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Historical Change and Impairment of Puget Sound Shorelines

Atlas and Interpretation of Puget Sound Nearshore Ecosystem Restoration Project Change Analysis

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PUGET SOUND NEARSHORE ECOSYSTEM RESTORATION PROJECT

Puget Sound Nearshore Ecosystem Restoration Project

U.S. Army Corps of Engineers, Seattle District
Seattle, Washington
and
Washington Department of Fish and Wildlife
Olympia, Washington

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Acronyms

DPU..delta process unit

EFG&S ....Ecosystem Functions, Goods and Services

GSU ....geographic scale unit

GI..General Investigation (USACE)

NST ....Nearshore Science Team (PSNERP)

PSNERP......................................Puget Sound Nearshore Ecosystem Restoration Project

PU...process unit

SPU...shoreline process unit

SSHIAP ....Salmon and Steelhead Habitat Inventory and Assessment Program

WDFW ....Washington Department of Fish and Wildlife

USACE..U.S. Army Corps of Engineers, Seattle District

UW ....University of Washington

Executive Summary

The Puget Sound Nearshore Ecosystem Restoration Project (PSNERP) has conducted a comprehensive, spatially-explicit analysis (Change Analysis) of net changes to nearshore ecosystems of Puget Sound—its beaches, estuaries, and deltas—since its earliest industrial development. These quantitative changes in the structure of Puget Sound's shorelines are indicators of qualitative change to nearshore ecosystem processes. Because historical documentation of nearshore ecosystem processes does not exist per se, and certainly not uniformly across the breadth of Puget Sound, we used the observed physical changes to the shoreline, PSNERP conceptual models, and other sources of understanding about the relationship among nearshore ecosystem processes, structures, and functions to interpret the levels and types of impairment of nearshore ecosystem processes. Our approach was to systematically quantify historical change in the physical structure of Puget Sound's shorelines over the past approximately150+ yr, between the earliest land surveys of the General Land Office and U.S. Coast and Geodetic Survey (1850s–1890s) and present conditions (2000–2006). We view historical condition as an important baseline or reference point for restoration and preservation, but caution that historical condition should not be made a restoration/preservation target without considering modern constraints.

To conduct this nearshore change analysis, PSNERP's Nearshore Science Team (NST) developed a geospatial template that allows us to interpret likely changes in ecosystem processes based on historic change in structure and in the amount and types of stressors in nearshore ecosystems. This approach is predicated on the distinctive spatial arrangements of the dominant ecosystem processes along Puget Sound's beaches, estuaries, and river deltas. We delineated the Puget Sound shoreline into geomorphic segments (shoreforms) based on the PSNERP (Shipman 2008) Geomorphic Classification, which provided us with the basis for independently classifying both historical and current shoreforms that reflect varying sedimentation processes (beaches) and freshwater inflow and tidal mixing (estuaries/deltas) as the dominant controlling factors. The Puget Sound geomorphic shoreforms became one of the primary units in a geospatial hierarchy of data organized into four geographic scale units: 1) shoreforms, 2) shoreline drainage (watershed) units, 3) nearshore process units (drift cell or delta hydrogeomorphic components), and 4) larger scales of shoreline-delta organization, such as seven sub-basins of Puget Sound, distinguished by oceanographic, ecological, and other physical/natural science characteristics.

In populating the the nearshore geospatial template, we located data on historical change that met the requisite criteria of being: 1) directly related to changes, both direct (documented) and indirect (inferred from current condition), in nearshore ecosystem processes; 2) spatially explicit; 3) comprehensive, complete, and of uniform resolution and quality Sound-wide; 4) well documented; and 5) in, or readily convertible to, GIS format. Because of the PSNERP emphasis on addressing change in nearshore ecosystem processes, we organized these data on nearshore change around the spatial limits of two prominent nearshore ecosystem "process units" (PU): 1) shoreline process units (SPU) for beaches associated with littoral drift cells, where the primary ecosystem process is sediment delivery and transport along the beach, and 2) delta process units (DPU) in large river deltas and drainages organized by different seawater-freshwater mixing zones, where the primary ecosystem process is flooding duration and frequency of different salinity ranges.

