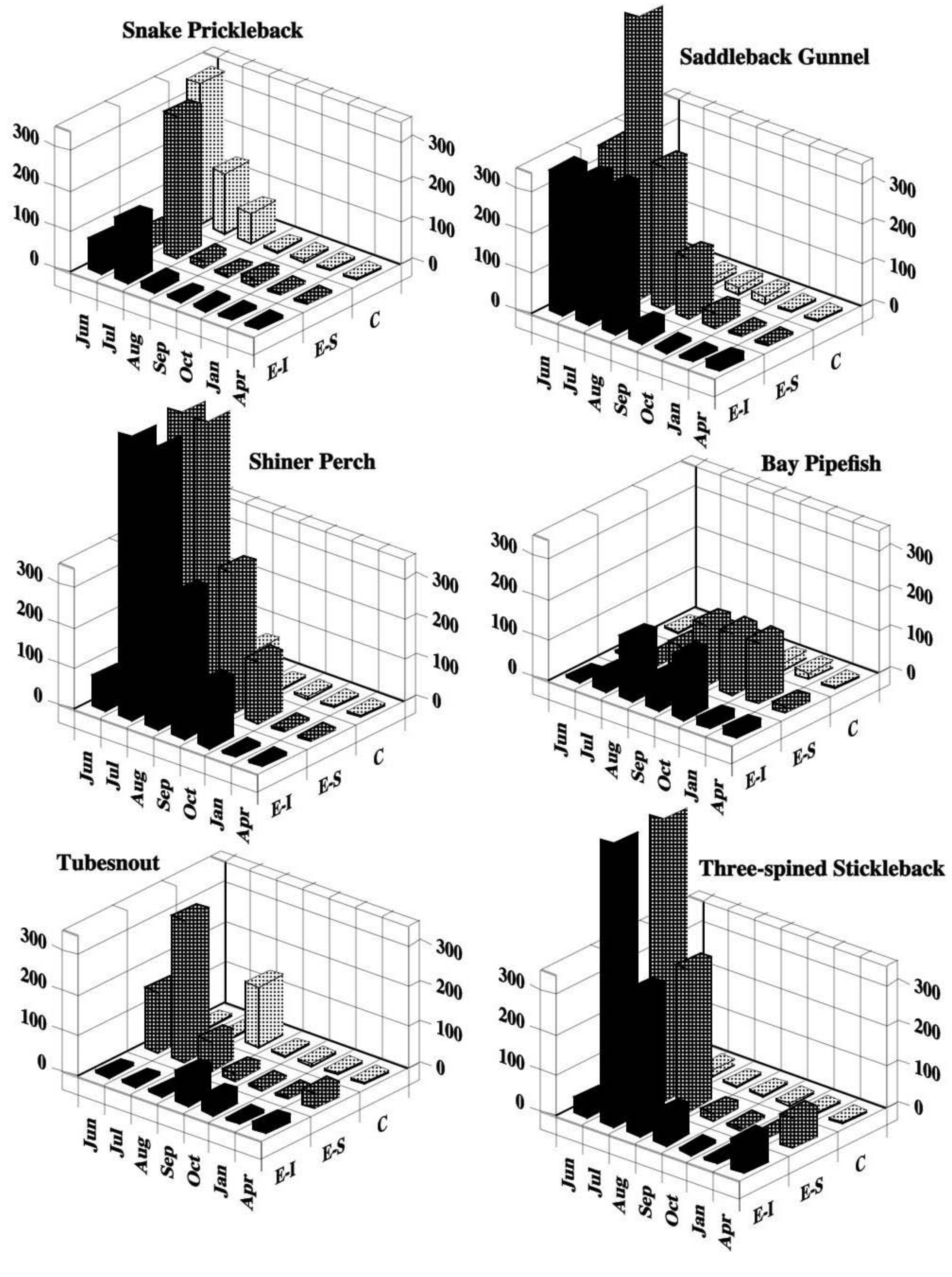


Figure 74a. Fish density (fish/hectare) during seven months (between June 1987 and April 1988) by habitat (E-I = Intertidal eelgrass; E-S = Subtidal eelgrass; C = Channels) of the twelve most common fish species caught in beam trawl tows. (From Dinnel et al. 1990)


Snake Prickleback

Saddleback Gunnel

Shiner Perch

Bay Pipefish

Tubesnout

Three-spined Stickleback

Figure 74b. Fish density (fish/hectare) during seven months (between June 1987 and April 1988) by habitat (E-I = Intertidal eelgrass; E-S = Subtidal eelgrass; C = Channels) of the twelve most common fish species caught in beam trawl tows. (From Dinnel et al. 1990) adhesive eggs on intertidal and subtidal marine vegetation, and Washington State Department of Fisheries and other agencies survey eelgrass beds for presence and density of herring spawn. Surveys of herring spawn in the vicinity of Padilla Bay have indicated spawn occasionally present in Padilla Bay (Trumble *et al*. 1977), but medium to heavy spawning areas are more regularly reported from both sides of March Point and in Fidalgo Bay than in Padilla Bay (Penttila 1984, 1985).

Five species of Pacific salmon spawn and rear in Puget Sound and watershed (Fresh 2006). Two of these species, Chinook Salmon and Chum Salmon, make the most extensive use of estuarine and nearshore habitats before migrating to ocean waters. Juvenile Chinook and Chum Salmon have been reported from Padilla Bay (Fresh 1979, Simenstad et al. 1995, Dinnel et al. 1990, Beamer et al. 2007, Miller et al. 1977). Padilla Bay was probably a very important rearing habitat for Skagit River salmon in the past. Prior to the 1930's, water from the North Fork of the Skagit River flowed into Swinomish Slough and from there into Padilla Bay. A very abundant salmon fishery flourished in the slough catching returning adult salmon (Yates 2001). However, the construction of a rock jetty in 1937 (rebuilt in 1973) and other landscape changes diverted freshwater flow of the North Fork of the Skagit River, and presumably juvenile salmon, away from Swinomish Channel and Padilla Bay (Yates 2001). Fresh (2006) listed four factors as important in determining how well nearshore habitats support juvenile salmon: 1) feeding and growth, 2) avoidance of predation, 3) the physiological transition from freshwater to saltwater, and 4) migration to ocean feeding habitats. Padilla Bay with the extensive eelgrass beds contains an abundance of 1) and 2) above. However, diversion of freshwater flow from the Skagit River has reduced substantially the third and fourth factors. Yates (2001) measured salinity along the length of the Swinomish Channel along with abundance of juvenile salmon. Both Chum and Chinook Salmon juveniles were less abundant at the north end (Padilla Bay end) of Swinomish Channel and Chinook Salmon juveniles were significantly more abundant at a low salinity site compared to a nearby high salinity site. Yates (2001) suggests that a "salinity barrier" in Swinomish Slough reduces the movement of juvenile Chinook Salmon from the Skagit River to the potential eelgrass rearing habitat in Padilla Bay.

In spite of the apparent reduction in the numbers of juvenile salmon moving into Padilla Bay from the Skagit River, Beamer et al. (2007) reported Chinook and Chum Salmon in Swinomish Channel during a three year study. And both species were present in Padilla Bay habitats. Peak numbers of juvenile Chinook and Chum salmon in Padilla Bay and Swinomish Channel were in February through May except in off-shore waters where peak abundance was in June. However, wild Chinook salmon juveniles were present in the subtidal fringe and off-shore waters of Padilla Bay through October.

Thus, Padilla Bay is utilized by juvenile Chinook and Chum Salmon at the present time for rearing. But the numbers are probably less than the numbers 100 years ago and less than the potential numbers if proposed restoration projects in Skagit Bay and Swinomish Channel were implemented.

WATERFOWL

The intertidal eelgrass community in Padilla Bay directly and indirectly supports an abundant avifauna. Study of the avifauna, however, is limited to periodic counts of the waterfowl in the bay and some study of the Brant, *Branta bernicula* populations. Brant are herbivores that feed on eelgrass, breed in the Canadian and Alaskan arctic, and winter along the Pacific coast of the United States and Mexico (Reed *et al*. 1989). Few Brant now overwinter north of the U.S. - Mexico border, but one of the remaining important over wintering sites is Padilla Bay (Jeffrey 1976, Reed *et al*. 1989). Brant begin arriving in Padilla Bay in November and may be present as late as June (Reed *et al*. 1989). Jeffrey (1976) reported average numbers of Brant for each month from October through April for the years 1970-1976 (Table 14). Spring migration swells the number of these geese on Padilla Bay to a maximum in April for the months when counts were made. During the 1987-1988 winter Reed *et al*. (1989) estimated that about 15,000 Brant were over wintering in Padilla Bay (Table 15). On the basis of different color phases and examination of leg-ringed geese, they suggested that most of the High Arctic Brant overwinter in Padilla Bay (Reed *et al*. 1989).

Table 14. *Mean number of Brant in Padilla Bay each month from October to April based on weekly to monthly counts made during 1970-1976 by Washington Department of Wildlife. (From Jeffrey 1976)*

Month	Mean number of Brant
October	250
November	1,720
December	2,970
January	2,830
February	1,650
March	4,090
April	28,250

Table 15. *Number of Brant recorded in Padilla Bay during aerial surveys conducted between November 1987 and February 1988. (From Reed et al. 1989)*

Date of survey	Number of Brant
17 November	4,990
4 December	16,290
18 December	14,450
24 December	16,110
4 January	15,320
4 February	18,120
25 February	19,800

Table 16. *Monthly average numbers of four species of dabbling ducks in Padilla Bay from 1966 to 1975. Aerial estimates were made weekly during fall and winter when weather conditions were appropriate. (From Jeffrey 1976)*

Month	Mallard	Pintail	Green-winged Teal	Wigeon	Total
October	2,760	10,530	4,670	9,290	27,250
November	3,910	7,560	3,000	13,540	28,010
December	5,940	10,570	3,040	16,810	36,360
January	2,950	4,150	1,430	8,450	16,980

Jeffrey (1976) summarized the periodic counts of dabbling ducks present in Padilla Bay during autumn and winter (Table 16). About 10,000 each of American Widgeon (*Anas Americana*) and Northern Pintail (*A. acuta*) are present in Padilla Bay during these months with about half as many Mallard (*A. platychynchos*) and Green-winged Teal (*A. crecca*). No habitat studies have been conducted in Padilla Bay, but Baldwin and Lovvorn (1994a, 1994b) reported in Boundary Bay (located about 70 km north of Padilla Bay) that these dabbling ducks were feeding mainly in eelgrass habitats. Their diet consisted of eelgrass and animals associated with eelgrass communities. *Z. japonica* was the preferred eelgrass ingested by both brant and dabbling ducks (Baldwin and Lovvorn 1994a, 1994b). With about 30,000 waterfowl present in Padilla Bay during autumn and winter, they are an important and significant part of the eelgrass community and have an important role in food webs, energy flow, and nutrient cycling.

FOOD WEBS AND ENERGY FLOW

Eelgrass habitats have been considered to be primarily detritus based ecosystems with the bulk of the eelgrass productivity becoming leaf detritus that is either trapped *in situ* or else exported from the system to adjacent open water areas or to shores and beaches (Klug 1980, Harrison 1989, Hemminga and Nieuwenhuize 1991). Export from the eelgrass meadow may be particularly true of the intertidal eelgrass habitat in Padilla Bay where semidiurnal tides may move broken leaves and dislodged plants either to channels and out to deeper waters or up onto the beaches. No studies in Padilla Bay have attempted to quantify such export of plant production from the bay. However, Ruckelshaus *et al*. (1993) estimated food sources for filter-feeding mussels in four habitats in Padilla Bay: slough, mudflat, eelgrass and neritic. In spite of Padilla Bay being a "well-mixed" estuary they found differences in local seston composition and mussel growth rates and suggested that such differences reflect in part the heterogeneous distribution of benthic primary producer habitats in Padilla Bay (Wissmar 1986, Ruckelshaus 1988, Ruckelshaus *et al*. 1988, 1990, 1993). Eelgrasses were a major source of the seston for mussels growing in the water column above intertidal eelgrass. Similarly, Palm (1996) demonstrated that Manila clams, *Venerupsis philippianarum*, can ingest detritus particles of *Z. marina*.

Studies by Thom *et al*. (1995) have indicated the importance of grazing in the eelgrass ecosystem in Padilla Bay. In particular, the high density of *Idotea resecata* combined with their estimated grazing rate indicates that *I. resecata* may graze 20% of the estimated annual production of the eelgrass ecosystem (Thom *et al*. 1991) and, in intertidal *Z. japonica* habitats, *I. resecata* may graze the total annual production. In contrast, grazing by birds is estimated to account for only 1.5% of the total seagrass productivity. Other important grazers of epiphytes in Padilla Bay are the snail, *Lacuna variegata*, the amphipod, *Caprella laeviuscula*, the sea hare, *Phyllaplasia taylori*, and the bubble shell, *Haminoea vesicula* (Shaw 1994, Shaw 1995, Thom et al. 1995, Delorenzo 1999).

The invertebrate grazers are an important food source for fish in the bay. Caine (1991) reported that shiner perch, *Cymatogaster aggregata*, appear to selectively feed on caprellid amphipods when they are available with caprellids making up 80-100% of the gut contents of shiner perch. After the abundance of caprellids decreases, shiner perch switch to other prey items (Caine 1991). However, Shaw (1995) found that shiner perch fed actively both during the daytime and nighttime. They appeared to be opportunistic feeders with their foregut contents including gammarid amphipods, harpacticoid copepods, isopods, and polychaetes as well as caprellids even during times of peak caprellid abundance (Shaw 1995). The maximum percent (of wet biomass) of caprellids in the foregut were 9% and 31% in two 24 hour studies of 199 and 110 shiner perch taken during the seasonal maximum abundance of caprellids (Shaw 1995). Amphipods and/or isopods were the most important prey item for five of the six most common marine fish caught by Dinnel *et al*. (1990) in Padilla Bay (Table 17). Harpacticoid copepods were the most important prey item for surf smelt, Pacific sand lance, chum salmon, and threespine stickleback caught by Simenstad *et al*. (1988) in Padilla Bay (Table 18). Similarly, harpacticoid copepods had a high Index of Relative Importance for chum salmon, Pacific herring, surf smelt, and Pacific sand lance during May 1989 at a site near eelgrass beds (Simenstad et al. 1995). These studies indicate that in Padilla Bay, energy is transferred from the eelgrass community to carnivores by way of grazers as well as through the detritus food chain. Staghorn sculpin, *Leptocottus armatus*, in Padilla Bay shift their food preference as they increase in size (Pantalone 1985). The smallest size classes of staghorn sculpins feed primarily on harpacticoid copepods, shifting to gammarid amphipods at size 70 mm and above except for two size classes for which polychaetes were the most important prey item.

Table 17. *Percent Indices of Relative Importance for six common marine fish caught by beam trawl in Padilla Bay. (from Dinnel et al. 1990)*

Group	n =	Staghorn sculpin (160 fish)	Silverspotted sculpin (22 fish)	Great sculpin (13 fish)	Padded sculpin (12 fish)	Whitespotted greeling (12 fish)	Saddleback gunnel (10 fish)
Amphipod		42.8	90.1	9.1	96.9	18.9	82.3
Isopod		17.8	9.6	29.2	0.0	68.2	16.4
Crab		14.0	0.1	1.0	0.3	3.1	0.0
Shrimp		3.1	0.2	13.0	0.0	6.3	0.0
Other crustacean		3.5	0.0	0.0	2.6	0.1	1.0
Mollusc		2.3	0.0	1.9	0.0	0.6	0.1
Polychaete		8.7	0.0	0.0	0.2	2.8	0.2
Fish		1.1	0.0	43.8	0.0	0.0	0.0
Algae, detritus, etc.		6.7	0.0	2.0	0.0	0.0	0.0

Table 18. *Percent Indices of Relative Importance for five species of fish caught in Padilla Bay in May, 1986. (From Simenstad et al. 1988)*

Group	Surf smelt	Pacific herring	Pacific sand lance	Chum salmon	Threespine stickleback
Polychaeta	5.2				0.1
Calanoida		0.2	3.5	4.4	0.3
Harpacticoida	86.3	37.0	92.6	83.2	50.7
Poecilostomatioda			0.2		0.2
Balanomorpha		0.1	1.1	0.1	0.1
Cumacea	1.4		0.2		
Gammaridea	6.5	1.1	1.2	9.8	48.6
Caprellidea					0.1
Euphausiacea				0.5	
Decapoda		61.6	1.1	2.1	

The food web of the eelgrass community is complex, in part, because of the diverse and abundant organisms that are present in the community. In addition, juvenile stages may shift their prey items as they grow in size or change life cycle stage. Simenstad *et al.* (1979) summarized the shallow sub littoral food web of a protected mud/eelgrass habitat (including sample sites in Padilla Bay) (Fig. 75). The food web of the intertidal eelgrass would be expected to be similar since some of the sampling on which the food web is based was from intertidal eelgrass sites.

SUBTIDAL EELGRASS COMMUNITY

The subtidal eelgrass habitat in Padilla Bay is located along the channel margins and along the edges of the intertidal eelgrass flats (Fig. 3). Thus, subtidal eelgrass patches tend to be linear, bordered on one side by intertidal eelgrass and on the other side by subtidal sand habitat. The approximate area of subtidal eelgrass in Padilla Bay is 200-400 hectares (Table 10).

The subtidal eelgrass is delineated from the intertidal eelgrass by extreme low water depth (Dethier 1990, Ray 1994). This depth is used to divide the intertidal from the subtidal because the ability to survive even short periods of exposure to the air (that is a few times during the year) is an important characteristic dividing whole groups of species into those that can live in the intertidal habitat from those that cannot. However, in Padilla Bay (and many similar bays with broad intertidal expanses of seagrasses) the exact depth relative to tidal datum is much less important than the micro topography and the ability of seagrasses to retard water flow. Much of the broad intertidal eelgrass flats retain some water during low tides, even during extreme low water spring tides (Bulthuis and Shaw 1993, unpublished data). Similar phenomena of water trapping has been

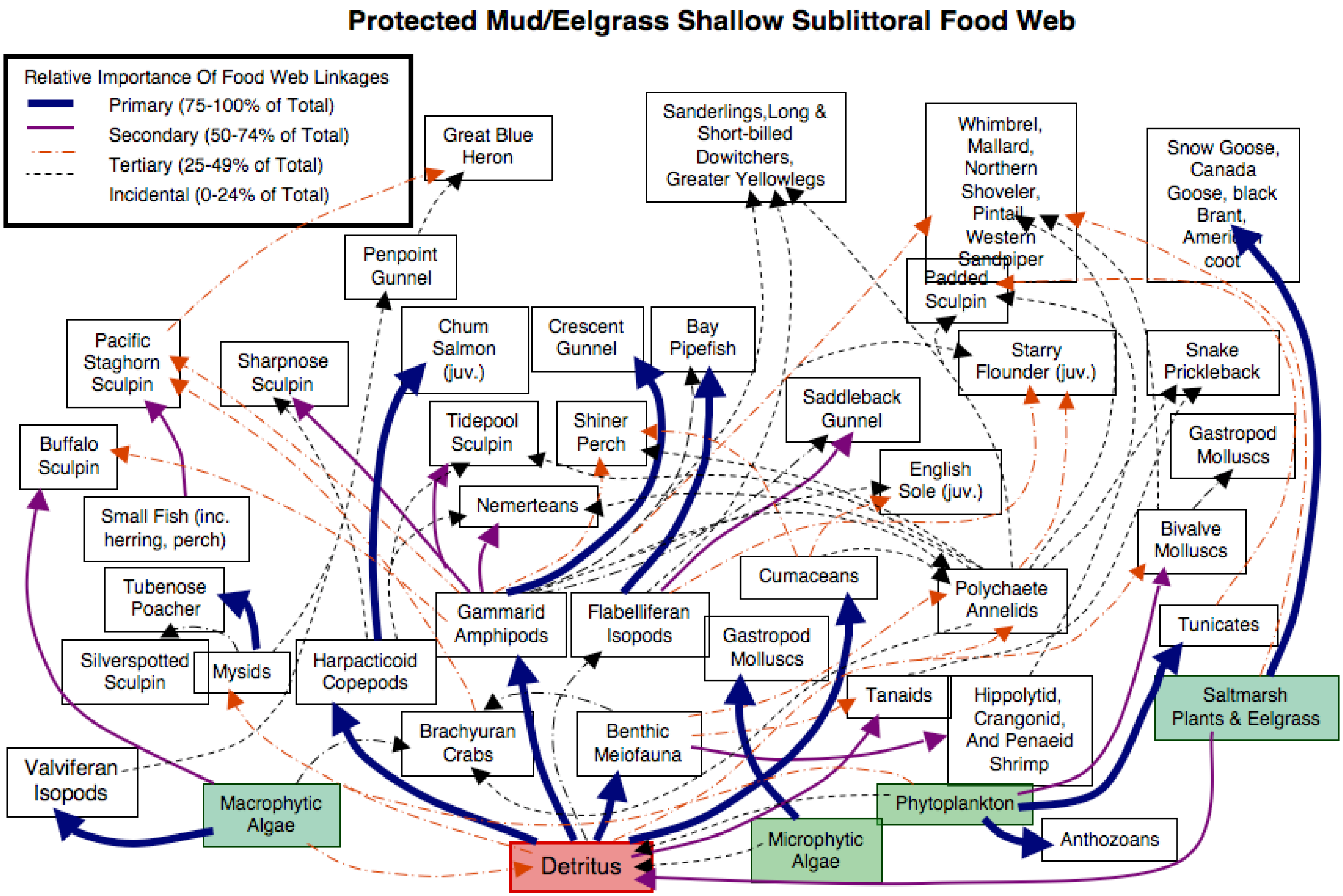


Figure 75. Generalized food web for shallow sublittoral protected eelgrass and or mud habitats in northern Puget Sound. (From Simenstad et al. 1979)

described in *Thalassia testudinum* with a greater depth of water retained where the biomass of seagrasses was greater (Powell and Schaffner 1991). Thus, biota that cannot survive exposure to the air for even a short period of time are able to survive (and thrive) in the intertidal eelgrass beds that are well above extreme low water depth. Because of this phenomena the distinction between the intertidal eelgrass habitat and the subtidal eelgrass habitat is blurred in Padilla Bay. Most of the studies of eelgrass communities in Padilla Bay were conducted on intertidal beds in which the eelgrasses were never fully exposed to the air. Therefore, the descriptions and summary of studies in the intertidal eelgrass habitat applies also to the subtidal eelgrass habitat. In the following discussion I will confine the review to studies that explicitly sampled in the subtidal eelgrass habitat and/or made some comparison with the intertidal habitat.