Historical change was analyzed for each PU in Puget Sound, as well as at the PSNERP sub-basin scale, in four categories, also referred to as "tiers": 1) Shoreform Transition (Tier 1): changes in shoreform class, either among natural geomorphic classes or to classifications of artificial or absent; 2) Shoreline Alterations (Tier 2): changes in historically documented attributes, such as wetlands, or current anthropogenic modifications (considered stressors) along the shoreline; 3) Adjacent Upland Change (Tier 3): anthropogenic changes within 200 meters of the adjoining uplands; and 4) Watershed Area Change (Tier 4): anthropogenic changes in the drainage area. Change data documented for each category included:

1) **Shoreform Transitions (Tier 1):**
   a) *change between historical and current shoreform class, including transition to artificial (e.g., nearshore fill) or total loss of shoreform*

2) **Shoreline Modifications (Tier 2):**
   a) *loss/gain of intertidal wetland classes*
   b) *shoreline armoring*
   c) *tidal barriers*
   d) *breakwaters and jetties*
   e) *overwater structures*
   f) *nearshore fill*
   g) *marinas*
   h) *roads*
   i) *active railroads*
   j) *abandoned railroads*

3) **Nearshore Zone Modifications (Tier 3):**
   a) *land cover*
   b) *impervious surface*
   c) *roads*
   d) *stream crossings*
   e) *active railroads*
   f) *abandoned railroads*

4) Drainage Area Modifications (Tier 4):

a) *land cover*
b) *impervious surface*
c) *roads*
d) *stream crossings*
e) *active railroads*
f) *abandoned railroads*
g) *impounded drainage areas (behind dams)*
h) *current drainage extent based on historical drainage extent (DPU)*

Change data is tabulated and mapped in a variety of analytical outputs at the individual PU level and summarized within Puget Sound sub-basins, among sub-basins, and Sound-wide. In addition to graphical and map representations of nearshore changes in these attributes, comparing historical and present conditions, we used multivariate analyses (i.e., cluster analysis, non-metric multidimensional scaling, and similarity percentage in the statistical softwarer package PRIMER) to categorize different degrees of nearshore ecosystem change (e.g., groups of PU having similar shoreform compositions or types and magnitudes of change).

For each shoreline process unit and delta process unit, we related the four categories of nearshore change (tiers) to shifts in the benefits of natural nearshore ecosystems to humans and their communities. To explore the potential significance of these relationships, we adapted the recent application of the Millennium Ecosystem Assessment's Ecosystem Functions, Goods and Services (EFG&S) for restoration and conservation planning, adapting it as a template for ranking the level of cumulative impairment to nearshore ecosystem processes from changes in attributes of SPU and DPU at each category of change (tier). We use definitions and lists of EFG&S modified for Puget Sound to specifically address how changes in Puget Sound's nearshore ecosystems have altered their ability to deliver EFG&S. In a three-phase process, we used the expertise represented by PSNERP's Nearshore Science Team (NST) through a Delphi process to arrive at relative ranks for each EFG&S in each change category. Within each category (tier), relative EFG&S ranks assigned by individual NST members were scaled to comparable levels of change by a simple multiplication of these ranks times the relative percent change within each Process Unit. We used these PU impairment scores to compare the status of each SPU and DPU and generate aggregate maps scaled across each Puget Sound sub-basin as well as Sound-wide.

The resulting PSNERP Change Analysis geodatabase documents historic changes over the (current) approximately 3969 km of Puget Sound shoreline and commensurate 36,080 km2 of drainage area. Change is characterized at each of 828 process units: 812 SPU and 16 DPU. We found very few nearshore PU of Puget Sound to be unchanged, and the vast majority of the changes are due to human alterations. The most pervasive change Sound-wide is the simplification of the shoreline—reduction of SPU and DPU shoreline length. A 41 percent total decrease in delta length accounts for much of the observed simplification, along with the complete disappearance of many embayments: 67.9 percent (168) of the closed lagoons/marshes, 44.6 percent (89) of the barrier lagoons, 38.2 percent (53) of the open coastal inlets, and 36.7 percent of the barrier estuaries that existed historically have disappeared as identifiable features along Puget Sound's shoreline.

In addition to shoreline simplification, the decline in the total area of estuarine wetlands in Puget Sound represents a dramatic change in the historic occurrence in these once-prominent nearshore ecosystems. This is particularly evident in the two classes of tidal wetlands in the upper reaches—tidal freshwater and oligohaline transition—of the 16 large deltas, where 97.8 (–90.2 percent) and 54.5 km2 (–98.5 percent) have disappeared across the Puget Sound basin, respectively. Loss of 39.7 and 40.6 km2 of estuarine mixing and euryhaline unvegetated wetlands is also notable, but proportionally less, –46.4 percent and –24.4 percent, respectively. The largest overall losses in the deltas occurred in the South Central Puget Sound and Whidbey sub-basins. Estuarine wetland loss in the smaller estuaries has involved considerably less area, but has been proportionally the same: 94.8 percent and –92.0 percent in tidal freshwater and oligohaline transition, respectively. Combined (not including the euryhaline unvegetated wetlands, that cannot be estimated from historical data), more than 300 km2—equivalent to over two-thirds the area of Whidbey Island—of these vegetated estuarine wetlands no longer support Ecosystem Functions, Goods and Services to the Sound and its populace.

Shoreline alterations are now pervasive throughout the Sound; we found only 6.5 percent (54) process units had no documented changes. The shorelines of the South Central Puget Sound (98.7 percent) and Hood Canal (97.5 percent) sub-basins were the most modified; the San Juan Islands–Strait of Georgia Sub-Basin (83.1 percent) was relatively less modified. Expectedly, the number of shoreline modifications increased with size (shoreline length) of PU, with most of the PU having two to four discrete modifications, the larger PU averaging five, and several having as many as eight modifications. The most common combination of shoreline changes or stressors in individual PU included the loss of estuarine mixing wetlands, armoring, and nearshore roads, which occurred in 517 of the 828 PU (62 percent) around the Sound. Such spatial coincidence may have implications for the disruption of particular nearshore ecosystem processes (i.e., armoring associated with bluff-backed beaches may inhibit sediment delivery) or represent greater degrees of stress to the nearshore resulting from multiple, cumulative impacts.

The majority of the adjacent upland and watershed area is classified as natural land, as opposed to developed land, which includes areas of industrial, residential, and agricultural development. The ratio of developed to natural land is always higher in the adjacent upland than watershed area, reflecting the concentration of human activities along the Sound's shoreline. Predictably, the most developed areas are the PU in the urbanized Seattle, Tacoma, Olympia, and Bellingham regions. The upland and watershed areas of the South Central Sub-Basin stand out as highly impacted, while the vast majority of the Hood Canal Sub-Basin remains as natural land, with very little area categorized as >10 percent impervious surface, despite a relatively high road density in the adjacent upland.

Our scaling of these historic changes shows a wide variety, both among and within sub-regions, in the current impairment of Functions, Goods and Services provided by nearshore ecosystems at the Sound-wide scale. The more developed sub-regions (e.g., South Central, South Puget Sound, and Whidbey) and areas of the Sound, especially those containing large and highly developed deltas, demonstrate some of the highest relative impairment, most evidently for shoreform transitions and shoreline alterations. Conversely, the Strait of Juan de Fuca, San Juan Islands–Strait of Georgia, Hood Canal, and often components of South Puget Sound illustrate moderate or low relative impairment, especially from the standpoint of changes in the adjacent upland and total watershed area.

The PSNERP Change Analysis is intended to support the greater Project by informing restoration and preservation planning experts about the types, extent, and consequences of changes to Puget Sound's shoreline. Additionally, a spatial geodatabase has been designed to accommodate future updates or expansions to datasets, providing a valuable and dynamic tool to the Puget Sound nearshore management and restoration community.

Introduction

PSNERP General Investigation

This report describes the approach, analytical framework and findings of the Change Analysis conducted by the Puget Sound Nearshore Ecosystem Restoration Project (PSNERP). PSNERP was initiated in September 2001 by the Seattle District Army Corps of Engineers (Corps) as a General Investigation (GI) Study, based on a feasibility cost-sharing agreement (FCSA) between the Corps and the Washington Department of Fish and Wildlife (WDFW). The purpose of a General Investigation study is to establish a partnership between the federal government and the local sponsor to investigate water resources problems and opportunities; the product of this investigation is a Feasibility Study. The PSNERP GI is a large-scale, comprehensive initiative to protect and restore the natural processes and functions in the nearshore environments of Puget Sound. Common acronyms are defined above, and a glossary of common terms is provided as Appendix A.