Aerial extent and distribution of subtidal eelgrass. The subtidal seagrass beds are more difficult to detect and map with remote sensing techniques. Satellite imagery was unable to distinguish the subtidal eelgrass beds from deep water in Padilla Bay (Webber et al. 1987). Bulthuis (1991) used color aerial photography to delineate some of the subtidal eelgrasses, but in some areas SCUBA diving was required to locate the lower limit of distribution. The lower depth limit of the subtidal eelgrass beds in Padilla Bay is about -3.0 to -3.7 m below MLLW (mean lower low water) (Bulthuis 1995, Bulthuis and Shull 2006, Dowty et al. 2005). Shoot density at one subtidal site near the lower limit of distribution fluctuated seasonally form 50-60 shoots m^{-2} in late winter and early spring to 100-150 shoots m^{-2} in summer (Bulthuis 1996b, Fig. 62). The shoot biomass of eelgrass increased with increasing depth in a study by Thom (1990), although the deepest site was not below -1.2 m, which is about equal to the extreme lower tide depth in Padilla Bay. If the pattern observed by Thom (1990) continues into the subtidal, the shoot biomass of eelgrass is likely to be higher than in the intertidal. This pattern was true for two experimental sites, one subtidal and the other intertidal (Bulthuis 1996b). The subtidal site contained a seasonal high of 330 g m^{-2} of above ground dry weight in July whereas the seasonal high for the intertidal site contained 175 g m^{-2}.

Infauna in subtidal eelgrass. The infauna of the subtidal eelgrass beds was similar to that in the intertidal eelgrass in Padilla Bay with similar taxa richness, but less abundance and biomass compared to lower intertidal eelgrass (Ray 1997, Figs 65-68). Caine (1991) reported that the density of caprellid amphipods was similar in the subtidal eelgrass along the channel edge to the densities in the intertidal flats, with populations in both habitats declining drastically when migrating shiner perch, *Cymatogaster aggregata*, entered Padilla Bay. Similar infaunal and epifaunal communities in the subtidal eelgrass and lower intertidal eelgrass may be a consequence of the water retention by eelgrasses in the intertidal, as discussed earlier.

Decapods in subtidal eelgrass. Young of the year Dungeness crabs, *Cancer magister*, are found primarily in the intertidal eelgrass habitat. However, as they grow and mature, the larger crabs move to the subtidal eelgrass beds and into the eelgrass covered channel bottoms (Dinnel *et al*. 1986, McMillan 1991, McMillan et al. 1995). As they continue to mature, they move out of the subtidal eelgrass and into the deeper channels. Thus, the subtidal eelgrass provides habitat for a specific stage in the life cycle of Dungeness crabs in Padilla Bay, although some crabs of all age classes are found in this habitat at times (Dinnel *et al*. 1986, McMillan 1991, McMillan et al. 1995, Dinnel 2001).

Fish in subtidal eelgrass. Studies of the fish assemblages in Padilla Bay have often included sampling over subtidal eelgrass habitat, in part, because of the ease of sampling compared to the intertidal flats. However, most sampling gear and techniques cover a large area and typically sample more than one habitat type. The fish and prey reported by Simenstad *et al*. (1988) appear to have been caught over eelgrass areas that included both intertidal and subtidal habitats (Table 19), including the five species for which stomach contents were analyzed: Surf Smelt, Pacific Herring, Pacific Sand Lance, Chum Salmon and Threespine Stickleback (Table 18). Dinnel *et al*. (1990) sampled fish in three habitats: intertidal eelgrass, subtidal eelgrass, and subtidal channel. In the subtidal eelgrass habitat, the estimated density of Staghorn Sculpin, Tadpole Sculpin, Silver-Spotted Sculpin, Shiner Perch, Saddleback Gunnel, Snake Prickleback, Three-spined Stickleback, Tubesnout, and Bay Pipefish exceeded 100 fish per acre at least some time

Table 19. Fish species caught in a beach seine and purse seine in Padilla Bay, May 9, 1986. (from Simenstad et. al. 1988)

Scientific Name	Life history stages[a]	Common name
Family Clupeidae		
Clupea harengus pallasi	J	Pacific herring
Family Salmonidae		
Oncorhynchus keta	J	Chum salmon
Family Osmeridae		
Hypomesus pretiosus	J, A	Surf Smelt
Family Gasterosteidae		
Gasterosteus aculeatus stickleback	J, A	Threespine
Family Syngnathidae		
Syngnathus leptorhynchus	J	Bay pipefish
Family Ammodytidae		
Ammodytes hexapterus	J	Pacific sand lance
Family Pleuronectidae		
Lepidopsetta bilineata	J	Rock sole
Pleuronectes (*Platichthys) stellatus*)	J	Starry Flounder
Pleuronectes (*Parophrys) vetulus*	J	English sole
Psettichthys melanostictus	J	Sand sole

[a] J = juvenile, A = Adult

during the year (Fig. 74). Other species, such as Buffalo Sculpin and English Sole are abundant in the adjacent channel habitat, but are rare in the subtidal eelgrass. Diets of these fish were considered in the section on intertidal eelgrass, and the data are presented in Tables 17 and 18.

INTERTIDAL ALGAE

The extensive intertidal flats in Padilla Bay include areas that are covered with macroalgae. Two hundred twenty hectares of intertidal flats were mapped in 1989 as covered with macroalgae (Bulthuis 1991, 1995, Table 20, Figs. 3 and 59). Most of the algal biomass was identified as *Ulva* sp. and *Enteromorpha* sp. The cover of macroalgae within such identified habitats varied from 20-100% cover. At one 1 hectare site with 80-100% cover, Bulthuis (1991) reported a mean algal biomass of 530 g dry weight m^{-2}, primarily *Ulva* sp. and *Enteromorpha* sp. The sediment surface beneath the algal mats was anaerobic beneath the high biomass areas. The area covered by these algal mats fluctuates among years in estimated aerial coverage (Table 10.) The delineation of these algal mats is made difficult in part because of the similar spectral characteristics of green macroalgae and eelgrasses, and in part because intertidal eelgrass beds contain a lot of green macroalgae, sometimes with a greater biomass than *Z. marina* (Bulthuis 1991). Shull (2000) used Compact Airborne Spectrographic Imager data and designated two habitat categories as eelgrass/macroalgae. Porter et al. (2006) used a Digital Mapping Camera to map intertidal habitats in Padilla Bay. The reported highest accuracy in the algae category was 39% user’s accuracy and 15% producers accuracy. Difficulty in distinguishing between eelgrass and macroalgae with color aerial photographs were also reported by Bulthuis and Shull (2002, 2006). Nevertheless, the area covered by macroalgae in Padilla Bay in different years was estimated at 162, 101, 204, 351, and 243 hectares by Bulthuis (1991, 1995), Shull (2000), Bulthuis and Shull (2002, 2006), and Porter et al.(2006) (Table 10). These estimates indicate that area covered by macroalgae can vary by a factor of three from one year to another.

Table 20. *Area of Coastal Habitats in Padilla Bay, Washington, based on aerial photography and ground truth investigations in summer 1989. Coastal Habitat classification is based on the scheme proposed by Ray (1994). (from Bulthuis 1991, 1996a)*

Habitat	Area (hectares)	Percent of Padilla Bay
Intertidal		
Rock Bottom		
Rubble	<1	<1
Unconsolidated Bottom		
Cobble - Gravel	<1	<1
Sand	1515*	23
Mud	350*	5
Aquatic Bed		
Rooted Vascular	2960	45
Algal	220	3
Marsh	70	1
Subtidal		
Rock Bottom	<1	<1
Unconsolidated Bottom		
Sand	1261	19
Aquatic Bed		
Rooted Vascular	252	4

* The delineation between sand and mud habitats was estimated from the total intertidal "Unconsolidated Bottom" category (1865 hectares).

In addition to fluctuations in the area covered, the location of these mats changes from one year to another. Comparison of mapping efforts in 1989, 2000, and 2004 indicates that large algae mats were much more extensive in the middle of Padilla Bay in 2004 compared to the extensive areas in the south of Padilla Bay in 2000 (Bulthuis and Shull 2007, Fig. 59). The changing locations of these mats of macroalgae may impact the eelgrass beneath them as well as the faunal communities.

When mats begin to decay, the bottom of the mat may be anaerobic (Bulthuis 1991). When these mats rest on top of eelgrasses the mats may impact survival of the eelgrass. Riggs (1995) studied the effect of hypoxia on photosynthetic rate and chlorophyll concentration on *Z. marina*. At three temperatures (10°, 20°, and 30° C) exposure to hypoxic conditions for as little as 24-72 hours caused lower photosynthetic rates when returned to normal conditions. Mats of macroalgae that remain over eelgrasses for weeks to months during the summer are likely to stress and/or kill eelgrasses beneath them.

The mats of macroalgae in Padilla Bay are composed primarily of green algal (Chlorophyta) species in two genera in the order Ulvales: *Ulva* and *Enteromorpha* (Bulthuis 1991, 1995, Hayden and Waaland 1998, 1999). The taxonomy of the Ulvales is being revised (Hayden and Waaland 2002, Hayden et al. 2003). The names used in this review are those given by the authors of the reports but see Hayden et al. (2003) for synonymy and new combinations. Fourteen species of chlorophytic macroalgal species were identified in Padilla Bay by Hayden and Waaland (1998, Table 21). Three of these species had notable amounts of biomass in September 1996 and summer of 1997 and may be the principle species in the large macroalgal mats that occasionally form in Padilla Bay (Bulthuis 1991, 1995): *Ulva fenestrata, Enteromorpha prolifera*, and *Ulvaria obscura* (Hayden and Waaland 1998). The assemblage of green macroalgal species in Padilla Bay is similar to the assemblages present in other bays and estuaries in Puget Sound (Hayden and Waaland 1999). Although the species assemblages were similar from month to month during the spring and summer, some species were common or abundant one month and not present the following month (Hayden and Waaland 1998, 1999). Such changes indicate the dynamic nature of these algal assemblages with rapid

Table 21. *Chlorophytic macroalgal species collected and identified in Padilla Bay from August 1996 to August 1997. (From Hayden and Waaland 1998, but see Hayden and Waaland 2002 and Hayden et al. 2003 for nomenclature changes)*

Species
Acrosiphonia coalita (Ruprecht) Scagel, Garbary, Golden *et* Hawkes
Blidingia minima (Nägeli *ex* Kützing) Kylin var. *minima*
Enteromorpha clathrata (Roth) Greville
Enteromorpha compressa (Linnaeus) Greville
Enteromorpha flexuosa (Roth) J. Agardh
Enteromorpha intestinalis (Linnaeus) Link *in* Nees von Esenbeck
Enteromorpha linza (Linnaeus) J. Agardh
Enteromorpha prolifera (Müller) J. Agardh
Rhizoclonium riparium (Roth) Harvey *emend.* Nienhuis
Ulva californica Wille *in* Collins, Holden *et* Setchell
Ulva fenestrata Postels *et* Ruprecht
Ulva stenophylla Setchell *et* Gardner
Ulvaria obscura (Kützing) Gayral var. *blyttii* (Areschoug) Bliding
Urospora penicilliformis (Roth) Areschoug

growth under good conditions and rapid decline due to decay, waves, currents, herbivory, or other causes.

The infauna associated with the intertidal macroalgae were similar in taxa richness, abundance, and composition to other intertidal habitats, but the biomass was considerably lower than intertidal habitats with eelgrass (Ray 1997, Figs 65-68). The macroalgae intertidal habitat is also important for Dungeness crab when the substrate includes gravel (McMillan et al. 1995). The density of young Dungeness crab (0+ year class) was highest in gravel-algae habitat compared to eelgrass habitat or bare sand (McMillan et al. 1995). However, this habitat type is rare in Padilla Bay and generally restricted to the upper intertidal offshore of upland bluffs.

There are no further reports on the intertidal algal habitat in Padilla Bay. Based on similar studies elsewhere, the presence of extensive macroalgal mats may be due to nutrient inputs in the southern part of Padilla Bay. Nutrient enrichment has increased growth of *Ulva* sp. and *Enteromorpha* sp. in other bays. (Bach and Josselyn 1978, Valiela et al. 1992). Such mats have caused decreases in seagrasses (Harlin and Thorne-Miller 1981, Cambridge *et al*. 1986, Den Hartog 1994, Hauxwell et al. 2001) and in benthic infauna (Perkins and Abbott 1972, Everett 1991). In a report of an investigation into potential pollution in Padilla Bay, Neale (1952) reported that "a heavy growth of seaweed (lettuce)" covered oyster beds in Padilla Bay. These oyster beds were located in the same general area as the macroalgal mats mapped or reported by Bulthuis (1991, 1995), Hayden and Waaland (1998, 1999), and Bulthuis and Shull (2002, 2006): west of Bay View and south of the Bay View Channel. Thus, for more than 50 years macroalgal mats have grown or accumulated on the tidal flats south of Bay View Channel.

INTERTIDAL SAND AND MUD FLATS

Padilla Bay has extensive intertidal habitats covering about 5,000 hectares, 85% of the bay. These flats are referred to as mudflats, tidal flats, or sandflats in various studies of

Padilla Bay. While there have not been any comprehensive surveys of the sediment size distribution in Padilla Bay the sediment size distribution has been measured as an adjunct measurement in many studies. A review of these various studies indicates that most of the intertidal flats in Padilla Bay are sand flats. Sites at which silt plus clay was the predominate grain size were two scattered sites in the central bay and sites in the southernmost part of Padilla Bay. In this review intertidal sand flats and mud flats are considered together as intertidal flats without macro-vegetation and called “intertidal flats” or “bare intertidal flats”.

The bare intertidal flats habitat in Padilla Bay is located primarily between the dikes (and ridges) that border Padilla Bay and the eelgrass covered intertidal flats that extend throughout most of Padilla Bay (Fig. 3). There are also some patches of bare intertidal flats intermixed among the eelgrass meadows. Such patches are particularly common along the channel edges and near the "headwaters" of the tidal channels (Bulthuis 1991, Bulthuis and Shull 2002, 2006). The total area covered by bare intertidal habitat is an estimated 1350 hectares.

Turner (1980) reported muddy sediments (silt plus clay >50% by weight) in the upper 30 cm at five sites in the southern part of Padilla Bay out of 35 sites sampled throughout the bay. In addition to particle size and organic matter, Turner measured the phosphorus, potassium, boron, calcium, magnesium, and cation exchange capacity of the sediments. The muddy intertidal sites had somewhat higher concentrations of organic matter, calcium, magnesium, and a higher cation exchange capacity than the sandy sediments in the rest of Padilla Bay in Turner's study (Turner 1980).

Bare intertidal sediments were sampled by Antrim (1985) and Wiggins (1992) for epibenthic species and by Ruckelshaus *et al*. (1993) for phytoplanktonic and epibenthic species. Antrim measured the concentration of metals in mollusks that were collected from the mud surface, *Crassostrea gigas*, *Macoma* spp., and *Mytilus edulis*. Wiggins collected epibenthic harpacticoid copepods from the muddy intertidal sediments near the abandoned Whitmarsh landfill. Mean density of harpacticoid copepods at three sites varied from 400 to 800 copepods m^{-2}. More than 95% of the copepods were in the genera *Harpacticus* or *Tisbe* with the remaining individuals in the genera *Dactylopodia*, *Zaus*, and *Scutellidium* and the families Ectinosomatidae and Lauphontidae. Ruckelshaus *et al*. (1993) collected planktonic and epibenthic samples from a bare intertidal muddy site in Indian Slough in August. The most abundant species were *Chaetocerus radicans*, *C. seriacanthus*, *Tetraselmis* sp. (a freshwater species presumably transported passively into the estuary), *Melosira moniliformis*, *Melosira* sp., *Navicula distans*, *N. seriata*, and a third *Navicula* sp.

The infauna of the unvegetated intertidal flats had the lowest richness of any of the habitats sampled by Ray (1997) and the lowest biomass, although overall abundance was similar (Figs. 65-67). Taxonomic distribution was similar to other habitats except for a large percentage of "miscellaneous" taxa (Ray 1997, Fig. 68). The top ten numerically dominant taxa in the unvegetated stratum included the polychaetes *Fabricia sabella, Streblospio benedicti,* and *Pseudopolydora kempi,* none of which were in the top ten for any of the eelgrass habitats except *Fabricia sabella* which was in 10th place in the *Z. japonica* habitat (Ray 1997, Table 22; cf. Tables 13 and 22). Smith and Webber (1978) reported high numbers of the clam, *Mya arenaria* but no other bivalves at sites along an intertidal transect where no eelgrass were reported.

Japanese oysters (*Crassostrea gigas*) were cultivated on the intertidal flats in Padilla Bay in the early to mid 1900's (Dinnel 2000). Pacific oysters were planted in Padilla Bay in the 1930's and 1950's and harvested in those decades with a maximum harvest of 24,600 cases in 1936. However, harvests were generally poor (Dinnel 2000). Various investigations into the causes for the poor growth and conditions of Padilla Bay oysters listed several possible causes including poor growing conditions, excessive growths of macroalgae, and pulp mill effluent (Saxton and Young 1948, Orlob et al. 1950, Neale 1952, Westley 1958). Without cultivation and reseeding Pacific oysters are no longer common on the bare intertidal flats where they were once cultured (Bulthuis, personal observation, Ray 1997).

Table 22. *Top ten taxa by numerical dominance in two intertidal habitats in Padilla Bay: "Unvegetated" = without eelgrass or macroalgae, "Macroalgae" = with macroalgal cover greater than 20%, 1 = greatest, 10 = tenth greatest, + = present but not in top 10. (From Ray 1997)*

Taxa	Habitat	
	Unvegetated	Macroalgae
Polychaete		
Malacoceros glutaeus	+	7
Pseudopolydora kempi	9	
Streblospio beendicti	3	3
Fabricia sabella	1	
Exogene molesta	8	2
Oligochaete		
Tubificoides foliatus	4	5
Grania paucispina		4
Amphipod		
Corophium acherusicum	2	6
Eobrolgus spinosus	+	10
Cumacean		
Leptocuma spp.	10	8
Leucon sp.	6	+
Tanaid		
Leptochelia savigni	7	1
Pancolus californiensis	5	+

Non-native fauna on the bare intertidal flats of Padilla Bay include the Asian snail, *Batillaria attramentaria* and the more recent invader, the Purple Varnish Clam, *Nuttallia obscurata*. *N. obscurata* was first recorded in Washington and beaches of Vancouver, British Columbia in 1991 (Selleck 2003). The purple varnish clam spread both north and south from the first recorded sites and was reported in Padilla Bay in 1999 (Yates 1999). Selleck (2003) measured recruitment of *N. obscurata* in several bays in North Puget Sound but there was no recruitment of juveniles in Padilla Bay in 2003 even though adults were present in 2003 and juveniles were in Padilla Bay in 2000 (Selleck 2003).

Foraminifera assemblages on the bare intertidal flats in northwestern Padilla Bay were reported by Scott (1973, 1974). Sediment grain size and depth of exposure were reported as the most important factors in determining the assemblages. Assemblages in both Padilla Bay and Samish Bay included large numbers of *Trochammina pacifica*. Other common foraminifera in Padilla Bay were *Elphidium hannai*, *Bucrella frigida*, *Eggerella advena*, and *Miliammina fusca*.