Goals and Objectives

PSNERP is guided by two overarching goals: 1) protect and/or restore natural processes that create and maintain Puget Sound nearshore ecosystems, and 2) protect and/or restore ecosystem functions and structures that support valued ecosystem components.

To address these goals, the PSNERP Feasibility Study will: 1) evaluate significant degradation of nearshore ecosystems in the Puget Sound Basin; 2) formulate, evaluate, and screen potential solutions to these problems; and 3) recommend a series of actions and projects that have a federal interest and are supported by a local entity willing to provide the necessary items of local cooperation.

This focus yields results that pertain primarily to the physical structure and conditions of Puget Sound's shoreline, estuaries, and deltas, and does not address factors such as environmental contaminant impacts on nearshore ecosystems. Although this focus is largely driven by the types of actions that can be implemented under authorities of the Corps of Engineers, the PSNERP team acknowledges that there are a myriad of stressors on nearshore ecosystems and we are dedicated to planning restoration and protection in coordination with other actions that address those needs.

Project Approach & Strategy

Under the guidance of the Project's Nearshore Science Team (NST), PSNERP has focused the Project's goals to: a) concentrate on shallow-water, nearshore (i.e., marine shoreline, estuarine) ecosystems; b) emphasize the (dominantly physical) processes that create and sustain natural ecosystems; and c) include both restoration and protection strategies. The emphasis on the underlying processes that support nearshore ecosystems provides the essential scientific foundation for protecting and restoring sustainable ecosystems, rather than technological fixes or actions focused on nearshore habitats of specific species. The scientific and technical basis for this approach is documented in PSNERP guidance documents (e.g., Fresh et al. 2004; Goetz et al. 2004; Finlayson 2006; Simenstad et al. 2006) and reflects much of the emerging scientific discussion about the need to integrate the spatial structure of ecosystem process information into conservation and restoration planning (Noss 1996; Leslie 2005; Palmer 2009). For all PSNERP project guidance documentation, see: *http://www.pugetsoundnearshore.org/technical_reports.htm*.

The NST emphasis on integrating measures of nearshore ecosystems processes and stressors diverges from other approaches that focus solely on ecosystem stressors or limited "target" organisms or functions. The NST has adopted this "process-based" approach for the preliminary screening analyses because: 1) the source of many stressors originates outside nearshore environments and thus cannot be directly addressed by nearshore restoration; 2) the distribution and concentration of many stressors, such as contaminants, are not known comprehensively around Puget Sound, which prevents a Sound-wide analysis; 3) many such stressors have been targeted by federal, state. and local programs or have recently been the objective of new initiatives; and 4) we believe that an ecosystem approach will widely address many target organisms or functions of concern because protection and restoration of nearshore ecosystem processes will benefit all associated Ecosystem Functions, Goods and Services.

As a result, PSNERP is generating broad categories of Sound-wide data on historical change and stressors on nearshore ecosystems that will inform more strategic, rather than opportunistic, restoration strategies. It is unlikely that large, functioning ecosystems, such as the large deltas and complex shorelines of Puget Sound, can be effectively restored through the cumulative effects of small-scale projects, without a larger framework (Manning et al. 2006). Barriers to large-scale restoration—such as shifting baselines, the scale and complexity of restoration, and its long-term and open-ended nature—can limit planning, implementation, and long-term success (ibid). Documenting historical changes in ecosystem structure, with inferences about processes and associated functions, goods, and services, once provided by intact ecosystems, is one means to hindcasting scenarios of future desirable (restored) states (Robinson 1982, 2003; Manning et al. 2006).

Scope and Definitions

Geographic Scope

The PSNERP GI study area includes the entirety of Puget Sound and the portions of the Strait of Juan de Fuca and the Southern Strait of Georgia within the borders of the United States; data are also acquired for watershed drainage areas of Puget Sound rivers that extend into Canada (Fig. 1). The area encompasses seven sub-basins that reflect somewhat distinct domains of varying geology, tidal hydrology, physiography, and oceanography settings in Puget Sound.