Harbor seals (*Phoca vitulina*) haul out on the intertidal flats in Padilla Bay during low tide. Harbor seals feed in the channels and over the eelgrass beds and, thus, are an important component of the fauna of these other habitats. However, most of the study of seals in Padilla Bay has been during haul out on intertidal flats. Seal pups have been reported from Padilla Bay in 1928 (Scheffer and Slipp 1944) and the bay has probably been used by harbor seals for haul out and pupping since prior to European settlement of the area. Pupping in Padilla Bay also has been reported by Newby (1973), Everitt *et al.* (1980), and McLanahan *et al.* a (unpublished report). McLanahan *et al.* b (unpublished report) tracked seals in Padilla Bay with radiotelemetry. They concluded that Padilla Bay appears to be an important summer haul out used intensively by pregnant and nursing females and their pups. Their studies also indicated a high degree of fidelity to the same haul out areas by seals of both sexes and all ages.

Various counts and estimates have been made of the seal populations in Washington State, Puget Sound, Padilla Bay, and vicinity. Different methods were used in each

Table 23. *Counts and estimates of the number of Harbor Seals,* Phoca vitulina*, in Padilla Bay from various studies.*

COUNTS AND ESTIMATES	DATE	LOCATION	SOURCE
100	1971-72	Padilla Bay	Newby 1973
165	Sep 1977	East of Rosario Strait[a]	Calambokidis et al. 1979
255	Aug 1978	East of Rosario Strait[a]	Calambokidis et al. 1979
0	Jan 1979	Padilla Bay	Everitt, Fiscus, and DeLong 1980
21-51	Mar-May 1979	Padilla Bay	Everitt, Fiscus and DeLong 1980
76-95	Jun-Aug 1979	Padilla Bay	Everitt, Fiscus and DeLong 1980
155	1983	Padilla Bay	McLanahan et al. unpublished report
208	1984	Padilla Bay	McLanahan et al. unpublished report
275	Apr-May 2005	Padilla Bay	Banks 2007
280	Jun 2005	Padilla Bay	Banks 2007
350	Jul-Aug 2005	Padilla Bay	Banks 2007
340	Sep 2005	Padilla Bay	Banks 2007
298-398	Jul-Aug 2007	Padilla Bay	Luxa 2008

[a] Includes Bellingham, Padilla, Samish, and Skagit Bays.

study, so that comparisons between studies are difficult, but the data indicate that around 100 - 200 harbor seals were in Padilla Bay during the summer using the intertidal flats as a low tide haul out site in surveys between 1971 and 1984 (Table 23). More recently, Banks (2007) estimated a mean of 250 non-pup harbor seals hauled out in Padilla Bay during April through September (Banks 2007). There was an increasing trend in the number of seals during this period. Peak numbers were reported in July and August when Banks counted 290 and 314 seals in Padilla Bay. Applying a correction factor developed by Huber *et al*. (2001) for seal counts in this area of Puget Sound, Banks estimated about 462 harbor seals in Padilla Bay NERR boundaries during July and August 2005 and 637 seals in the Padilla Bay and Fidalgo Bay area (Banks 2007). The various estimates in Table 23 indicate that seal numbers in Padilla Bay are increasing over the last several decades. This is consistent with population estimates for Puget Sound and Georgia Strait indicating that harbor seal numbers have increased since the early 1970's (Jeffries *et al*. 2003). Both Everitt *et al*. (1980) and McLanahan *et al*. b (unpublished report) concluded that Padilla Bay was important as a haul out area for harbor seals, in part, because of the lack of boat activity near the haul out sites. Padilla Bay also seems to be important as a pupping area with peak pup numbers reported during July and August (Banks 2007).

SALT MARSHES

Intertidal marsh area was much more extensive in the Padilla Bay region until diking and drainage of the marshes during the last 150 years (Thom and Hallum 1990, Collins 2000, Collins and Sheikh 2005). Collins and Sheikh (2005) estimated that about 4500 hectares of wetland area, about 90% of the historic area, have been lost in the "North Coast and San Juan Island" area of Puget Sound that includes Padilla Bay and watershed. The remaining intertidal marshes in Padilla Bay are mainly narrow bands located seaward of the dikes, lining the sloughs seaward of the tidal gates and fringing the sand islands formed from dredge spoils along Swinomish Channel (Fig. 3). Bulthuis (1991) estimated the area of these native salt marshes as 62 hectares in Padilla Bay in 1989 (Table 20).

Estimates in 2000 and 2004 indicated that these native salt marshes occupied 47 to 58 hectares in Padilla Bay (Shull and Bulthuis 2002, Bulthuis and Shull 2006).

The low intertidal marshes that occur on the perimeter of Padilla Bay are dominated by *Salicornia virginica* and *Distichlis spicata* with *Triglochin maritimum* and *Atriplex patula* also common (Granger and Burg 1986, Bulthuis 1991, Bulthuis and Scott 1993, Riggs 2004, 2006a, 2007a). Granger and Burg (1986) described seven plant communities in a 3.4 ha strip of salt marsh along Bay View ridge – the "Sullivan-Minor marsh." This marsh had been diked and drained in the late 1800s or early 1900s, but had reverted back to salt marsh after the failure of the seawall protecting the diked land. *S. virginica*, *D. spicata*, and *A. patula* were the most widespread species in the marsh with some 15 other species also noted. Freshwater species such as *Typha latifolia*, *Phalaris arundinacea*, and *Carex lyngbyei* dominated in the corners of the marsh and near the base of the cliff where freshwater from upland drainage flows into the marsh. *Distichlis spicata* occurs in all of the salt marsh associations in this marsh and dominates in the transitional areas between high and low marsh. The *S. virginica* community is found at low elevations in the marsh and around salt pans. Riggs (2004, 2006a, 2007a) measured percent cover in the Sullivan-Minor marsh in 2004, 2006, and 2007. *Distichlis spicatum* and *Salicornia virginica* were widespread throughout the marsh with each species present in 50 to 75% of the plots (Riggs 2006a, 2007a). *Atriplex patula* was present in 5% of the plots in 2006 and in more than 20% in 2007 (Riggs 2007a). None of the other plants listed in the marsh by Granger and Burg (1986) were present with even 5% cover in 2006 or 2007 (Riggs 2007a).

The vertical range for native salt marsh species in Padilla Bay as measured by Beale (1990), and Bulthuis and Scott (1993) is from about 1.2 to 1.9 m above mean sea level. *D. spicata* ranges from about 1.2 to 1.7 m in the Sullivan-Minor marsh (Beale 1990) and from 1.5 to 1.9 m adjacent to Dike Island in southern Padilla Bay (Bulthuis and Scott 1993).

The Sullivan-Minor salt marsh apparently developed at its present location about 4000 years ago and since then, the area has alternated between salt marsh and tidal flat (Beale 1990, Beale and Schwartz 1991). Radiocarbon dating of peat samples indicate a relative sea level rise of 2-3 m between 5000 and 3000 years ago and about 1 m rise between 3000 and 1000 years ago. In the last 1000 years sea level rise has been less than 1 m (Beale 1990). Thom (1992) measured the rate of accretion during the last 40 years in this same marsh and estimated a rate of 4.5 mm yr^{-1}, about three times the annual relative rate of sea level rise.

Standing stock of native salt marsh in the few measurements that have been taken, are similar to values reported elsewhere. Thom (1992) reported about 550 g dry wt m^{-2} in July/August for a site in the Sullivan-Minor marsh of which about 150 g was *Distichlis spicata* and the remainder *Salicornia virginica*. At one site on Dike Island in southern Padilla Bay the range of mean standing stock during July and August 1992 and 1993 was 70-160 g m^{-2} for *Atriplex patula*; 22-94 g m^{-2} for *Distichlis spicata*,; and 90-580 g m^{-2} for *Salicornia virginica* (Bulthuis and Scott 1993).

Large woody debris is often present in Pacific Northwest marshes although its ecological role is poorly understood (MacLennan 2005, Hood 2007). Sullivan-Minor marsh has an accumulation of logs and large woody debris that has been present for at least 50 years (Shull and Bulthuis 2002, MacLennan 2005). More than 90% of the wood is of anthropogenic origin (MacLennan 2005). The aerial coverage of logs and large woody debris in Sullivan-Minor marsh increased in aerial coverage from 1956 to a maximum in 1989 and has since been declining (MacLennan 2005). This large woody debris caused disturbance and reduced species richness and cover of marsh vegetation in Sullivan-Minor marsh (MacLennan 2005). The woody debris also acted as substrate for both halophytic and upland vegetation (MacLennan 2005).

In addition to the relict native salt marshes in Padilla Bay, the non-native eastern United States species, *Spartina alterniflora* became established in Padilla Bay, apparently having been introduced to Padilla Bay in the 1940s to stabilize the sediment (Parker and Aberle

1979, Frenkel and Kunze 1984, Wiggins and Binney 1987). *S. alterniflora* spread vegetatively to cover about 4.8 ha (Riggs 1992) with clumps of *S. alterniflora* growing laterally about 1.1 to 1.7 m year^{-1} (Riggs 1992). *Spartina anglica* was planted in Skagit Bay and has spread into Padilla Bay via seed transport (Hacker et al. 2001, Riordan 1999). *Spartina* species are perceived as a threat to estuaries in Washington State (Mumford *et al*. 1991) and have been declared a noxious weed in parts of the state (Washington State 1989, Washington State Aquatic Nuisance Species Committee 2007). *Spartina* growth and control in Padilla Bay are further discussed in Chapter 5 under "Non-native Species in Padilla Bay".

ROCKY HABITATS

Intertidal rock habitat is sparsely distributed in Padilla Bay. The shoreline of Hat Island, Saddlebag Island, and Dot Island have intertidal bedrock. Along the shoreline below Bay View Ridge and Samish Island, as well as in pockets around Hat, Saddlebag, and Dot Island, intertidal rock rubble is scattered on sands. There are no estimates of the area of these habitats, although the combined perimeter of Hat, Saddlebag, and Dot Islands mainly consist of intertidal rock bottom. Rocks are only sparsely scattered along the Samish Island and Bay View Ridge shoreline (Kueler 1979, Bulthuis unpublished data).

Sylvester and Clogston (1958) reported species they collected at one intertidal site on the southwest coast of Hat Island. Rocks on the upper beach had *Littorina sitka*, *Acmea digitalis*, and a sparse population of *Balanus glandula*. Rocks in the middle and lower beach were covered with a rich growth of algae including *Laminaria* sp., *Ulva* sp., *Costaria costata*, and *Gigartina* sp. Rocks in the lower intertidal had *Balanus cariosus*, *Mytilus edulis*, *Thais lamellosa*, the turban snail, *Calliostoma costatum*, *Acmea pelta*, and the limpet, *Diodora aspera*. Other common species included *Mopalia muscosa*, the green sea urchin, *Strongylocentrotus droebachiensis*, the seastar *Pisaster ochraceous*, *Henrecia leviuscula* and *Leptasterias hexactis*. Common species that Dethier (1990) listed for the estuarine intertidal bedrock included many of those reported by Sylvester and Clogston (1958). In a second intertidal survey site beneath Bay View Ridge, Sylvester and Clogston reported tufts of *Ulva*, *Balanus glandula*, *Mytilus edulis*, and *Acmea digitalis* on the boulders.

Common species in the rocky intertidal on Saddlebag Island include the alga, *Fucus gardneri,* the barnacle *Chthamalus dalli,* the snail, *Littorina scutulata,* the shore crab, *Hemigrapsus nudus,* and the sea star, *Pisaster ochraceus* (Harley 1998). The mussels *Mytilus californianus* and *M. trossulus* are absent or rare on Saddlebag Island though both are common in the rocky intertidal further west in the Strait of Juan de Fuca (Harley 1998). The predator, *P. ochraceus*, is able to forage over the free intertidal range of these mussels and thus restrict their abundance on Saddlebag Island (Harley 1998). *P. ochraceus* preferentially feeds on the blue mussel, *Mytilus trossulus*, on Saddlebag Island although more than 80% of their prey are barnacles which are more than 90% of the prey assemblage available to them (deHeij 1999). Similarly, the barnacle *Balanus glandula* is common in the western Strait of Juan de Fuca, but rare at Saddlebag because of *P. ochraceus* predation (Harley 1998). On the other hand, the barnacle, *Chthamalus dalli,* increases its coverage in the intertidal because *P. ochraceus* preferentially prey on the competitively superior barnacle, *Balanus glandula* (Harley 1998). A simplified interaction web for Saddlebag Island based on predator exclusion experiments and regional comparisons indicates the differential impact that environmental gradients on the vertical ranges of these species creates dramatic differences in the intertidal species assemblage (Harley 1998, Harley and Helmuth 2003, Harley 2003).

Barnacles are also preyed upon by dipteran species in the genus *Oedoparena*. Infestation rates as high as 20% of *Balanus glandula* and higher for *Chthamalus dalli* were reported on Saddlebag Island (Harley and Lopez 2003). The larvae of *Oedoparena* spp. survived better in cooler temperatures and increased mortality of both barnacles under shady conditions. Thus, barnacle distribution and abundance on Saddlebag Island are strongly influenced by both a macro predator, *P. ochraceus* and a meso predator, *Oedoparena* spp. (Harley and Helmuth 2003, Harley and Lopez 2003).

The brown seaweed, *Fucus gardneri* is widely distributed in the intertidal on rocky substrate on Hat, Saddlebag, and Dot islands (Sylvester and Clogston 1958, Harley 1998, Speidel 1999, deHeij 1999). The *Fucus* canopy lowers the temperature of the rock during exposure compared to rock surfaces without the canopy (Speidel 1999, Speidel et al. 2001) Recovery of *Fucus* after removal of the canopy was strongly non-linear. When up to 80% of the canopy was removed, *Fucus* recovered fully within 12 months (Speidel 1999, Speidel et al. 2001). When more than 80% of the canopy was removed, recovery was only 50% after one year (Speidel et al. 2001). These results indicated the non linear response of species to disturbance and indicate the importance of leaving a few individuals of *Fucus* to facilitate recovery in situations where the canopy is cleared, e.g. oil spills (Speidel 1999, Speidel et al. 2001).

Subtidal rock habitat occurs in Padilla Bay around Hat Island, Saddlebag Island, and Dot Island (Bulthuis, unpublished data). However, there are no surveys of the organisms in these habitats in Padilla Bay. Sylvester and Clogston (1958) referred to beds of the kelp, *Nereocystis luetkeana* on the subtidal rocks off of Hat Island. Dethier (1990) lists *Nereocystis luetkeana*, *Agarum* spp., and *Metriduim* spp. as diagnostic species in estuarine shallow subtidal rock habitats and would be expected to occur also in Padilla Bay. Carney (2003) investigated five techniques for restoring bull kelp, *Nereocystis luetkeana*, on the rocky subtidal on Saddlebag Island. Transplanting juvenile sporophytes, < 15 cm stipe length, was the only method that resulted in reproductive adults. These had a survival rate of 28% (Carney 2003). One of the primary causes for the failure of the other four transplant methods was grazing damage by the numerous grazers in the rocky subtidal (Carney 2003).

ESTUARINE CHANNELS

Most of the 700 hectares of subtidal unvegetated habitat in Padilla Bay is made up of sandy bottom channels and a deep area off Hat Island (Fig. 3). The Swinomish Channel is dredged regularly with a minimum reported depth of 7.6 feet below mean lower spring tides. The remaining channels have depths ranging from just subtidal to about 30 feet below MLLW. The bottom sediments in the channels are generally unstable with shifting sand waves. In subtidal areas west of Padilla Bay, the sediments are mixed sand, shell, and mud based on grain size descriptions in a variety of surveys (Sylvester and Clogston 1958, Smith 1979, Barreca 1982, Ray 1997).

The fauna of the subtidal area were sampled by dredge by Sylvester and Clogston (1958) at two sites at a depth of 30 feet. Characteristic fauna were small clams, serpent stars, and polychaetes worms. Common biota in the samples included the polychaetes, *Sternaspis fossor*, *Lumbrineries latreilli*, *Nephthys ciliata*, and *Armandia brevis* and the serpent star, *Amphioda urtica*. Other animals in the dredge samples at 30 feet were the clams *Macoma nasuta*, *Protothaca staminea*, *Yoldia* sp., *Nucula* sp. Gammarid amphipods and *Pinnida schmith*. One of Sylvester and Clogston's sites was between Saddlebag and Huckleberry Island at a depth of 265 feet where they reported finding many bryozoans (*Membranipora* sp.) and hydroids (*Abietinaria variabilis*, *Abictinaria* sp., *Thuiaria argeutea*, and *Halecium* sp.) on shells; numerous crustacea including isopods (*Rocinela angrestata*), shrimps (*Crago alaskensis*), and crabs (*Oregonia gracilis*, *Hyas* sp. and *Cancer oregonensis*) and many mollusks (*Ischonchiton mertensii*, I. *cooperii*, *Trichotropus* sp., *Calyptaea fastigiata*, *Yoldia* sp., *Cardita* sp., *Acila* sp., and *Humilarea* sp.).

Smith (1979) sampled the fauna at 8, 23, and 43 feet below MLLW. At all three depths high counts of bivalves, polychaetes, isopods, and amphipods were reported although genera and species are not reported specifically for the Padilla Bay samples. Goodwin (1973) reported no commercial size butter clams (*Saxidomus gigonteus*) nor native littleneck clams (*Protothaca staminea*) at five subtidal sites off the northern eelgrass beds in Padilla Bay.

Barreca (1982) reported infauna from three sites between March Point and Hat Island at a depth of -9 m. Numerically abundant taxa and those taxa comprising the highest biomass included the bivalve *Psephidia lordi*, the crustacean *Euphilomedes carrharodonta*, the echinoderm *Amphiodia urtica*, and the polychaete *Pista brevibranchiata*. The species composition and diversity at the three sites appeared to be associated with sediment grain size rather than concentrations of petroleum or densities of petroleum-degrading bacteria.

Ray (1997) sampled subtidal infauna in three depth strata, < 5 m, 5-20 m, and > 20 m depth. The total abundance of organisms in all of the subtidal habitats were lower than the intertidal habitats (Ray 1997, Fig. 66). Polychaetes composed about 75% of the biomass in the 0-5 m strata, but mollusks were the primary group in the two deeper strata (Ray 1997, Fig. 68). The most abundant taxa in these strata were the polychaetes, *Owenia fusiformis* and *Syllis gracilis* and the bivalves *Lucina tenusculpta, Transnella tantilla* and *Acila castraensis* (Ray 1997, Table 24).

The sandy subtidal habitat including the channels is particularly important for the Dungeness crab in Padilla Bay because of the proximity of the intertidal and subtidal eelgrass beds. In contrast to younger (first year) crabs that were found in greater numbers in the intertidal eelgrass, the older crabs favored the deeper channels (Dinnel *et al*. 1986). In the channels nearest the intertidal eelgrass beds the mean density of Dungeness crabs was up to 1600 crabs per hectare with averages of 500 to 900 in many of the channels (Dinnel *et al.* 1986). Seasonally, more crabs were caught during summer and autumn than during winter. The channels are used heavily by commercial and recreational fishermen for catching Dungeness crabs with baited crab pots. Size frequency histograms indicate that the crabs in the channels are grouped in size just below the minimum allowable size that can be taken (~ 150 mm). In addition to Dungeness crabs, Rock Crab and Red Rock Crab are found in high numbers in the subtidal sandy habitat in Padilla Bay in densities up to 80 and 50 crabs per hectare respectively (Dinnel *et al*. 1986). Thus, the sandy subtidal channels in Padilla Bay are important habitat for Dungeness, Rock, and Red Rock crabs.

Fish that were abundant (> 100 per hectare) and those caught specifically above the sandy subtidal bottoms of the channels included English Sole, Staghorn Sculpin, Buffalo Sculpin, Padded Sculpin, Tadpole Sculpin, Snake Prickleback, Shiner Perch, and

Table 24. *Top ten taxa by numerical dominance in three subtidal habitats without eelgrass cover in Padilla Bay: "Shallow" = 0-5 m depth, Intermediate" = 5-20 m depth, "deep" = greater than 20 m depth, 1 = greatest, 10 = tenth greatest, + = present but not in top 10. (From Ray 1997)*

Taxa	Habitat		
	Shallow	Intermediate	Deep
Polychaete			
Mediomastus sp.	+	+	8
Aricidea neosuecica	6		
Prionospio cirrifera	+	5	+
Prionospio steenstrupi	+	10	5
Owenia fusiformis	1	1	10
Syllis gracilis	3	+	+
Nepthys cornuta franciscana		+	9
Oligochaete			
Tubificoides foliatus	7	+	6
Bivalve			
Lucina tenuisculpta	+	+	3
Mysella tumida	4	+	4
Transenella tantilla	+	2	1
Acila castraensis	+	3	2
Ademete gracilior		6	
Amphipod			
Photis brevis	2	+	+
Cheirimedeia macrodactyla	9	+	
Eyakia robustus		8	7
Rhephoxynius tridenta	+	9	+
Isopod			
Synidotea nodulosa	8	+	
Cumacean			
Eudorella sp.	+	4	+
Tanaid			
Leptochelia savigni	5	+	
Echinoderm			
Amphioda occidentalis	+	7	+

Tubesnout (Dinnel et al. 1990, Fig. 74). All of these fish were seasonally abundant with high catches (> 100 fish per hectare) reported during June, July, and/or August, but not for any other months of the year. The English Sole and Buffalo Sculpin were found mainly in the channel habitat, whereas the rest of the fish were caught in even higher numbers in the subtidal or intertidal eelgrass habitats. Thus, only the English Sole and Buffalo Sculpin showed a preference for the channel habitat. For many fish the channel habitat may provide an important pathway for access to the intertidal eelgrass habitat as well as a “refuge” during times of intertidal exposure.

Diving ducks and sea ducks are common in Padilla Bay (Jeffrey 1976, Table 25) and move from one habitat to another. At least part of their time feeding in Padilla Bay is spent in the channels over the sandy subtidal habitat as well as over the eelgrass habitats. Surf scoters have declined by 45% in northern Puget Sound since the 1970’s, but they continue to move into Padilla Bay as winter progresses (Anderson 2006). Early in the winter Surf Scoters are abundant in Penn Cove (about 20 km south of Padilla Bay) where they appear to be feeding on mussels. As numbers of mussels in Penn Cove decrease, Surf Scoter numbers increase in Padilla Bay (Anderson 2006, Fig. 76). Gut contents of surf scoters from Padilla Bay, Penn Cove, and Birch Bay indicate a diversity of prey including bivalves, gastropods, crustaceans, polychaetes, and brittle stars (Anderson 2006). In contrast, the prey of the somewhat larger White-winged Scoters were almost exclusively bivalves (Anderson 2006). In summer, only Padilla Bay hosted large numbers of Surf Scoters (Anderson 2006, Fig. 76). Many of these birds were molting and Padilla Bay may provide food resources or refuge from predators. Padilla Bay had a greater abundance and diversity of epifaunal invertebrates than Birch Bay or Penn Cove (Anderson 2006)

PLANKTON IN PADILLA BAY

The plankton in the waters of Padilla Bay are exchanged daily with diurnal tides and thus there is no resident plankton community in Padilla Bay. The plankton assemblage that is

Table 25. *Annual estimates of the number of diving and sea ducks in two sample plots in Padilla Bay from 1965 to 1974 and an estimate of the total in Padilla Bay. (From Jeffrey 1976)*

Year	Canvasback	Scaup	Goldeneye	Bufflehead	Old Squaw	Scoter
1965	0	131	25	43	18	87
1966	0	201	27	45	0	474
1967	1	57	3	131	0	119
1968	15	133	8	66	0	195
1969	10	571	11	427	3	80
1970	0	9	13	178	0	220
1971	15	33	9	377	4	273
1972	0	426	24	142	0	156
1973	85	475	10	411	0	69
1974	0	390	73	274	0	0
Average	12.6	242.6	20.3	209.4	2.5	167.3
Padilla Bay Total	118	2,280	191	1,968	23	1,572

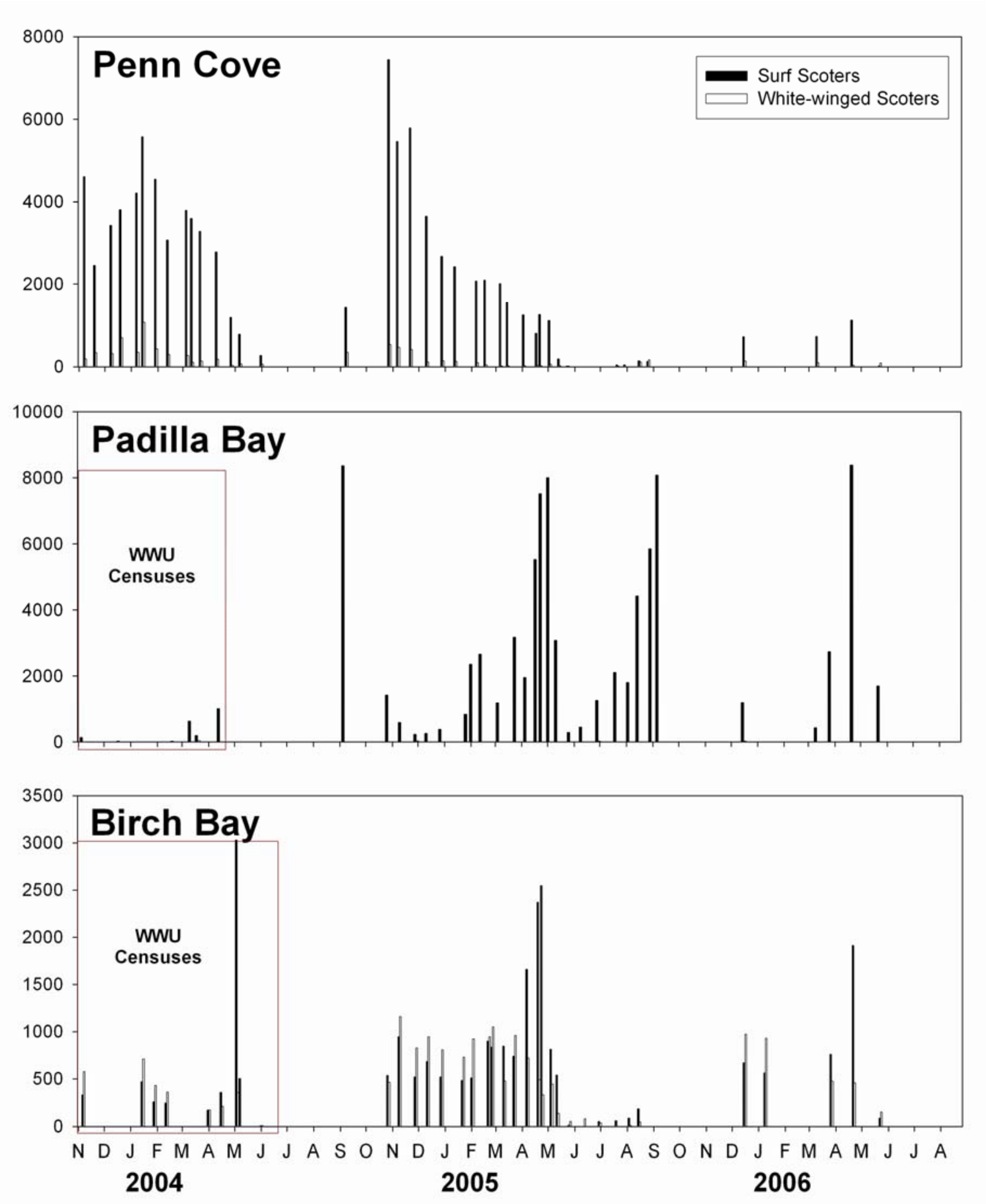


Figure 76. Censuses of scoters in Padilla Bay and two other sites in North Puget Sound: Penn Cove and Birch Bay. Only Birch Bay had substantial numbers of White-winged scoters. Note the unique patterns of use by Surf Scoters among the three sites: Penn Cove is used mainly during early winter, Birch Bay is used during spring staging (when herring spawn is available), and Padilla Bay is used during both spring staging and molting in late summer. (From Anderson 2006)

in Padilla Bay includes plankton from the north Puget Sound waters that flow into the bay and plankton that usually grow on the sediment surface or as epiphytes on eelgrass but are dislodged and brought up into the water column. Sylvester and Clogston (1958) listed the predominant plankton species from five stations in and around Padilla Bay. Common species included diatoms in the genera *Coscinodiscus, Ditylum, Biddulphia, Chaetoceros, Melosira*; plankton stages of polychaetes and echinoderms; copepods in the genera *Microcalanus, Pseudocalanus*, and *Corycaeus* and numerous zoea and megalops of crabs (Sylvester and Clogston 1958, Jeffrey 1976).

The phytoplankton biomass in Padilla Bay and surrounding waters is generally low throughout the year with phytoplankton "blooms" rare. During an 18 month period chlorophyll concentration fluctuated from less than 1µg chl *a* L^{-1} to 8 µg chl *a* L^{-1} with concentration of 3 or less most of the year (Muller-Parker and Peele 1998). Similarly, Brainard reported that chlorophyll *a* concentrations were less than 1 µg chl *a* L^{-1} in fall and winter, 4 µg chl *a* L^{-1} in spring and 12 µg chl *a* L^{-1} in summer (Brainard 1996). Most of the chlorophyll in spring and summer was in the > 8 size fraction (Brainard 1996). The predominant pigments during spring and summer were chlorophyll *a*, chlorophyll *c*, and fucoxanthin with only very small proportion of chlorophyll *b*, alloxanthin, and zeaxanthin (Brainard 1996). Bernard reported chlorophyll *a* concentrations from 1.5 to 3.5 µg chl *a* L^{-1} from June to October (Bernhard 1993). Burnett et al. (unpublished data) measured chlorophyll *a* semi-monthly during 2007 at two sites in Padilla Bay. Chlorophyll *a* concentrations were less than 2 µg L^{-1} during six months of the year (January to March and October to December) and increased to maxima of about 9 µg chl *a* L^{-1} during June to August (Fig. 56).

The phytoplankton in Padilla Bay show evidence of nutrient limitation during spring and summer. Addition of nitrogen in short-term (4-7 days) nutrient enrichment assays stimulated phytoplankton growth June through October (Bernhard 1993, Bernhard and Peele 1997). Addition of phosphate and silicate alone did not stimulate growth of phytoplankton. When the nanoplankton (< 20 µm) were tested separately, their response to nitrogen addition was greater than for the total phytoplankton in August, but the nanoplankton did not respond to nutrient enrichment in October (Bernhard 1993, Bernhard and Peele 1997). At three stations in Padilla Bay, phytoplankton responded to nitrogen enrichment during spring and summer but not during fall and winter (Muller-Parker and Peele 1998). Growth rate of phytoplankton during summer was 1.3 day^{-1} with biomass of about 8 µg chlorophyll *a* L^{-1} and during the winter was 0.5 day^{-1} with biomass of about 0.5 µg chlorophyll *a* L^{-1} (Muller-Parker and Peele 1998). These authors conclude that phytoplankton growth may be limited in Padilla Bay by nitrogen during spring and summer and by light in fall and winter.

Grazing of phytoplankton may also be an important mechanism controlling the biomass of phytoplankton. Phytoplankton growth rate ranged seasonally from -0.4 to 2.6 day^{-1} and microzooplankton (< 200µm) grazing rates from 0 to 1.3 day^{-1} (Bernhard 1993). Grazing rates generally did not differ among seasons. The proportion of algal growth consumed by micrograzers ranged from 0 – 100% through the year with a close balance between algal growth rate and grazing rate in summer (Bernhard 1993, Strom et al. 2001). Grazing by microzooplankton tended to be proportionally greater when phytoplankton biomass was high and often more chlorophyll was ingested by microzooplankton than was available for all other loss process combined (Strom et al. 2001). Microzooplankton grazing appears to be one of the important controls on phytoplankton biomass during spring and summer in Padilla Bay. Microzooplankton are also important links in the transfer of phytoplankton primary production to higher trophic levels in Padilla Bay (Strom et al. 2001).

CHAPTER 5

SELECTED BIOTA OF PADILLA BAY

The communities and habitats in Padilla Bay have been investigated by a variety of scientists and students and these studies have been summarized in the previous chapter. In addition, there are specific fauna and flora that have been the focus of particular interest in Padilla Bay. The reasons for the focus are varied including commercial harvest, recreational interest, or a threat to other species and habitats in Padilla Bay. In this chapter, the research conducted in Padilla Bay, north Puget Sound, or the Pacific Northwest on several of these selected biota is summarized.

JUVENILE SALMON AND EELGRASSES

The extensive eelgrass meadows in Padilla Bay and the importance of salmon to the Puget Sound ecosystem raise the issue of the relationship between salmon and eelgrasses. The following discussion of juvenile salmon and eelgrasses is based on an unpublished review by Melora Haas (Haas unpublished manuscript). Three of the five species of Pacific salmon, chum (*Oncorhynchus ketel* Walbaum), pink (*O. gorbuscha* Walbaum), and ocean-type Chinook (*O. tshauytscha* Walbaum) are closely associated with nearshore estuarine and marine environments during their juvenile life history stage until they reach 45-55 mm fork length, after which they move offshore. These three species may use eelgrass habitat in the Pacific Northwest as juveniles. Evidence linking juvenile salmon with eelgrass in the Pacific Northwest includes: 1) juvenile salmon reported in or near eelgrass habitats, 2) diet of juvenile salmon that includes prey organisms associated with eelgrass, 3) the density of prey organisms in eelgrass habitat, 4) refuge, and 5) the productivity of eelgrass community in the marine environment.

Juvenile salmon are frequently found in or near eelgrass habitats when such habitats are identified. Miller et al. (1977) reported small schools of chum in sand/eelgrass habitat in north Puget Sound. Fresh (1979) reported pink, chum, and Chinook salmon in eelgrass habitats, as well as other habitats, from fifteen sites around north Puget Sound, including Padilla Bay. Simenstad et al.(1980) reported pink and chum from Hood Canal in sites that included eelgrass and mixed sand and eelgrass habitat. Healy (1979, 1980) reported presence of chum and Chinook at sites containing eelgrass in the Nanaimo River estuary. Gordon and Levings (1984) reported pink, chum, and Chinook at three areas near the mouth of the Fraser River, and higher numbers of pink and chum at the eelgrass site. Simenstad et al. (1988) and Thom et al. (1989) reported chum, Chinook, and pink present in the vicinity of eelgrass both at Neah Bay and Drayton Harbor with higher densities of chum at eelgrass habitats than non-eelgrass sites. Collectively, these studies indicate a strong presence of pink, chum, and Chinook salmon in or near eelgrass habitats in Puget Sound/Georgia Strait, as well as being present in a variety of other nearshore habitats.

In addition to the presence of juvenile salmon in eelgrass habitats, diet analyses have demonstrated that juvenile salmon feed on organisms occurring in eelgrass. Simenstad et al. (1988) sampled in eelgrass and non-eelgrass sites in Padilla Bay and found that over all sites harpacticoid and gammarid amphipods made up the vast majority of the stomach contents of juvenile chum. Within the harpacticoids, *Harpacticus uniremis, Tisbe* spp., and *Zaus* spp. were the most important with *H. uniremis* the most abundant and comprising almost half of the contents by weight. *H. uniremis* was very strongly associated with eelgrass (Simenstad et al. 1988) and all harpacticoida were abundant in eelgrass. Similarly, in other Pacific Northwest estuaries, diet analyses have indicated the importance of harpacticoid copepods and other eelgrass associated taxon in juvenile chum, pink, and Chinook salmon (Healy 1979, 1980; Simenstad et al. 1988 (Neah Bay); 1980; D'Amours 1987, Webb 1989, 1991).

A third line of evidence that eelgrasses are important to juvenile salmon is the abundance of prey items reported in eelgrass habitats, particularly the three harpacticoids, *Harpacticus uniremis, Tisbe* spp., and *Zaus* spp. In Padilla Bay, these three taxa were abundant in eelgrass habitats, with *Tisbe* spp. common across several habitat types but *H. uniremis* and *Zaus* spp. found almost exclusively on leaves of eelgrass (Simenstad et al.

1988). The non-native eelgrass, *Zostera japonica* supported certain salmon prey organisms, although in lower densities then the native *Z. marina* (Simenstad et al. 1988). On Roberts Bank, 100 km north of Padilla Bay at the mouth of the Fraser River, the three harpacticoid prey were abundant over eelgrass during chum salmon out migration and densities were always higher on eelgrass leaves than on sediments (D'Amours 1988; Webb and Parsons 1992). Among four sites along the Strait of Juan de Fuca the highest abundance of epibenthos was in dense eelgrass habitat and in Hood Canal. The site with the highest abundance of epibenthos was in the highest density eelgrass (Simenstad et al. 1979, 1980). In central Puget Sound, nine epibenthic taxa were clustered at eelgrass sites, six of which taxa were salmon prey organisms (Thom et al. 1984). In Drayton Harbor, about 50 km north of Padilla Bay, there was no significant difference in total epibenthos between any eelgrass and mudflat pair of sites, although peak abundance remained high for a longer period of time at eelgrass sites. In Swinomish Channel, which flows into Padilla Bay at its northern end, epibenthos in eelgrass beds included the numerically dominant salmon prey, *Tisbe* spp., *H. uniremis*, and *Zaus* spp. (Wyllie-Echeverria et al. 1994, 1995). Thus, collectively these studies indicate high abundance of salmon prey in eelgrasses in the Pacific Northwest, and generally high densities in eelgrasses when comparisons were made with other habitats.

Eelgrasses may also function as refuge from predators for juvenile salmon. One of the reasons small ocean-type salmon stay in shallow, nearshore water is to avoid larger predators. Nearshore water with eelgrass adds structured complexity and is generally considered to provide greater shelter from predation. There are many anecdotal accounts (personal observations) of salmon darting into eelgrass when disturbed, but there are no quantitative observations or experimental work addressing the issue of eelgrass as predation refuge for juvenile salmon in the Pacific Northwest.

Eelgrasses are generally considered as highly productive environments. Thom (1990) estimated annual net primary productivity of the eelgrass community in Padilla Bay to be 350g C m^{-2} with the epiphytes contributing about half of the total. In a review of carbon flux in seagrass ecosystems around the world, Mateo et al. (2006) estimated an average of about 800g C m^{-2} yr^{-1}, although above ground production rates are highly variable. These high rates of productivity provide carbon that may be exported from the seagrass bed or support herbivores and detritivores within the seagrass ecosystem. Many of the most important salmon prey items, including *Harpacticus uniremis* are detritivores (Simenstad and Wissmar 1985, Sibert 1979). Thus, eelgrass ecosystems are highly productive, supporting secondary production of juvenile salmon prey items via both detritus and herbivory within the eelgrass beds and exported from eelgrass beds. The relative importance of eelgrasses within particular estuarine systems varies depending on the spatial extent and productivity of other primary producers (Sibert 1979, Simenstad and Wissmar 1985).

Eelgrasses function in other ways that directly or indirectly affect juvenile salmon, although there has been little or no quantitative data published. The rhizomes and roots stabilize mud and sand that would otherwise be subject to disturbance and suspension in the water column. The leaves of eelgrasses slow water currents and promote settling of suspended material and thus improve water clarity. Another function of eelgrass may be as a migratory corridor for juvenile salmon moving seaward from Puget Sound and Georgia Strait. While these juveniles are nearshore dependent and thus in the same depth range as eelgrasses, studies are needed to determine whether eelgrass has a special function as a migratory habitat or corridor.

Thus, juvenile salmon of chum, pink, and ocean type Chinook are closely associated with the nearshore and are present in and near eelgrass beds. Prey items associated with eelgrasses are important in their diet, and eelgrass communities have high densities of many epibenthos, including prey items of these juvenile salmon. Eelgrass communities have a high productivity that contributes to the detritus based food web that is important to juvenile salmon. While definitive studies are lacking in the Pacific Northwest, eelgrasses also apparently function as refuge from predators, promote water clarity by reducing suspended solids, and may serve as a migratory corridor for juvenile salmon.

CRABS OF PADILLA BAY

In Padilla Bay, the subtidal and intertidal eelgrasses, intertidal flats (both bare and with macroalgae) and tidal channels provide a mosaic of habitats that are important for crabs. Twenty-two species of crab have been reported from Padilla Bay in more than 40 studies (Dinnel 2001, Table 26). Most of these studies record the presence of various species as part of an inventory or survey with sample sites in Padilla Bay (Dinnel 2001). Species that were reported from Padilla Bay include hermit crabs (5 species), pea crabs (4 species) shore crabs (2 species), kelp crabs (2 species) and 4 species of *Cancer*. All of the species reported for Padilla Bay are native species. This is a contrast to most other groups of biota that include non-native species, often having been introduced via aquaculture practices such as Pacific Oyster (*Crassostrea gigas*) among bivalves, Japanese eelgrass (*Zostera japonica*) within macrophytes, and *Batillaria attramentaria* among gastropods. However, the European green crab (*Carcinus maenas*) has been extending its distribution north along the west coast of the North America and is now present in significant numbers in Willapa Bay and Grays Harbor, and has been found on the outer coast of Vancouver Island (Dinnel 2001). Padilla Bay NERR has conducted surveys for green crabs in coordination with Washington Department of Fish and Wildlife (Riggs 2003). In 2001 – 2002, crab catching trays were used in coordination with selected reserves in the National Estuarine Research Reserve System (Riggs 2003). Again, no green crab or other non-native crabs were reported from Padilla Bay (Riggs 2003, Hartman et al. 2003, Bushek *et al.* 2004).