Nearshore Ecosystems and Processes

Within this prescribed geographic region, PSNERP confined its focus of restoration and preservation to nearshore ecosystems, defined to occur within estuarine delta/marine shoreline, beaches and areas of shallow water from the top of the coastal bank or bluffs, and tidal waters from the head of tide to depth of the lower limit of the photic zone, about 10 m relative to Mean Lower Low Water (Fig. 2). By definition, this includes the entire shoreline within the study area as a contiguous band of diverse ecosystems shaped by coastal geomorphology and local environmental conditions, such as wave energy and salinity.

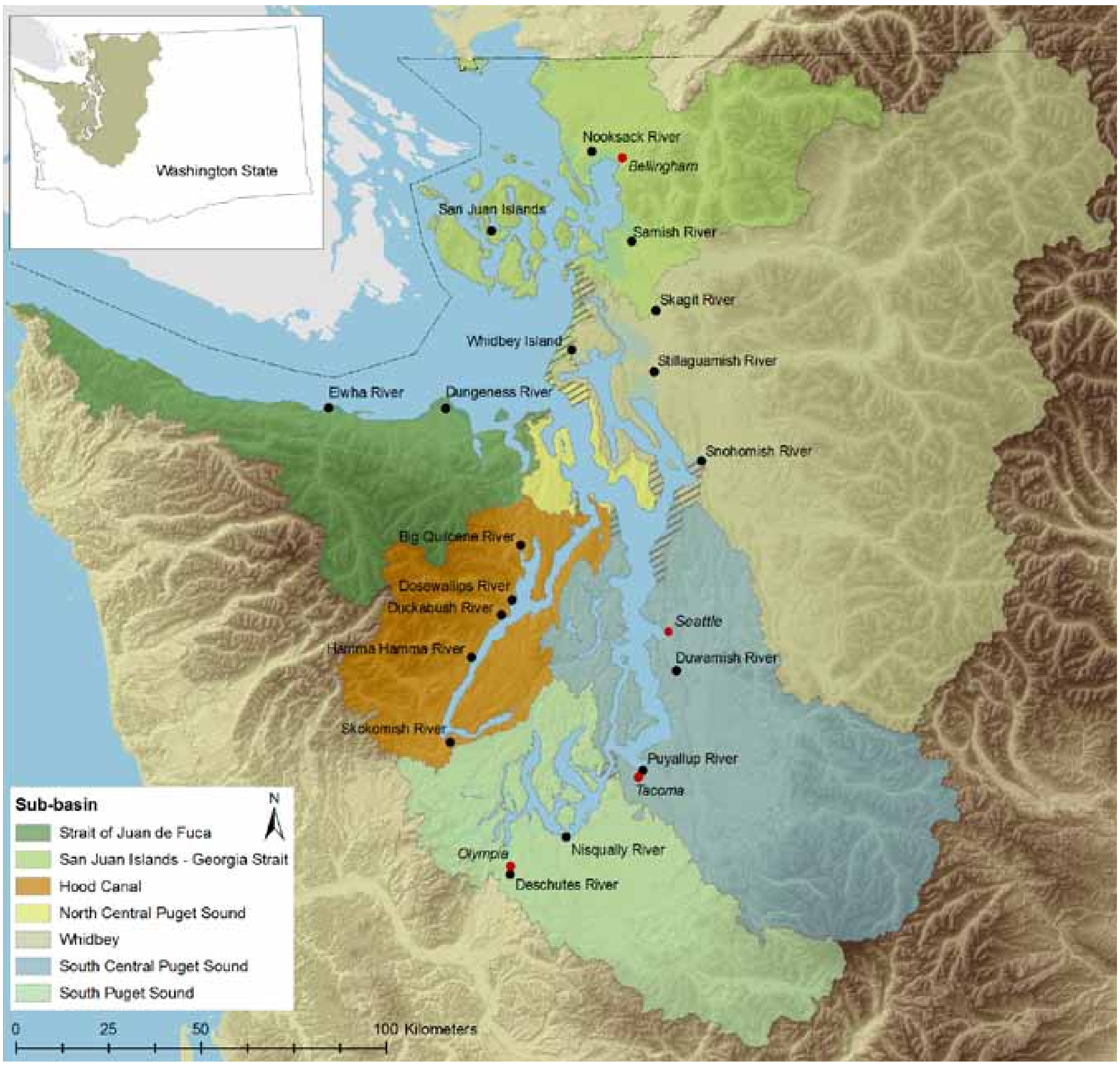


Figure 1. PSNERP study area, encompassing Puget Sound and the U.S. portion of the Strait of Juan de Fuca and Strait of Georgia. Seven physiographic sub-basins of Puget Sound are distinguished by color; cross-hatched areas represent overlapping adjacent sub-basins.