One of the most abundant native crabs reported from Padilla Bay was *Hemigrapsus oregonensis* (Yellow Shore Crab) in the study by Riggs in which she used trays of crushed shell set out in the intertidal (Riggs 2003). Riggs measured size distribution of more than 3,000 *H. oregonensis* captured during four seasons at one sampling transect. In October (2002) and January (2003) more than 80% of the *H. oregonensis* were less than 8 mm (carapace width) with a large pulse of new recruits in January (Riggs 2003, Fig 77). In April there was a slight increase in sizes 8-10 mm. And in July, more than

Table 26. *Decapod crustaceans reported from Padilla Bay, Washington as of December 2001. (From Dinnel 2001)*

Species Name	**Common Name**	**Reference Number***
Brachyura		
Cancer magister	Dungeness or commercial crab	1,3,4,5,7,9,12,13,14,16,17,19,20,21,22,23,24,26,27,29,31,32,33,35,38,39,40,42
Cancer productus	Red rock crab	2,6,7,9,12,13,19,20,21,35,42
Cancer gracilis	Purple or slender crab	19,21,26,35
Cancer oregonensis	Oregon or pygmy rock crab	1,6,19,33,35,38
Pugettia producta	Northern kelp crab	1,6,9,12,19,35,38,42
Pugettia gracilis	Graceful kelp crab	1,2,9,11,12,19,35,38,42
Hyas lyratus	Pacific lyre crab	1,6,19,33,35
Oregonia gracilis	Graceful decorator crab	1,6,9,12,19,33,35,38,42
Scyra acutifrons	Sharpnose crab	1
Telmessus cheiragonus	Helmet or horse crab	1,2,6,7,9,10,12,18,19,21,26,35,38,39,42
Petrolisthes eriomerus	Flattop crab	1,6,9,12,35,42
Hemigrapsus nudus	Purple shore crab	1,2,4,6,8,9,12,35,36,41,42
Hemisgrapsus oregonensis	Yellow shore crab	1,2,4,6,7,8,9,12,31,35,41,42
Pinnixa eburna	Pea crab	4
Pinnixa faba	Mantel pea crab	43
Pinnixa occidentalis	Pea crab	10,35,42
Pinnixa schmitti	Pea crab	1,4,6,11,12,35,42
Pinnixa tubicola	Pea crab	12,30,35,41,42
Pinnixa sp.	Pea crab	25,26,41
Hemigraspus sp.	Shore crab	21
"Crabs"		15,34,37
Anomura		
Pagurus beringanus	Bering hermit crab	38
Pagurus granosimanus	Grainyhand hermit crab	1,2,6,9,12,35,42
Pagurus hirsutiusculus	Hairy hermit crab	2,4,7,9,12,35,38,42
Pagurus kennerlyi	Bluespine hermit crab	9,12,35,42
Pagurus setosus	Hermit crab	1,6,35
Pagurus sp.	Hermit crab	1,4,8,10,11,19,25,41

*Key to reference numbers: See next page.

Key to Table 26 reference numbers:

1= Sylvester and Clogston 1958
2= Ehrsam et al. 1972
3= Pacific Ocean Farms, undated (about 1973)
4= Webber 1975
5= English 1976
6= Jeffrey 1976
7= US Army Engineer District, Seattle, Washington 1976
8= Smith and Webber 1978
9= NOAA and Washington State Department of Ecology 1980
10= Barreca 1982
11= Riggs 1983
12= Western Washington University 1983
13= Antrim 1985
14= Dinnel et al. 1985
15= Pantalone 1985
16= Valdez 1986
17= Nyblade 1986
18= Wissmar 1986
19= Armstrong et al. 1987
20= U.S. Bureau of Indian Affairs 1987
21= Dinnel et al. 1986
22= Evans-Hamilton and D.R. Systems 1987
23= Higman 1988
24= Fagergren et al. 1989
25= Riggs 1989
26=Dinnel et al. 1990
27= McMillan 1991
28= Dinnel et al. 1993
29= Johnson 1994
30= Kahler 1994
31= Egnotovich 1995
32= McMillan et al. 1995
33= Bulthuis 1996a
34= Ray 1997
35= Riggs 1997
36= Harley 1998
37= deHeij 1999
38= Giver 1999
39= Yates 1999
40= Johnson 2000
41= Nolan 2000
42= Western Washington University 2000
43= Dinnel 2001

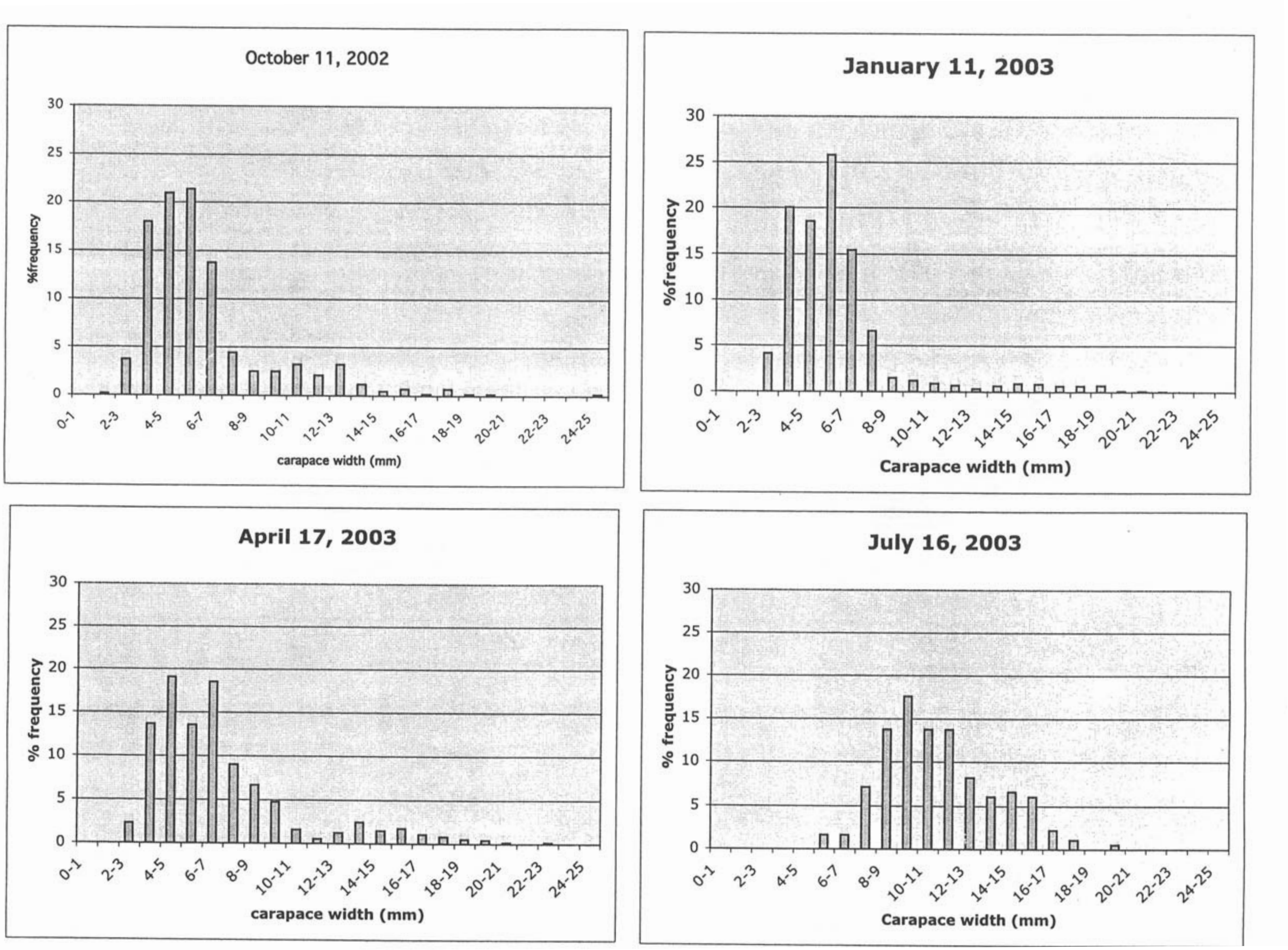


Figure 77. Percent frequency of size classes of *Hemigrapsus oregonensis* caught in shallow trays (n=7) along one transect in Padilla Bay, Washington, in 2002-2003. (From Riggs 2003)

85% of the *H. oregonensis* were greater than 8mm, with virtually no new recounts in the samples (Riggs 2003, Fig 77).

The hermit crab, *Pagurus hirsutiusculus* and *P. granosimanns*, were also abundant in the Riggs study. Most of these native crabs were using shells of the non-native gastropod, *Batillaria attramentaria* (Riggs 2003, Wonham et al. 2005).

Dungeness Crab, *Cancer magister*, are abundant in Padilla Bay and economically important. Commercial and recreational fishing for Dungeness crab is important in Puget Sound, with reported commercial harvest increasing substantially in recent years with an estimated value of over $14 million during the 2000-2001 season (Dinnel 2001, Fig. 78). The channels and eelgrass beds around and within Padilla Bay have consistently been important fishing areas for both commercial and recreational fishers (Dinnel 2001). Abundance and density of Dungeness crab in Padilla Bay were estimated by English (1976) and Dinnel et al. (1986). English (1976) sampled with a beam travel at four depths in Padilla Bay and reported an average density of about 150 crabs/hectare in Padilla Bay. Dinnel et al. (1986) sampled with a trawl, modified crab pots, intertidal quadrate (for juveniles) and diver surveys. They reported that Dungeness crabs dominated the crab catches in all gear types by substantial margins and that density of trawl-caught Dungeness crabs (139/ha) was very similar to that reported by English (150/ha) ten years earlier (English 1976, Dinnel et al. 1986, Dinnel 2001).

The widespread consumption of Dungeness crabs has raised concern about potential contaminants in crab tissue. In sample from Padilla Bay, the concentrations of metals and organic compounds in muscle and hepatopancreas tissues of Dungeness crab were found to be generally low (Antrim 1985, Johnson 2000, Dinnel 2001).

The life cycle of Dungeness crab includes an external egg, larval, and planktonic periods during which they experience high mortality and can be carried long distances. Adult females extrude fertilized eggs in October to December in Washington and mature in two to three months (Cleaver 1949, Armstrong et al. 1987, Dinnel 2001). Hatching occurs

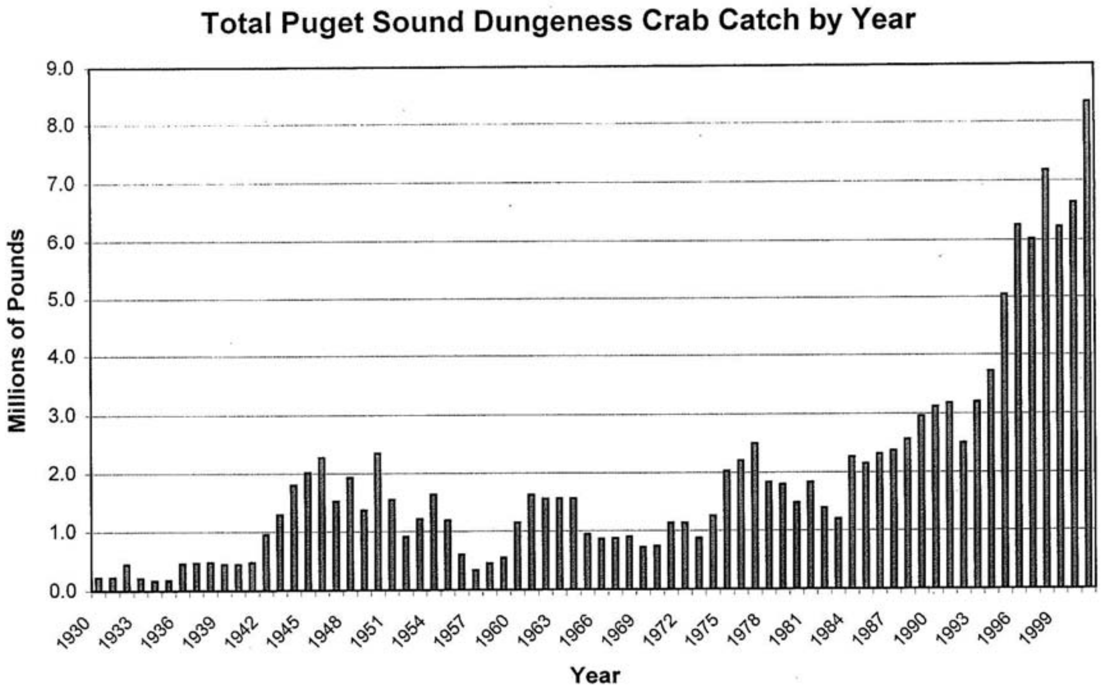


Figure 78. Total catch of Dungeness crab in Puget Sound from 1930 to 2001. (From Dinnel 2001)

from January to April on the Pacific Coast of Washington and from March to May in Puget Sound (Dinnel et al. 1993). There are five free-swimming planktonic stages that last three to four months (Lough 1976, Dinnel 2001). Settlement occurs during April through June on the Washington Pacific Coast and July through September in Puget Sound (Stevens and Armstrong 1984, Fernandez et al. 1993, Dinnel et al. 1993, McMillan et al. 1995). Juveniles settling in Padilla Bay may come both from oceanic cohorts and Puget Sound cohorts with about half coming from each cohort during 1988 (Dinnel et al. 1993, Fig. 73). Juvenile crab inhabit low intertidal flats and shallow subtidal areas to a depth of about 5 m. In a study of habitat preferences in Padilla Bay, young-of-the-year crabs preferred areas with eelgrass, macroalgae, or cobble and gravel with macroalgae. The 1+ age class (crabs entering their second year of growth) preferred shallow channels and older crabs moved into deeper channels (Dinnel et al. 1986). Gravid females were rare in Padilla Bay, probably having migrated to areas near deep water for mating and egg production (Dinnel et al. 1986, McMillan et al. 1995). Because the two cohorts, oceanic and Puget Sound, settle in early vs. late summer respectively, their growth rates may differ substantially during the first summer. During 1983-1984, the oceanic cohort grew rapidly reaching 40 mm mean carapace width by the end of the summer, while the Puget Sound cohort did not reach this size until the following summer (McMillan 1991, Dinnel 2001, Fig. 79).

Mortality of Dungeness crabs is exceptionally high during both the larval stages and following settlement. Post-larval mortality is primarily due to fish, bird, or crab predation (Fernandez et al. 1993, Dinnel 2001). In Padilla Bay, fish predation on Dungeness crab was found to be low. Staghorn Sculpin was the only fish of the 18 most common fish caught in Padilla Bay by Dinnel et al. (1990) that had an index of relative importance for all species of crabs greater than three percent (Dinnel et al. 1990). Less than one percent of the average diet of Staghorn Sculpin, *Leptocottus armatus*, was Dungeness crab. Dinnel et al. (1990) concluded that Staghorn Sculpin could account for up to about five percent of the summertime mortality of newly settled Dungeness crabs.

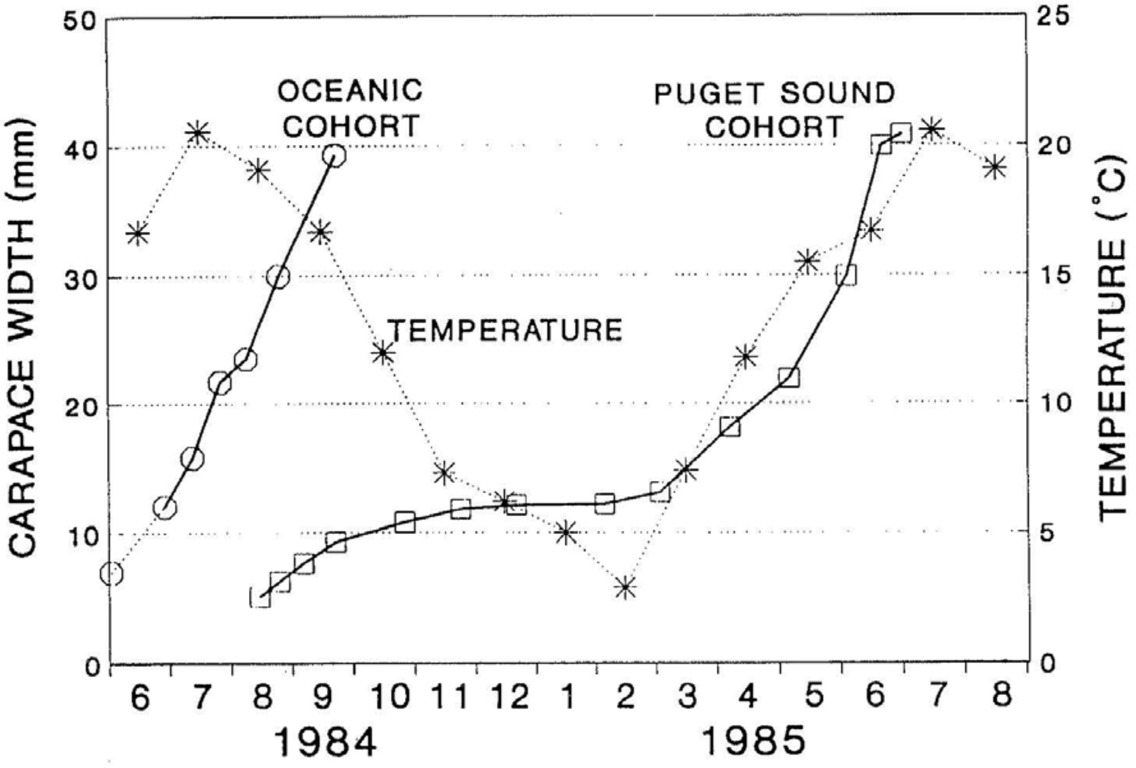


Figure 79. Growth (mean carapace widths of two cohorts ("oceanic" and "Puget Sound") of young-of-the-year Dungeness crabs that settled in North Puget Sound during spring and summer of 1984 and monthly mean water temperatures. (From McMillan 1991 and Dinnel 2001)

Dungeness crabs are sexually mature by the end of their second year, but males usually do not copulate until their third year (Butler 1961, Smith and Jamieson 1991, Dinnel 2001). Adults move to shallow water and tend to aggregate during mating where copulation occurs usually in late spring or early summer immediately after the females molt (Dinnel 2001). After mating the males move into deeper waters while the females may remain in protected waters to incubate their eggs (Armstrong et al. 1987, Dinnel et al. 1988a and b, Dinnel 2001). From the data in these studies, Dinnel (2001) concluded that it seems highly probable that, upon sexual maturity, female Dungeness crabs exit the Padilla/Fidalgo Bay region westward through Guemes Channel. They probably stop their westward migration when they encounter rocky habitat at Shannon Point. High densities of egg-bearing females were found along the north shore of Fidalgo Island along Guemes Channel during winter, while few gravid crabs were found at 19 other locations. Eggs hatch from these concentrated females in mid-winter and the larvae are dispersed to unknown locations, although most probably remain within the North Puget Sound/Strait of Georgia region to finally settle as first instars in July and August (Armstrong et al. 1987, Dinnel et al. 1986, Dinnel 2001).

In a review of studies of crabs in Padilla Bay, Dinnel (2001) concluded “that the thousands of acres of eelgrass beds in Padilla Bay provide an immense amount of juvenile settlement and growth habitat during the first year of life, and the shallow channels provide foraging habitats for older crabs. Without these habitats, the populations of Dungeness crabs in North Puget Sound would be significantly lower.”

WATERFOWL AND EELGRASSES

Waterfowl are seasonally abundant in Padilla Bay and form an important component of the Padilla Bay ecosystem. The importance of Padilla Bay for migrating and over-wintering waterfowl was recognized early and led to some of the first efforts to protect Padilla Bay. Furthermore, when Padilla Bay was first designated a National Estuarine

Research Reserve (Estuarine Sanctuary at the time), Washington State designated the Department of Game as the managing agency and the first Director was from the Institute of Wildlife Ecology at WWU. Thus, waterfowl and Padilla Bay have been closely linked for many years. It is the extensive eelgrass community that seems to be important to waterfowl directly or indirectly. The main function of the eelgrass beds is providing food directly and via the food web. Brant are herbivores and apparently feed almost exclusively on eelgrasses. The dabblers (American Widgeon, Northern Pintail, Mallard, and Green-winged Teal) feed both on eelgrasses and invertebrates. Many other waterfowl in Padilla Bay are piscivores and feed on fish that may be associated with the eelgrass beds in Padilla Bay.

BRANT AND EELGRASSES

Brant (*Branta bernicula*) have been closely associated with eelgrasses in Europe and eastern North America as well as western North America. However, Atlantic Brant shifted their diet from eelgrasses to include other vegetation, and they feed on salt marsh plants and on farm fields as eelgrass declines seasonally and/or following declines in eelgrass abundance (Lovvorn 2001). Pacific Brant continue to depend on marine vegetation throughout their migration and wintering (Reed, A. et al. 1998). In Boundary Bay British Columbia, 40 km north of Padilla Bay 98% of the diet of Brant was eelgrass leaves, including both *Z. marina* and *Z. japonica* (Baldwin and Lovvorn 1994a, b, Fig. 80). There have been no studies of Brant diet in Padilla Bay, but presumably their diets in Padilla Bay would be similar for those feeding in Boundary Bay and consist almost exclusively of the leaves of the two eelgrasses. From Washington to Baja California migrating and wintering Brant ate eelgrasses with occasional reports of their eating other seagrasses (Surfgrass *Phylospadia* spp. and Widgeon grass, *Ruppia maritima*) (Cottam et al. 1944, Yocum and Keller 1961, Ward 1983, Lovvorn 2001). Consumption of eelgrass and building lipid and fat reserves prior to spring migration to nesting grounds may be important for breeding success (Ankey 1984, Vangilder et al. 1986, Ebbinge and Spaans 1995). Brant numbers at Willapa Bay and the Dungeness Spit area of Washington during spring staging fluctuated with the aerial extent of eelgrass (Wilson and Atkinson 1995).