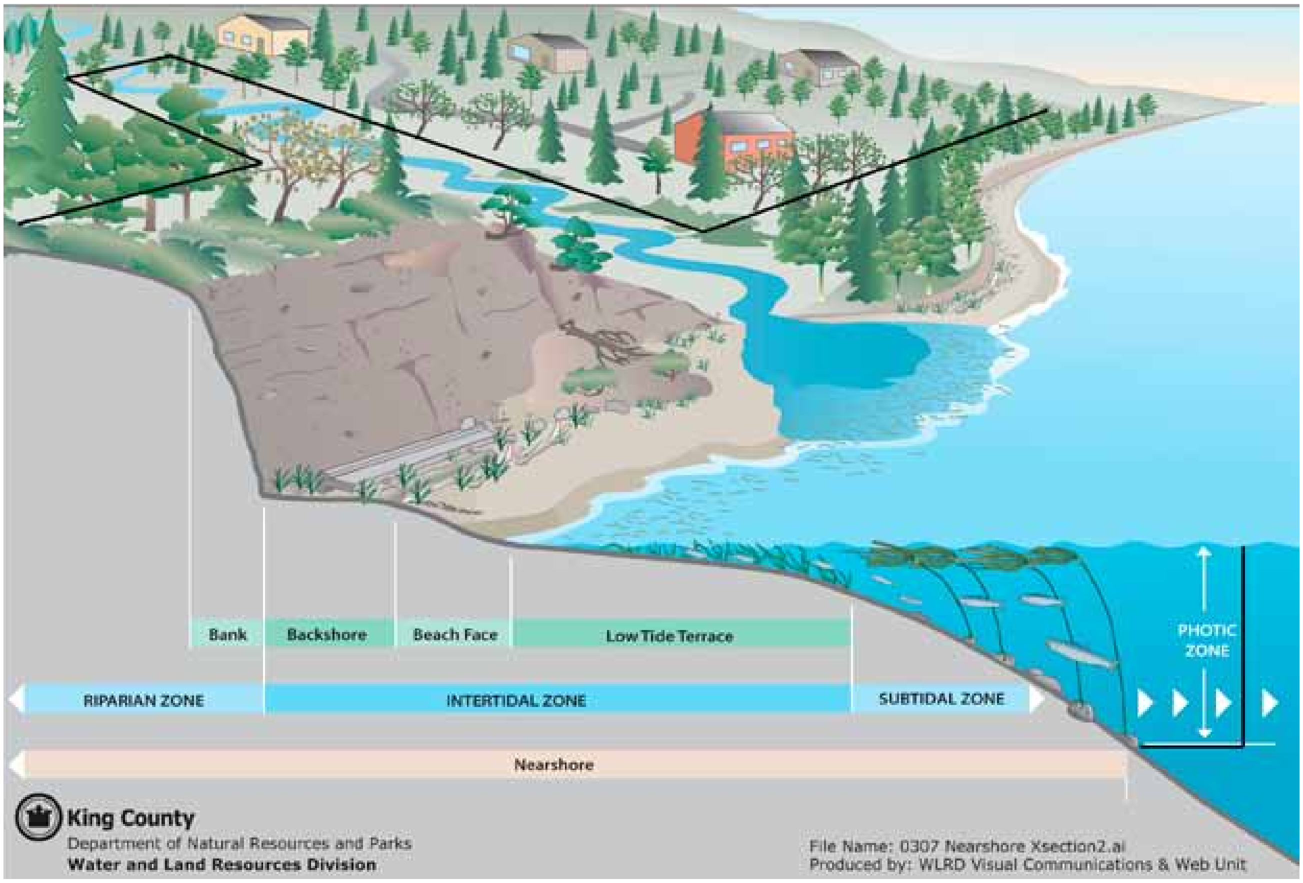


Figure 2. Boundaries of nearshore ecosystems between riparian and subtidal zones (PSNERP, after Gelfenbaum et al. 2006; modified from original by King County Department of Natural Resources and Parks).