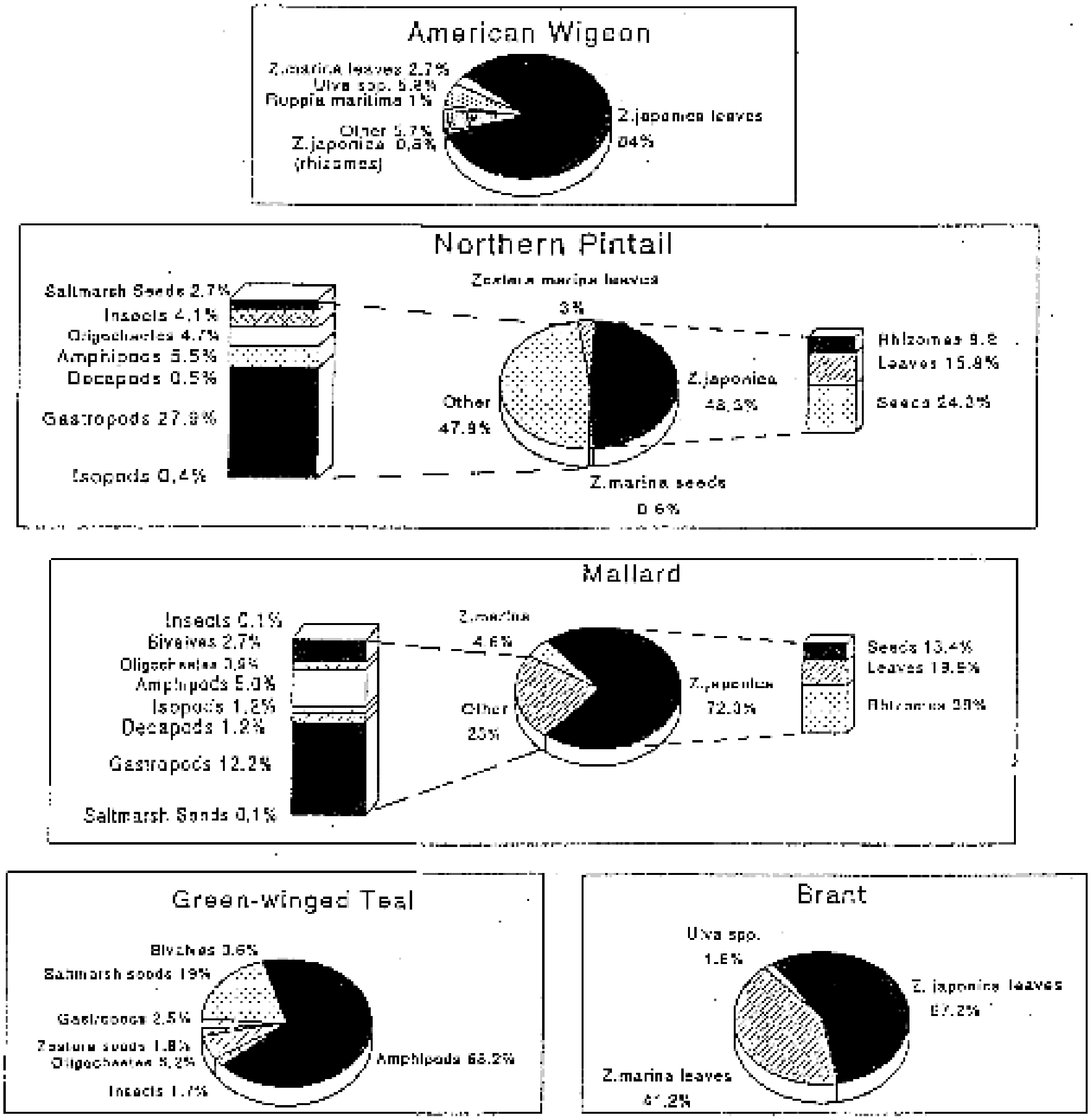


Figure 80. Aggregate percent dry mass of the diets of dabbling ducks collected October to January 1990-91 and 1991-92, and of Brant collected 1 to 10 March 1992 in Boundary Bay, British Columbia. (From Lovvorn 2001 and Baldwin and Lovvorn 1994b)

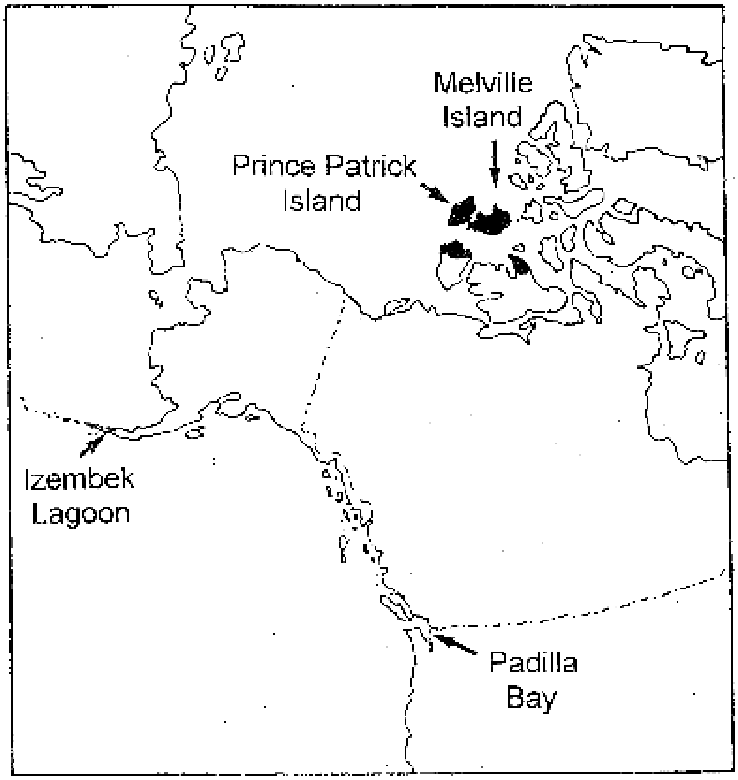


Figure 81. Breeding location of the Melville Island subpopulation of gray-bellied Brant (including those that breed on Melville, Prince Patrick, and adjacent islands). This subpopulation winters exclusively in Padilla Bay, Washington, after staging during migration at Izembek Lagoon, Alaska. (From Lovvorn 2001 and Reed et al. 1989)

Seasonal declines of eelgrass often cause Brant to abandon eelgrass feeding areas and may have negative effects on Brant that overwinter in Puget Sound/Strait of Georgia or as for south as Baja California (Charman 1979, Madsen 1988, Percival and Evans 1997, Baldwin and Lovvorn 1994a, b, Lovvorn and Baldwin 1996, Leopold and Smith 1953, Reed, E.T. et al. 1998a). Brant from particular breeding areas are typically philopatric to certain wintering areas (Reed, E.T. et al. 1998b). Among Pacific Brant, there are two genetic subpopulations, a grey-bellied form and a dark-bellied form. The grey-bellied form breeds almost exclusively on Melville and adjacent islands in the Canadian high arctic and winters almost exclusively in Padilla Bay (Sedinger et al. 1994, Reed et al. 1998a, Fig. 81). This subpopulation numbers about 15-18,000 birds although numbers were fewer in the 1990's than in the 1960's (Sedinger et al. 1994). Thus, this subpopulation of Brant are critically dependent on the eelgrass beds in Padilla Bay (Lovvorn 2001).

DABBLING DUCKS AND EELGRASSES

Large numbers of dabbling ducks, mainly American Widgeon (*Anas Americana*), Northern Pintail (*A. acuta*), Mallard (*A. platychynchos*) and Green-winged Teal (*A. crecca*), use Padilla Bay during the winter (Jeffrey 1976, Table 16). These dabbling ducks feed over the eelgrass beds in Padilla Bay, and presumably, their diets are similar to those reported for Boundary Bay, British Columbia, 40 km north of Padilla Bay. Based on esophagus contents in Boundary Bay, Widgeon ate mainly *Zostera japonica* leaves, Pintails ate about 50% *Z. japonica* and 50% invertebrates, and Mallards ate about 75% *Z. japonica* and the rest invertebrates (Baldwin and Lovvorn, 1994a, b, Lovvorn and Baldwin 1996, Fig. 80). In contrast, Teal ate invertebrates and salt marsh plants and almost no eelgrasses (Baldwin and Lovvorn 1994b, Fig. 80). Thus, the dabbling ducks (except Teal) in Padilla Bay apparently are feeding primarily on the non-native eelgrass *Zostera japonica*. This may be due to its accessibility higher in the intertidal than the native eelgrass *Z. marina* (Baldwin and Lovvorn 1994a, b). Lovvorn and Baldwin also reported that the dabblers tended to feed on the eelgrass community in the early fall, but moved to adjacent farmlands after winter storms eliminated *Z. japonica* (Lovvorn and Baldwin 1996). However, Lovvorn and Baldwin (1996) reported that dabblers continued to use the intertidal areas (Boundary Bay) at night, while feeding on the adjacent farmlands during the day. The close proximity of these two habitats appears to be important to dabbling ducks (Lovvorn and Baldwin 1996, Eamer 1985, Colwell and Dodd 1995, Lovvorn 2001). Thus, Padilla Bay with adjacent farmlands provides an important combination of habitats for dabbling ducks.

DIVING DUCKS AND EELGRASSES

Among the diving ducks (taxonomic tribes of Oxyurini, Aythyini, and Mergini), which generally do not nest in the Puget Sound region, but are present during winter and spring migration, Greater Scaup (*Aythya marila*) and sea ducks (Mergini tribe) feed in shallow soft-bottom bays or eelgrass beds (Lovvorn 2001). There have been no studies of the diets of these diving ducks in Padilla Bay (although Eric Anderson [University of Wyoming, Department of Zoology and Physiology] is conducting studies on Scoters in Padilla Bay and Puget Sound). Studies of their diets in the Frazer Delta, 50 km north of Padilla Bay, indicate that many of these diving ducks may be feeding on eelgrasses and the associated invertebrates in Padilla Bay. Greater Scaup diet was about 75% vegetative (algae and eelgrass) and 25% snails and bivalves. Surf Scoters (*Melanitta perspicillata*) ate about 75% bivalves and the rest other invertebrates (Vermeer and Levings 1977, Lovvorn 2001). These two species were the most abundant diving ducks in the Boundary Bay area during winter and summer respectively (Vermeer and Levings 1977, Lovvorn 2001). Other diving ducks in the Fraser Delta area, including White-winged Scoters (*M. perspicillata*), Long-tailed Auchs (*Elangula hyemalis*), Common Goldeneye (*Bucephala clangula*), and Barrows' Goldeneye (*B. islandica*), ate mainly bivalves, gastropods, crustaceans, polychaetes, and crabs (Lovvorn 2001). Buffleheads (*B. albeola*), on the other hand, consumed mainly eelgrass plants and seeds as well as isopods (Vermeer 1982, Lovvorn 2001). Many of the prey items in the diets of these ducks have higher standing crops in eelgrass beds than in unvegetated areas (Simenstad et al. 1988, Baldwin and Lovvorn 1994b, Ray 1997), which again emphasizes the importance of eelgrass beds to these diving ducks. Eelgrasses are also important for diving ducks and other waterfowl because they are the primary substrate for herring spawn. The herring spawn provides an important high nutrient food source for some waterfowl and may provide an important source of nutrient reserves for some diving ducks, just prior to spring migration to nesting areas (Lovvorn 2001).

PISCIVOROUS BIRDS AND EELGRASSES

A variety of piscivorous birds are observed over eelgrass and/or are frequently seen in Padilla Bay, but there are no detailed studies of their diets in Puget Sound that would document their dependence on eelgrass. Studies in the Strait of Georgia and British Columbia indicate that the diet of Common Loons (*Gavia immer*), Red-throated Loons (*G. stellata*) and Western Grebe (*Aechmophorus occidentalis*), Double-breasted Cormorants (*Phalacrocorax auritus*), Common Mergansers (*Mergus merganser*), and Red-breasted Mergansers (*M. serrator*) include a wide variety of fish including shiner perch, Pacific herring, Pacific sandlance, snake prickleback, gunels, Pacific staghorn sculpin, threespine stickleback and bay pipefish. The diversity of fish indicates that these birds are highly opportunistic, responding to prey availability. However, most of these fish are associated with eelgrass during part or all of their life cycles and are common in Padilla Bay (cf. Figs. 74 and 75 and Tables 17 and 18). The relative extent to which birds obtain these fish by foraging in or near eelgrass beds is not known and would require further studies (Lovvorn 2001). However, there is evidence that eelgrasses are indirectly important for these birds: they are often observed over or near eelgrasses and many of the fish in their diets are common or abundant in eelgrasses (cf. Figs 74 and 75).

Great Blue Herons (*Ardea herodias*) are abundant in Padilla Bay and obtain fish in the eelgrass habitat. In the Fraser Delta and at Sydney Island, British Columbia herons ate mainly Shiner Surfperch, Pacific Staghorn Sculpin, Starry Flounder, Saddleback Gunnel and Crescent Gunnel, all common fish in or near the eelgrasses in Padilla Bay. Initiation of breeding in herons appeared to be cued to the seasonal abundance of these fish, especially Shiner Surfperch (Butler 1993, Lovvorn 2001). The presence of two heron colonies close to Padilla Bay may well be related to the extensive intertidal eelgrass beds where the adults may feed. This is consistent with the suggestion of Butler et al. (1995) and Lovvorn (2001) that location and productivity of eelgrass beds might affect the location and productivity of heron colonies.

ROLE OF WATERFOWL IN EELGRASS ECOSYSTEMS

The high numbers of waterfowl in Padilla Bay for about six months of the year (cf. Table 16) raises questions about the role of these birds within the ecosystem. What percentage of the productivity or standing biomass of eelgrass is consumed by waterfowl each year? What proportion of aboveground to underground parts are consumed? What proportion of the invertebrate populations are consumed? What affect does this consumption have on the eelgrass population and on the various invertebrate populations? How does the seasonal distribution of this consumption – fall, winter, spring – alter the effects on eelgrass and invertebrates? For example, in Boundary Bay, 40 km north of Padilla Bay, Baldwin and Lovvorn (1994a) estimated that grazing by Brant and dabbling ducks removed 50% of the aboveground biomass and 43% of the belowground biomass of *Zostera japonica* by early December. However, most of the *Z. japonica* in that bay that was not grazed was uprooted by waves in early winter. What significance then does the grazing have on the population of *Z. japonica*? Estimates of the percentage of standing crop or productivity consumed by waterfowl have been made in a variety of bays and estuaries in the U.S. and Europe. These estimates vary from 0.8% up to 90% of the maximum standing stock and appear to be very site specific (Lovvorn 2001). Waterfowl disturbance, consumption, and defecation may play an important role in nutrient cycling as well as increasing the rate of bacterial and fungal colonization and transfer of energy to higher trophic levels.

Very little is known about the role of birds in eelgrass ecosystems beyond gross consumption estimates (Lovvorn 2001). However, waterfowl are likely to be an important component of the eelgrass community and ecosystem in Padilla Bay and probably have significant effects on (1) standing stocks and habitat structure, (2) primary and secondary productivity, (3) nutrient cycling, and (4) population and community dynamics of plants, invertebrates, and fish (see Lovvorn 2001 for a fuller discussion of some of these questions).

NON-NATIVE SPECIES IN PADILLA BAY

Non-native species are widespread in Padilla Bay and vary from recent introductions to well established species, and from those for which there is a single record of occurrence to those that are among the most common species throughout the bay. In the Pacific Northwest, there has been an exponential increase in recorded marine invasions in the last 100 years (Wonham 2001) and the pattern for Padilla Bay has probably been similar. Non-native species have been purposefully introduced to Padilla Bay (e.g. *Spartina alterniflora* and *Crassostrea gigas*), accidentally introduced with aquaculture (e.g. *Zostera japonica* and *Mya arenaria*), and accidentally introduced probably via ballast water (e.g. *Nuttallia obscurata*). Our understanding of the ecological impact and role of non-native species in Padilla Bay is limited.

Two non-indigenous plants that have been of special concern in Padilla Bay have been the subject of several investigations in the bay: *Spartina spp*. and *Zostera japonica*. The ecology of *Z. japonica* in Padilla Bay was reviewed previously in this report in Chapter 4.

SPARTINA

Spartina alterniflora (smooth cordgrass) was planted in Padilla Bay in the 1940's to help with stabilization of the beach on Dike Island (Parker and Aberle 1979, Wiggins and Binney 1987). The *S. alterniflora* spread, apparently vegetatively, around Dike Island and at isolated spots in the sloughs and blind channels at the southern end of Padilla Bay (Wiggins and Binney 1987). No viable seed production was reported by Parker and Aberle (1979) or by Riggs (1992). However, Riggs and Bulthuis (1994) reported flowering of *S. alterniflora* in Padilla Bay late in the growing season. No seedlings of *S. alterniflora* have been reported in Padilla Bay and presumably the growth of *S. alterniflora* in Padilla Bay has been by vegetative expansion of individual stands and transport of clumps of vegetative material to new sites (Parker and Aberle 1979, Wiggins and Binney 1987, Riggs 1992).

Spartina alterniflora in Padilla Bay was growing well and highly productive in the early 1990's, prior to control efforts. Net primary productivity of *S. alterniflora* was about 1500 g/m^2/year during 1992-1993 (Riggs and Bulthuis 1994). This estimate is among the higher values among ten sites along the east coast of North America from Nova Scotia to Louisiana (Riggs and Bulthuis 1994). Culm densities ranged from 220-520 clums/m^2 and mean monthly biomass from a low of 335 dry weight/m^2 in April to a high of 1340 g/m^2 in November. *S. alterniflora* grew throughout the year in Padilla Bay producing a mean of 11.3 leaves per year, with leaf abscission continuing throughout the year (Riggs and Bulthuis 1994). The population at Padilla Bay is the northernmost reported population of *S. alterniflora* on the west coast of North America, but the productivity and seasonal growth indicated a healthy population, with no indication that it would not grow well vegetatively further north along the west coast.

Control of *Spartina alterniflora* and *S. anglica* in Padilla Bay was recommended by the Padilla Bay Research Advisory Committee in December 1994. This recommendation was based on the continuing vegetative expansion of *S alterniflora* in Padilla Bay, and the experience in Willapa Bay, Washington, where *S. alterniflora* began flowering after some 40 years of apparent vegetative growth and then spread through many parts of the bay changing intertidal flats that had been bare of vegetation to monospecific meadows of *S. alterniflora*. Surveys of the extent of *Spartina* infestation in Padilla Bay indicated that *S. anglica* was also present as seedlings and small clones. Control of both species of *Spartina* began with some experimental work on the effectiveness of glyphosate herbicides (Bulthuis and Scott 1993, Riggs and Bulthuis 1995). In cooperation with other organizations, Padilla Bay NERR developed an integrated pest management program that included regular surveys, digging of seedlings and small clones, and combinations of mowing and herbicide applications. This very active management program has resulted in a decrease in the acreage of *Spartina* in Padilla Bay from an apparent peak of more than 20 acres to scattered seedlings and clones totaling less than one acre in 2006 (Riggs 2005, 2006b, 2007b, Fig. 82).

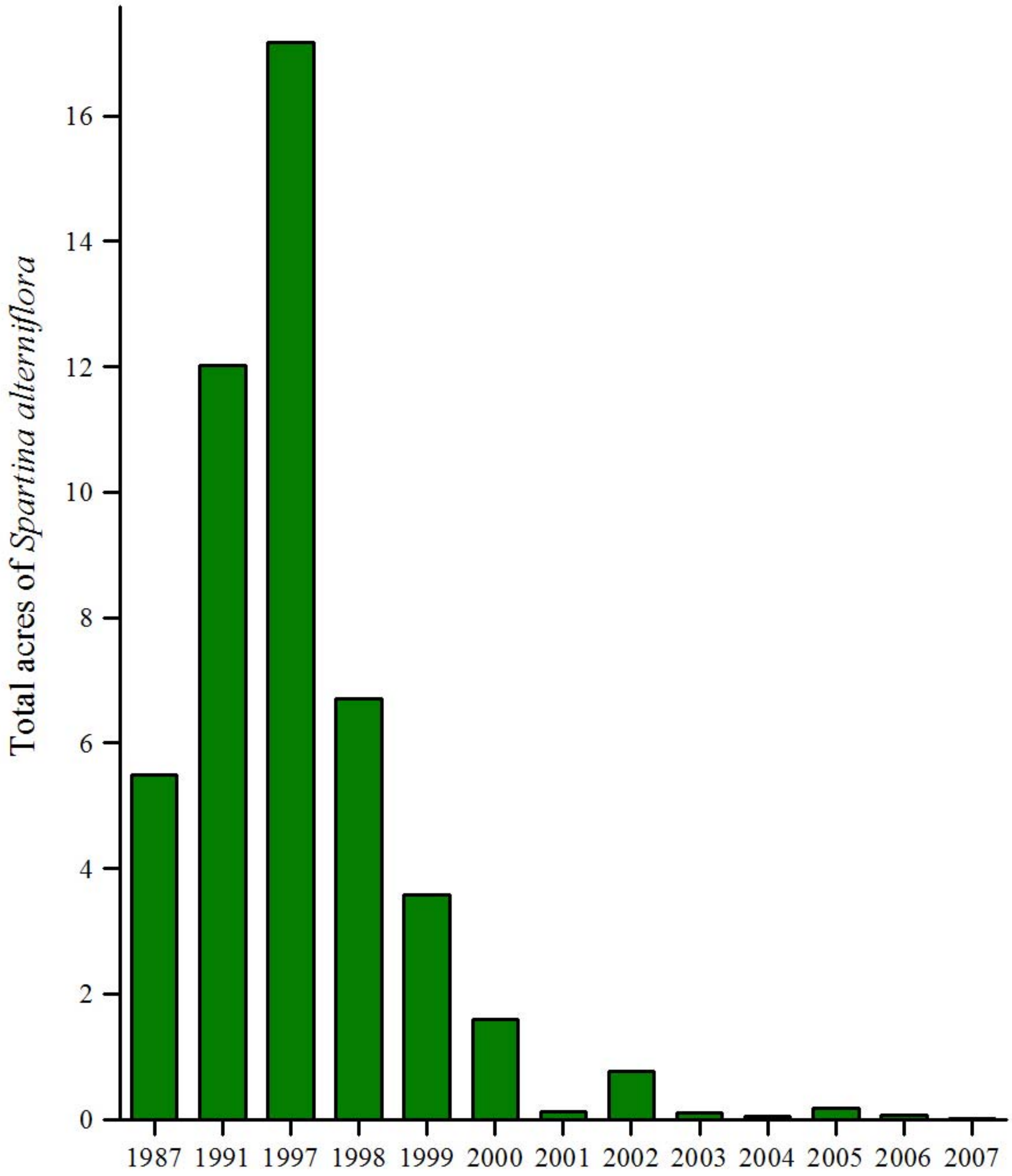


Figure 82. Total acres of *Spartina alterniflora* in Padilla Bay, 1987-2007. (Data extracted from Wiggins and Binney 1987, Riggs 1992, 2005, 2006b, 2007b)

Spartina alterniflora and *S. anglica* in Padilla Bay provide contrasting illustrations of the effects of vegetative vs. seed dispersal and reproduction of two non-native marsh plants and effectiveness of an active adaptive management program. *S. alterniflora* spread in Padilla Bay exclusively (or primarily) by vegetative means. With a very active management program, *S. alterniflora* in Padilla Bay has been reduced to a few plants with prospects for eradication possible in the next few years (Riggs 2005, 2006b, 2007b, Fig. 82). In contrast, *S. anglica* has been spreading into Padilla Bay by seeds from flowering populations in nearby bays and within Padilla Bay on non-NERRS lands. With a very active management program, flowering clones of *S. anglica* have been almost eliminated from NERRS owned lands in Padilla Bay (Riggs 2005, 2006b, 2007b, Fig 83). But the seeds from non-NERRS land and adjacent bays require major effort each year to deal with new seedlings and prevent them from going to seed with little prospects for reduced annual effort until populations in adjacent bays and non-NERRS lands are controlled.

Both *Spartina alterniflora* and *S. anglica* have invaded intertidal flats in Padilla Bay. Maricle (2002) investigated aerenchyma development and oxygen transport in these two species. Under flooded conditions, *S. alterniflora* developed maximum area of aerenchyma while development of aerenchyma did not increase in *S. anglica* under flooded conditions (Maricle 2002). On the other hand, oxygen transport was high in *S. anglica*, but undetected in *S. alterniflora*. Aerenchyma development in *S. alterniflora* may function in reducing metabolic oxygen demand by lowering cell counts (Maricle 2002).

Spartina alterniflora traps sediments so that the elevation of the sediment is raised inside stands of *S. alterniflora* (Sayce 1988, Ball 2004). Following control of *S. alterniflora* in Padilla Bay, Ball measured changes in sediment elevation in areas previously colonized by *S. alterniflora* (Ball 2004). During the course of the 2-year study, (2002-2004), no differences were found in change of elevation between mounds of former *S. alterniflora* and adjacent mudflat (Ball 2004). However, organic matter content was almost twice as high in the mounds as in the surrounding mudflat, indicating that 3-5 years after control

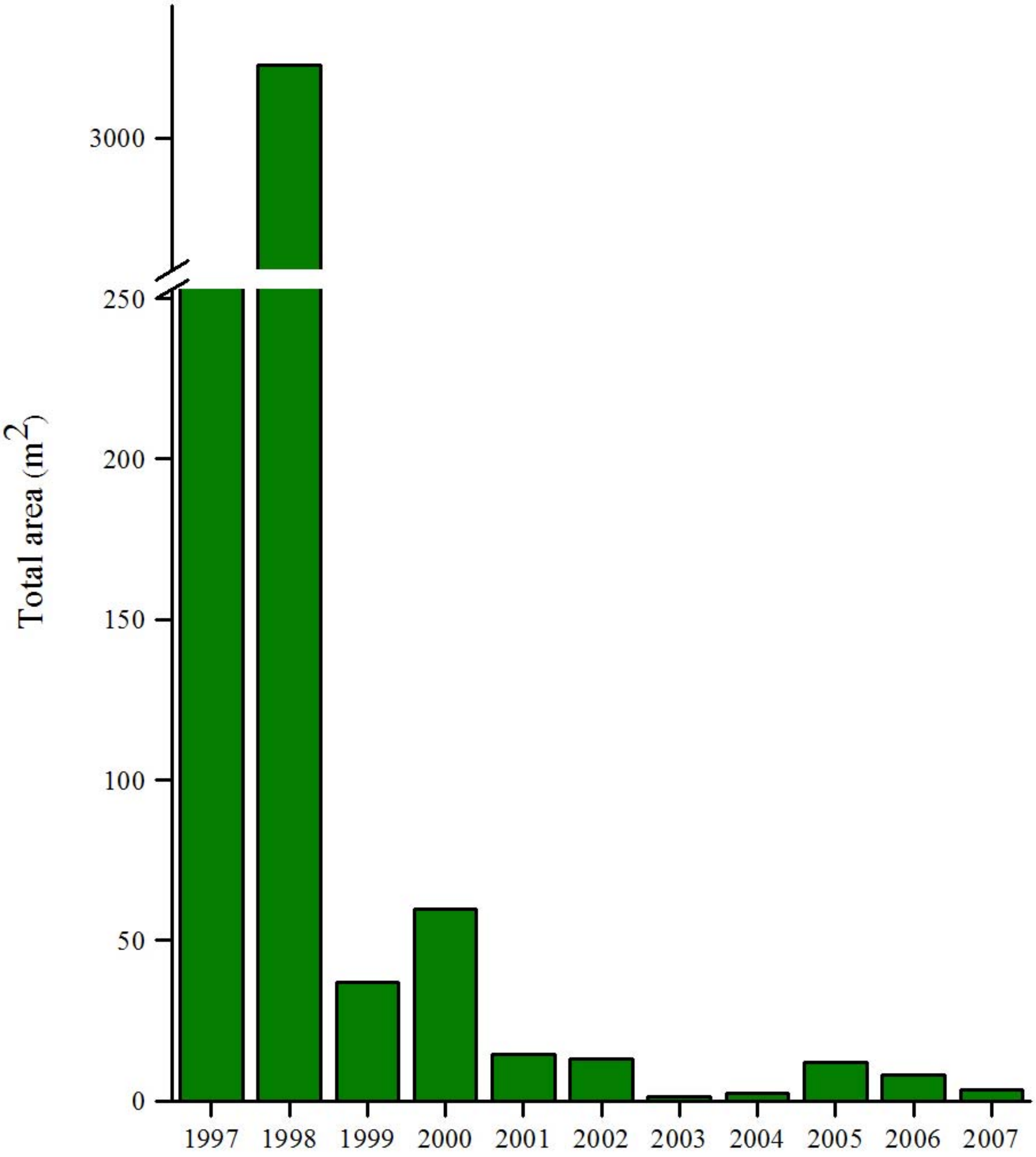


Figure 83. Total area (m^2) of *Spartina anglica* in Padilla Bay, 1997-2007. (Data from Riggs 2005, 2006b, 2007b)

decomposition and resulting sediment collapse in *S. alterniflora* mounds may still be in progress (Ball 2004).

SARGASSUM

A third non-native plant that has been studied in Padilla Bay is the seaweed *Sargassum muticum*. *S. muticum* was accidentally introduced to the west coast of North America with Japanese oyster (*Crassostrea gigas*) spat in the 1940's (Abbott and Hollenberg 1992) and its distribution now extends from Mexico to British Columbia (Ribera and Boudouresque 1995). *S. muticum* may out-compete and replace *Zostera marina* (Mumford 1990), *Nereocystis integrifolia* (Thom and Hallum 1990) and *Laminaria saccharina* (Giver 1999). However, Giver reported 107 taxa as epifauna on *S. muticum* in Padilla Bay. *S. muticum* supported a more abundant and species rich community than the native alga, *L. saccharina* (Giver 1999). Overall epibiont diversity (primarily native) and abundance increased in areas where *S. muticum* invaded areas of *L. saccharina* (Giver 1999).

MANAGEMENT OF NON-NATIVE SPECIES

Contrasting public policy and management strategies have been applied to two non-native plants in Padilla Bay: *Spartina alterniflora* and *Zostera japonica*. *Spartina* species are perceived as "ecosystem engineers" that have altered intertidal morphology and ecological communities in Washington State and the Pacific Northwest (Mumford et al. 1991). *Spartina spp*. have been declared a "noxious weed" and public and private funds have been applied to controlling *Spartina spp*. (Washington State Department of Agriculture 1992, Washington State Department of Ecology 1992, Washington State Noxious Weed Board 1995, 1997). In Padilla Bay NERR, an active integrated pest management program is being implemented to control *Spartina spp*. (Riggs 2005, 2007b). In contrast, the ecological role of the non-native *Z. japonica* is generally perceived to be beneficial to native fauna (Pawlak 1994, Lovvorn 2001, Hahn 2003). The existing policy and practice regarding eelgrass does not seek to differentiate between the native *Z. marina* and non-native *Z. japonica*. The Z. *japonica* then receives *de facto* protection from the management and policies that protect native eelgrass (Pawlak 1994, Fresh 1994, Pawlak and Olson 1995, West 1997).

NON-NATIVE FAUNA IN PADILLA BAY

Non-native fauna in Padilla Bay include a wide variety of species (Ray 1997, Riggs http://padillabay.gov/stewardshipinvasive.asp). These species have arrived in Padilla Bay via several vectors, with aquaculture one of the major pathways. Many of these species are native to the northwest Pacific (Asia) from which Pacific oyster seed were regularly introduced into Padilla Bay starting in 1932 (Dinnel 2000). One of the species likely introduced with Pacific Oyster culture was the Asian hornsnail, *Batillaria attramentaria*, that is now conspicuously abundant on the mudflats in Padilla Bay. *B. attramentaria* forage on the mud surface and consume benthic diatoms (Cooper 1997, O'Connor 2000, O'Connor et al. 2001). Wonham et al. (2005) studied the effect of *B. attramentaria* on the mudflat community in Padilla Bay. The *B. attramentaria* shells provided hard substrate on the mudflat. The shells of *B. attramentaria* provided habitat for the non-native Atlantic slipper shell *Crepidula conveca*, the non-native Asian anemone *Diadumene lineata*, and two native hermit crabs *Paqurus hirsutiusculus* and *P. granosimanus* (Wonham et al. 2005). In addition, manipulative experiments showed that abundance of the non-native mudsnail *Nassarius braterculus* and percent cover of the non-native eelgrass *Zostera japonica* increased in the presence of *B attramentaria* (Wonham et al. 2005). They defined *B. attramentaria's* impacts on the four non-native and two native species as positive (Wonham et al. 2005). Thus, the non-native *B. attramentaria* appears to increase the diversity and potential population size on the mudflats of Padilla Bay.

The purple varnish clam, *Nuttallia obscurata*, was first recorded in Puget Sound and Georgia Basin in 1991 in Semiahmoo Bay, British Columbia (about 100 km north of Padilla Bay, Forsyth 1993). *N. obscurata* spread rapidly in the 1990's and was reported in bays as far south as Port Ludlow and Holmes Harbor, including Padilla Bay by 2001 (Barkas 2002). *N. obscurata* is native to Japan and Korea and was probably introduced to Puget Sound/Georgia Basin via ballast water (Forsyth 1993). This burrowing bivalve was reported in densities greater than 700 individuals per m^2 in Puget Sound and up to 32 per m^2 in Padilla Bay (Barkas 2002). The effect on native and established fauna is not clear. Studies sponsored by Padilla Bay NERR have focused on other bivalves: native littleneck, *Protothaca staminea*, and Manila clam, *Venerupsis Philippinarum*. *N. obscurata* spawns earlier, recruits earlier, and recruits at greater densities than the commercially important *V. philippinarum* (Selleck 2003). *N. obscurata* may compete with *P. staminea* and *V philippinarum* for space and food (Barkas 2002), but the effect on these and other native and established species is not known (Barkas 2002, Selleck 2003).

The non-native European Green Crab (*Carcinus maenas*) spread along the east coast of North America and in 1989/90 was recorded in San Francisco Bay on the west coast. Distribution spread north along the west coast of North America with *C. maenas* reported in Oregon in 1997, on the Washington coast in 1998, and British Columbia in 1999. Anticipating the spread of this non-native crab into Puget Sound, the Washington State Department of Fish and Wildlife has worked with a variety of organizations, including Padilla Bay NERR, to monitor for *C. maenas*. No *C. maenas* have been reported for Padilla Bay or for Puget Sound after six years of monitoring using the Washington State Department of Fish and Wildlife protocols (Riggs unpublished data). In Padilla Bay, a yearlong project monitoring for crabs indicated that there were no non-native crabs in the bay in 2002-03 (Riggs 2003).

BIVALVES AND OYSTER CULTURE IN PADILLA BAY

The bivalves reported in Padilla Bay are similar to the mix of species in other eelgrass dominated estuaries in the Pacific Northwest (Shelford et al. 1935, Phillips 1984). Shelford et al. (1935) characterized the intertidal community in Padilla Bay and other intertidal sand and mud habitats in the San Juan Islands. More than 50 species of bivalves in 39 genera have been reported in Padilla Bay (Dinnel 2000). Common bivalves in Padilla Bay include several native species of *Macoma*, *Protothaca stamina, Clinocardium nuttallii, Saxidomus giganteus, Tresus capax, and Tellina modesta* and non-native species *Mya arenaria, Venerupsis philippinarum,* and *Nuttallia obscurata*. In addition pacific oysters, *Crassostrea gigas*, have been cultured in Padilla Bay for commercial culture in the past and for recreational harvest in recent years (Dinnel 2000). The geoduck that is common in Puget Sound and in eelgrass meadows in the Pacific Northwest, has not been reported for Padilla Bay (Phillips 1984, Ray 1997, Dinnel 2000).

In common with most bays in Puget Sound and Washington, the intertidal flats of Padilla Bay were sold by Washington State for oyster cultivation and harvest. Oysters (*Crassostrea gigas*) were first planted in Padilla Bay in 1932 and planting continued through the early 1930's (Dinnel 2000). In the late 1930's the Padilla Bay Oyster Company was liquidated and reorganized as Pioneer Oyster Company, which company sued the Puget Sound Pulp and Timber Company of Anacortes and Bellingham claiming that sulfite waste liquor effluents were causing mortality and poor growth of oysters in Padilla Bay The court ruled against Pioneer Oyster Company, stating that the oyster problems were the result of overcrowding and the poor growing condition of the beds in Padilla Bay (Dinnel 2000). However, following closure of the Anacortes mill in 1943, some 20,000 bushels of shucked oysters were harvested from Padilla Bay beds and oyster harvest continued until about 1960. Various investigations concluded that a variety of factors may be responsible for the generally poor condition of oysters in Padilla Bay, including both natural factors and pollution, and that commercial oyster culture in Padilla Bay is probably only marginal economically (Saxton and Young 1948; Orlob et al. 1950; Westley 1958, Fagergren et al. 1989; Dinnel 2000).

CHAPTER 6

RESEARCH AND MONITORING AT PADILLA BAY NATIONAL ESTUARINE RESEARCH RESERVE

The review in the previous chapters of studies conducted in Padilla Bay provides a summary and indication of what is known about the ecology of Padilla Bay at this time. The review also indicates gaps in our knowledge and areas for future research and monitoring. As a National Estuarine Research Reserve (NERR), Padilla Bay promotes, coordinates, and conducts research and monitoring in Padilla Bay and surrounding areas to increase our understanding, and to better conserve and manage these estuarine systems. This chapter is a brief summary of 1) the context and goals of research and monitoring at Padilla Bay NERR, 2) research gaps, needs, and priorities for Padilla Bay NERR, and 3) the research and monitoring program and facilities at Padilla Bay NERR.

CONTEXT AND GOALS OF RESEARCH AND MONITORING AT PADILLA BAY NERR

MANAGEMENT AND INSTITUTIONAL CONTEXT

Padilla Bay is located in the greater Puget Sound/Georgia Basin estuary and the research and monitoring conducted in Padilla Bay has the greatest relevance and value for the understanding and conservation of greater Puget Sound/Georgia Strait. The research is also relevant throughout the Pacific Northwest and the Columbian Bioregion in which Padilla Bay was designated a National Estuarine Research Reserve. Research in Padilla Bay is carried out in coordination with the scientific research conducted throughout Puget Sound by academic institutions, and federal, state, local, and tribal governments. In part the coordination is achieved by scientists who conduct research in Padilla Bay who are often conducting similar research in other parts of Puget Sound. In addition, the issues that are of importance in Puget Sound are issues that are studied in Padilla Bay.

Padilla Bay NERR, representing the larger Puget Sound ecosystem, has many management issues to address. Several of these issues are now the focus of the new Puget Sound Partnership, created by the Governor to clean up the Sound, making it “fishable, swimmable, and diggable” by the year 2020. The Washington State Department of Ecology (Coastal Management Office) is increasingly involved in these actions, with additional mandates for Puget Sound Health. Some of these issues of regional importance are: protection and restoration of habitat, reduction of toxic inputs, reduction of human and animal waste inputs, protection of ecosystem biodiversity and imperiled species, controlling invasive species and understanding the impacts of climate change.

Management issues that provide a context for the research in Padilla Bay include subsets of several of those noted above. Some of these include winter runoff from the predominately agricultural watershed, residential and commercial development in the Padilla Bay watershed, various proposals to divert part of the Skagit River flood waters to Padilla Bay, potential threats to the eelgrasses in Padilla Bay, the interaction between the non-native Japanese eelgrass and the native eelgrass, spread of the non-native *Spartina* on the intertidal flats, effects of chronic hydrocarbon pollution, potential effects of oil spills drifting into Padilla Bay, and the effects of future climate change and sea level change on habitats, shorelines, biota, and water quality.

Padilla Bay NERR is located institutionally in the Washington State Department of Ecology in the Shorelands and Environmental Assistance Program. In this setting Padilla Bay supports research on priority issues of Ecology and of the Shorelands and Environmental Assistance Program, including issues related to broader coastal zone management. In addition, conservation and environmental quality in Puget Sound is and has been the concern of federal and state agencies. Padilla Bay NERR research has supported the priorities and issues of the U.S.E.P.A. Puget Sound Estuary Program, the Washington State Puget Sound Water Quality Authority, the Puget Sound Action Team, and beginning in late 2007, the Puget Sound Partnership. Support for the priorities of these many organizations has included funding, conducting, or supporting research in

Padilla Bay that is consistent with their funding priorities. Research conducted in and by Padilla Bay NERR will continue, both formally and informally to advance scientific knowledge to address the issues of importance in Puget Sound and other organizations within the Padilla Bay organizational landscape.

THE VALUE OF PADILLA BAY NATIONAL ESTUARINE RESEARCH RESERVE FOR THE RESEARCH COMMUNITY

Padilla Bay and the National Estuarine Research Reserve designation and operation contribute to the value of research in Puget Sound/Georgia Basin and estuarine research in Washington State in numerous ways. Specific factors that contribute to Padilla Bay NERR’s value to estuarine research include:

- The protected status of Padilla Bay and its habitats as part of the National Estuarine Research Reserve System that is protected both by federal and state agreements.
- The extensive areas of eelgrass in Padilla Bay that provide a laboratory in which to better investigate eelgrasses, the eelgrass community, and the role and functioning of eelgrasses in the larger estuarine system.
- The mosaic of other habitats in Padilla Bay such as native salt marsh, sand flats and mud flats devoid of macro-vegetation, rocky shores, and an extensive channel network.
- Padilla Bay can serve as a “control” site or reference site for a variety of studies because the bay and its communities are relatively unimpacted directly by anthropogenic activities.
- Baseline data and studies that have been conducted because Padilla Bay is set aside as a research reserve, provide background and context for research projects, including short-term studies.
- Monitoring data of basic water quality, nutrients and weather are collected by Padilla Bay NERR and are available to scientists to assist in the understanding and interpretation of their studies.

- Padilla Bay NERR facilities include a laboratory with space for a variety of different types of studies, bunkhouse facilities for overnight or short-term stays at Padilla Bay, and a library with copies of most reports and publications on Padilla Bay and the North Puget Sound area.
- NERRS Graduate Research Fellowships and Padilla Bay Research Assistantships provide funding for graduate students conducting research in Padilla Bay.
- The variety of studies conducted in Padilla Bay and the connections with other National Estuarine Research Reserves provide opportunities for collaborative studies.

GOALS OF RESEARCH AND MONITORING AT PADILLA BAY NERR

Within this ecological, institutional, and management context, the goals of research and monitoring at Padilla Bay have been articulated as:

> **To promote, conduct, and coordinate research and monitoring in Padilla Bay and the adjacent waters and watershed to advance scientific knowledge for the conservation, management, restoration, and greater understanding of the nation's estuaries, in particular, greater Puget Sound and other estuaries in the Pacific Northwest.**

RESEARCH GAPS, NEEDS, AND PRIORITIES AT PADILLA BAY NERR

The review in the previous chapters of what is known indicates many gaps in our knowledge of the Padilla Bay estuarine system and indicates the needs for better understanding for good management and conservation of Puget Sound/Georgia Basin, other estuaries in the Pacific Northwest, and seagrass systems throughout the United States and the world. Padilla Bay is a good site at which to address a wide diversity of these gaps in our knowledge and understanding. Among this diversity of gaps and needs the following topics are listed as some of the priority areas for research and monitoring in Padilla Bay.

- Eelgrasses, their seasonal and interannual variation, their productivity, the factors controlling their growth and survival, and interactions with other flora and with fauna. There have been and continue to be studies on eelgrasses throughout the United States and in Europe. While there is much that we do know about eelgrasses, there is also much we do not know. Padilla Bay, with its extensive meadows is a good place to further our understanding of these eelgrass systems. We can build models that predict eelgrass growth and productivity based on current understanding of rates of productivity and growth. And yet, eelgrasses unexpectedly die from bays and estuaries (for example in Westcott Bay in the San Juan Islands) and the causes are unknown. The eelgrasses in Padilla Bay have been consistent in their coverage for many years; but they are occupying a habitat (intertidal) which in many locations in Puget Sound and the Pacific Northwest is sub-optimal. What is the areal extent of eelgrasses each year and what are the interannual fluctuations in areal coverage? The areal coverage of eelgrasses should be monitored regularly to detect changes in distribution and threats to the eelgrasses. How can we better delineate and distinguish the coverage of *Zostera marina*, *Z. japonica* and macroalgae? What are the controlling factors and potentially threatening factors to productivity, growth, and survival in Padilla Bay? What is the role of the huge production of organic matter in Padilla Bay in the surrounding waters? Is this productivity important to the adjacent communities or does most of the productivity remain in the bay? What is the historical ecology of eelgrasses in Padilla Bay? Are the extensive meadows a recent phenomena that may be associated with anthropogenic changes to the surrounding area?
- Faunal community associated with eelgrasses, including the many juvenile and early life stages that are part of the eelgrass community, salmon and other fish, birds, invertebrates. Very few of the many eelgrass-associated species have been studied. Early life stages of many estuarine and marine species are reported to be associated with eelgrasses, but studies and documentation of these associations are not common. What is the movement and interaction between the zooplankton

that move with the semidiurnal tides in and out of Padilla Bay and the fauna in and on the eelgrasses?

- The interactions between *Zostera marina* and *Z. japonica*. The non-native *Z. japonica* is generally perceived to be beneficial to many native species and receives some defacto protection in Washington. Are the faunal communities associated with each species the same? Are some species favored by one or the other eelgrass? Both species grow and thrive in Padilla Bay, but there is some evidence that *Z. japonica* is expanding its coverage in areas that had been dominated by *Z. marina*. What is the interaction between these two species? Are there habitats that favor one species of eelgrass over the other? Can *Z. japonica* outcompete *Z. marina* under some conditions?
- Non-eelgrass habitats in Padilla Bay. Extensive intertidal sand and mud flats in Padilla Bay lack macro vegetation and generally attract little research interest. What is the role of these intertidal flats in the Padilla Bay ecosystem? What are the primary fauna in and on these flats? What is the movement of organic material between these flats and adjacent habitats? Native salt marshes are located on the fringes of Padilla Bay and are only a remnant of their former extent. What are the depositional and erosional dynamics that affect these remnant marshes? Will they continue in Padilla Bay under present or future conditions? Estuarine channels are important for water flow onto and off of the intertidal flats and as refuge for mobile fauna during low water. But there is very little study of the role of these estuarine channels in eelgrass meadows.
- Fine scale bathymetry of Padilla Bay. The bathymetry of the intertidal flats and channels exerts important control mechanisms on the flora and fauna that are able to grow and survive in these micro-habitats. But this baseline information has not been determined for Padilla Bay. Such data could help understand patterns observed in distribution of vegetation and fauna and would help site selection of future research projects and provide a baseline to develop hypotheses about the role of micro-habitat.

- Sediment dynamics and sea level rise in Padilla Bay. What is the origin of the intertidal sediments in Padilla Bay? Were they built up gradually over centuries as the Skagit River flowed into Padilla Bay or were there catastrophic events such as volcanoes that brought sediment from lahars to Padilla Bay in short time periods? What is the depositional history of sediments in Padilla Bay? What is the sediment budget in Padilla Bay now and how has that changed over the last one hundred and fifty years with anthropogenic changes to the watershed, sloughs, and rivers? Are the sediments in Padilla Bay sinking, being compacted, or rising? What is the relative sea level rise in Padilla Bay and how is that likely to change under different global sea level rise scenarios? How will various sea level rise scenarios impact plant and animal communities in Padilla Bay?
- Water flow to and from Padilla Bay and water quality in Padilla Bay. Studies have indicated short-term flow into Padilla Bay over a single flood tide. What are the longer-term water flow dynamics? How much of the water flowing out of Padilla Bay returns in the incoming tide? What are the sources of the water that flows into Padilla Bay? Are they different in the southern part of the bay than in the north? We have good data on temporal changes in basic water quality at two sites within Padilla Bay, but little is known about the horizontal distribution of water quality in Padilla Bay. Is there a north to south gradient? During high tide, is water over the channels different than water over the intertidal flats? Is there a east to west gradient in water quality?
- Zooplankton and phytoplankton communities in Padilla Bay. Most research has focused on the eelgrass communities in Padilla Bay and much less is known about the zooplankton and phytoplankton communities. What are the interactions and movement of organisms and materials between the eelgrass beds and the plankton communities? How are the plankton communities changed as they enter Padilla Bay from the surrounding straits and exchange materials and organisms with the eelgrass community and the epipelic communities on the intertidal flats?
- Intertidal algae. Extensive mats of algae develop on the intertidal flats some years. Little is known about their growth, development and dynamics. Why the

strong interannual variation? Did they grow in situ or are they accumulations washed in from elsewhere? What is their affect on the eelgrass communities and the intertidal flat communities? What species are dominant and the main constituents of these mats? Are they native algae or non-native algae? What are the nutrient dynamics associated with these algal mats? Is the presence of these mats a consequence of anthropogenic nutrient inputs?

- Waterfowl. Extensive numbers of waterfowl are in Padilla Bay during fall and spring migrations and large numbers of waterfowl winter in Padilla Bay. What is the role of these waterfowl in the eelgrass ecosystem of Padilla Bay? What is the diet of different species including diving ducks? How do they interact with other species in the bay, and what is their impact on prey and non-prey species?
- Non-native species and their role and impacts in the estuary. Examples of non-native species needing research in Padilla Bay besides *Zostera japonica* are *Spartina* spp, *Batillaria attramentaria* and the Purple Varnish Clam, *Nuttallia obscurata*. A better understanding of the mechanisms of seed dispersal, germination, growth, and seed production of *Spartina anglica* could assist management and control efforts. Monitoring for the arrival and impact of Green Crab, *Carcinus maenas*, should continue. What are the populations and dynamics of native crabs and other native fauna that may be impacted if and when *C. maenas* is abundant in Padilla Bay?
- Watershed-estuary interactions including agriculture-estuary interactions and effects of development in the watershed on the estuary. What is the impact of development on water quality in the watershed? Does development change the rate of discharge to Padilla Bay of suspended solids or other constituents? Examples of issues include effects of storm water, water quality, agricultural practices, and tidal restrictions in the sloughs flowing to Padilla Bay.
- Contaminants and nutrients such as hydrocarbons, toxins, and nitrogen. Examples of contaminant issues include the Whitmarsh Landfill over former marsh in the southwest corner of Padilla Bay and the Inman Landfill with potential for leachate in groundwater that flows to Joe Leary Slough and Padilla

Bay. There are newly recognized contaminants such hormone mimics and derivatives and PPBs. What concentrations are found in Padilla Bay and does Padilla Bay serve as a comparison site reflecting regional contaminant concentrations without point inputs? What agricultural pesticides reach Padilla Bay and what is their impact? A few studies in Padilla Bay indicate that only very low concentrations of these chemicals reach Padilla Bay. However, agricultural practices change and new pesticides are used as old ones are phased out. With agriculture the largest land use in the Padilla Bay watershed, periodic studies are needed to monitor changes and any new threats to Padilla Bay flora and fauna. Nutrient inputs to Puget Sound/Georgia Basin continue to increase because of the increasing human population. Such increased nutrient inputs have caused profound and long-term problems in many estuaries worldwide. How will increased nutrient inputs affect the fjord estuaries of Puget Sound and Georgia Strait? What is the role of shallow water vegetation on the nutrient cycling? What are the trends and intrannual variation in dissolved inorganic nutrients in Padilla Bay? How do the extensive eelgrass meadows in Padilla Bay affect nutrient cycling in the bay and in the surrounding waters?

- Management and stewardship issues that identify topics for which research is needed in order to make appropriate decisions for management and natural resource stewardship of Padilla Bay. Examples include an assessment of historical conditions and ecology of Padilla Bay to assist in restoration plans, an understanding of human impacts under current conditions of use on fauna and flora in Padilla Bay, and oil spill response. Specific issues may arise such as the effects of proposed diversion of Skagit River floodwater to Padilla Bay either directly or indirectly. If Skagit River floodwater enters Padilla Bay indirectly, how will this affect the long-term growth and survival of the eelgrass community?
- Species of special concern such as salmon (including Puget Sound Chinook) Dungeness crab, herring, and scoters. Puget Sound Chinook are listed as threatened species and generally spend a longer time in the estuary than other salmon species. What is the role of Padilla Bay, without natal rivers with Puget

Sound Chinook flowing into the bay, but with extensive eelgrass meadows and located in the regional estuary with large runs of Puget Sound Chinook? Pacific Herring populations in the Strait of Georgia are declining steeply. Herring are usually closely associated with eelgrasses. And yet, spawning surveys have indicated little dense spaen on eelgrasses in Padilla Bay. Are Padilla Bay eelgrasses important to herring in the region? Why don't the eelgrasses in Padilla Bay support a denser herring spawn?

RESEARCH AND MONITORING PROGRAM AT PADILLA BAY NERR

The research program at Padilla Bay NERR includes student-supported research, cooperative research with other institutions, agencies and scientists; research conducted by Padilla Bay NERR; and support for research, monitoring, geographic information systems, and stewardship activities in Padilla Bay.

PBNERR Research Assistantships in Estuarine Science and Coastal Zone Management are awarded ($5000 in 2009) to students conducting research in Padilla Bay as part of their Master's or Ph.D. thesis work or occasionally outside of their thesis research (Fig. 84). Research on coastal zone management issues that have been identified as important issues may be conducted anywhere in Puget Sound and funded by Padilla Bay Research Assistantships. Funding for the assistantships are sought from a variety of sources including private foundation grants, coastal zone

Figure. 84. Padilla Bay Research Assistantships in Estuarine Science and Coastal Zone Management provide support for student thesis research in Padilla Bay.

management grants, and Padilla Bay Reserve operations funds. Proposals are requested from students, reviewed by the Padilla Bay Research Advisory Committee and other scientists and agency staff, and awarded as contracts to the students.

The **NERRS Graduate Research Fellowship** Program provides $20,000 a year (in 2009) for up to three years for Ph.D. or Master's thesis research in Padilla Bay NERR. Two fellowships are funded each year so that there may be two, one, or no openings at Padilla Bay in any particular year. Padilla Bay NERR promotes the fellowship opportunities, arranges for reviews of the proposals, and works with the students to promote the best possible research in the bay. The students provide assistance to Padilla Bay NERR in some aspect of monitoring or research.

Cooperative Research and Other Scientists

Another element of the Padilla Bay NERR research program is cooperative investigations with other scientists or institutions. Many research issues require multiple investigators and funding sources often prefer or require multiple investigator teams. Padilla Bay research staff work cooperatively with scientists from a variety of institutions with differing levels of involvement including principle investigator, field investigations, field or laboratory support, or scientific advice or context. These projects are principally funded through another institution and necessarily vary widely from year to year for Padilla Bay depending on the issues being investigated and the opportunities for involvement. Padilla Bay also promotes research by outside investigators. Assistance is provided to some outside investigators by the provision of facilities and field support at Padilla Bay, including laboratory space and equipment, field instruments, GIS support, overnight facilities, and vessel support.

Research by Padilla Bay NERR Staff

A third element of the Padilla Bay NERR research program is research conducted by Padilla Bay staff (Fig. 85). These projects may include cooperation with other scientists and institutions with Padilla Bay NERR is the principle research institution. These projects are funded by a variety of sources. In the past funding has been received from organizations such as Cooperative Institute for Coastal and Estuarine Environmental Technology, Environmental Services Data and Information Management, NOAA, and Washington State Department of Ecology. The specific projects change from year to year depending on the projects that are funded.

Figure 85. Planktonic stages of many estuarine species are found in plankton tows in Padilla Bay. Zooplankton in general taxonomic groups are monitored monthly by Padilla Bay staff.

A **Padilla BayNERR Technical Report** series and **Reprint** series are produced by Padilla Bay NERR. These series are produced both as printed copies and as digital copies in PDF format. The PDF reports and reprints are available on the Padilla Bay website. These series provide a mechanism for thesis research and other research at Padilla Bay to be made available to a wider audience.

Web site. Information about the research program, student research opportunities, and reports on research in Padilla Bay is provided on the Padilla Bay web site (http://padillabay.gov/researchreports.asp).

PADILLA BAY NERR MONITORING PROGRAM

Outlined below is the basic design for the Padilla Bay NERR Monitoring Program. This design will be changed and refined as data analyses or practical difficulties indicate changes are needed, and as the plan is peer reviewed both internally and externally.

NERRS SYSTEM-WIDE MONITORING PROGRAM

Padilla Bay NERR participates fully in the NERRS System-wide Monitoring Program (SWMP). The NERRS System-wide Monitoring Program includes three broad components:

1. Abiotic parameters (such as physical and nutrient water quality parameters, meteorological, sediment quality)
2. Biological (including biodiversity and fluctuations in populations and communities)
3. Land-use and land-cover (in the Reserve watershed)

The NERR system has initially focused on the first component, abiotic monitoring, and recently has conducted trials and pilot studies in the second component, biological monitoring. In coordination with the rest of the NERRs, Padilla Bay NERR is implementing physical water quality monitoring, water column nutrient monitoring, and meteorological monitoring as part of the first component (abiotic parameters) of the NERRS System-wide Monitoring Program. As additional portions of the NERRS System-wide Monitoring Program are adopted the site-based (Padilla Bay) program will change to incorporate these elements.

Water quality monitoring sites. Four water quality sites have been established in Padilla Bay: one in the southern half of the bay (Bay View Channel site), one in the northern half of Padilla Bay (Ploeg Channel site), one west of Padilla Bay between Samish and Guemes Islands (Gong buoy site), and one near the mouth of Joe Leary Slough (Fig. 33). The Bay View Channel site was placed to monitor water quality in the main body of Padilla Bay. The Ploeg Channel site was placed to monitor water quality in the northern part of Padilla Bay in contrast to Bay View Channel in the southern part of Padilla Bay. The Gong buoy site was placed to monitor the water that flows into Padilla Bay with each tidal cycle. The Joe Leary Slough site was placed to monitor the quality of the freshwater that flows into Padilla Bay from the largest sub-basin in the Padilla Bay watershed. One of the objectives of long-term monitoring at the Joe Leary Slough site is determining the effectiveness of implementation of the Skagit County watershed planning process for the Padilla Bay/Bay View watershed. In addition to the above rationale for placement of the monitoring sites, the four sites also monitor a gradient of water from the freshwater in Joe Leary Slough, to mid-bay water quality (Bay View Channel and Ploeg Channel), to the "marine" end of the gradient at Gong buoy. The Padilla Bay sites (Bay View Channel and Ploeg Channel) are in small channels that drain eelgrass-covered tidal flats, and thus will reflect water quality over the eelgrass. The Joe Leary Slough site is located near the mouth of the slough to indicate long-term changes in water quality as a result of changes in the watershed. The site west of Padilla Bay (Gong buoy site) indicates the quality of water flowing into Padilla Bay during the semi-diurnal tides.

Physical water quality. One element of System-wide Monitoring Program data collection is basic physical water quality measured with multi-parameter data loggers. A few basic physical parameters (temperature, salinity/conductivity, turbidity, dissolved oxygen, and pH) are measured at 15-minute intervals continuously, except for equipment calibration, downloading and malfunction.

Water column nutrients. Nutrients and chlorophyll *a* in the water column are measured at two spatial and temporal scales. Semi-monthly throughout the year nutrients and chlorophyll are sampled at four water quality sites. Hourly for 26 hours at one water quality site in the bay, nutrients and chlorophyll are sampled once a month. Parameters that are measured include nitrate, nitrite, ammonia, total nitrogen, soluble reactive phosphate, total phosphorus, chlorophyll and phaeophytin.

Meteorological. Weather related factors are measured at a weather station located at the Padilla Demonstration Farm at the southeast corner of Padilla Bay (Fig. 86). Parameters that are measured include rainfall, wind speed, and direction, air temperature, relative humidity, barometric pressure, and photosynthetically active radiation (400-700 nm). Protocols for frequency of data collection, data entry and management are implemented as recommended by the NERRS System-wide Monitoring Program.

Watershed water quality

Figure 86. The weather station is located near the southeast shore of Padilla Bay on the Padilla Demonstration Farm

The water quality in the sloughs and streams that flow into Padilla Bay is periodically monitored for various purposes. Water quality and quantity in No Name Slough is being monitored in association with studies on the Padilla Bay Demonstration Farm. This farm, located in the proposed boundaries of the Padilla Bay Reserve and owned by the Washington Department of Ecology as part of the Reserve, is being used to demonstrate agriculture/development/water quality/water quantity issues. Part of the ongoing operation of the farm will be monitoring of some water quality parameters and flow in No Name Slough and in drainage ditches on the farm. Monitoring will be designed on a project specific basis each year or season.

BIOLOGICAL MONITORING

Areal coverage of eelgrass. Monitoring the areal coverage of eelgrass is conducted with remote sensing methods as completed for the year 2004 with funding as a SWMP Biomonitoring pilot site (Shull and Bulthuis 2002, Bulthuis and Shull 2006, Fig. 59). True color aerial photos are taken near mid-summer once a year. When possible, ground reference sites are monitored throughout the bay during summer. Coverage of estuarine vegetation are then delineated on screen using methods outlined in Shull and Bulthuis (2002) and Bulthuis and Shull (2006). Other vegetative communities that will be monitored with these methods include *Spartina spp*., native salt marsh, and macroalgal mats.

In addition to monitoring the coverage of eelgrasses, salt marshes and macroalgal mats in Padilla Bay, other biological monitoring is conducted for specific purposes.

Zooplankton. Monitoring for zooplankton in the water column was initiated in 2007. Zooplankton are sampled monthly and identified in broad taxonomic groups to indicate seasonal trends, spatial differences, and interannual variability. Zooplankton monitoring will continue with monthly sampling at the three water quality monitoring sites in Padilla Bay and modified as data are analyzed and interpreted.

Barnacle settlement. Barnacle settlement is being monitored at the three water quality sites in Padilla Bay (Bay View Channel site, Ploeg Channel site, and Gong buoy site). At each site, settlement plates are set out for 3 to 5 weeks and the number of barnacles that settled during the interval measured.

Non-native species monitoring. The *Spartina spp.* (principally *S. anglica*) is monitored annually for the purpose of control of this non-native salt grass. Monitoring for presence of green crab is conducted using protocols developed by the Washington State Department of Fisheries and Wildlife. The objectives of these monitoring programs include detection of non-native species, evaluation of the effectiveness of control efforts, and planning for future control efforts.

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