The framework for PSNERP's analysis of restoration and preservation needs rests on linking changes in nearshore ecosystem processes to physical (structural) changes of the shore and the resulting impairment of Ecosystem Functions, Goods and Services that natural ecosystems provide. Ecosystem processes are *interactions* among physical, chemical and/or biological attributes of an ecosystem that lead to an outcome of change in character of the ecosystem and its components, i.e., changes in ecosystem *state*.

Ecosystem processes (see Appendix B) that affect the structure and function of nearshore environments, such as beaches, estuaries, and deltas of Puget Sound, vary over diverse spatial and temporal scales, from the large-scale, long-term factors (*regional influences*) that form the backdrop for *broad physiographic processes* to fine-scale, *local geochemical and ecological processes*. Regional influences include factors such as climate, wave exposure, geology, inherited physiography, sea level history, and tidal regime. The *broad physiographic processes* are those we consider landscape-forming processes, which are embedded within regional influences but can vary considerably on scales of kilometers or fractions thereof. Because of their importance in regulating the structure and dynamics of nearshore ecosystems on the scale of feasible restoration and preservation, we frame our analyses of change around the broad physiographic processes (Table 1). This table addresses processes that currently shape coastal landforms and associated ecosystems, and that do so over relatively short time frames — years or decades at the most. Regional influences such as glaciation and tectonic processes were influential in creating the landscape, but operate at time scales that have little influence over the dynamics of the modern landscape. In addition, we focused on processes that humans are able to modify; for the most part, we have neither disturbed these processes nor are we suggesting "restoring" them.

Context of Change Analysis in PSNERP Process and Components

The PSNERP Change Analysis is designed to inform the Project's restoration and preservation planning process about the types, extent and consequence of changes that have occurred to Puget Sound's shoreline. The resulting body of data and its interpretation provides the basis for the "statement of need" (Strategic Needs Assessment, Fig. 3) and ultimately planning for restoration and preservation actions defined by the GI Feasibility Report.

Table 1. Broad physiographic processes identified as important to the creation and maintenance of Puget Sound's shoreline ecosystems.

Ecosystem Process	Description
Sediment Input	• flux of sediment from bluff, stream and marine sources; depending on landscape setting, can vary in scale from acute, low frequency (hillslope mass wasting from bluffs) to chronic, high frequency (some streams and rivers)
Sediment Transport	• bedload and suspended transport of sediments and other matter by water and wind along (longshore) and across (cross-shore) shoreline
Erosion and Accretion of Sediments	• erosion (coastal retreat) of coastal bluffs and shorelines • deposition (accretion; dune formation) of sediments and mineral particulate material by water, wind and other forces • settling (accretion) of sediments and organic matter on marsh and other intertidal wetland surfaces
Tidal Flow	• localized tidal movements, differing from regional tidal regime mostly in tidal freshwater and estuarine ecosystems
Distributary Channel Migration	• combined freshwater and tidal flow that change distributary channel form and location
Tidal Channel Formation and Maintenance	• geomorphic processes, primarily tidally driven, that form and maintain tidal channel geometry • natural levee formation
Freshwater Input	• freshwater inflow from surface (streamflow) and groundwater (seepage)
Detritus Import and Export	• import and deposition of particulate (dead) organic matter • soil formation • large wood recruitment, disturbance and export
Exchange of Aquatic Organisms	• organism transport and movement driven predominantly by water (tidal, fluvial) movement
Physical Disturbance	• impact of local wind and wave energy input to the shoreline as a function of exposure • localized disturbance
Solar Incidence	• exposure, absorption and reflectance of solar radiation (e.g., radiant heat) and resulting effects

Objectives of Change Analysis

The primary objective of Change Analysis is to produce a comprehensive, spatially-explicit assessment of net changes to shorelines, estuaries, and deltas since the period of early industrial development of Puget Sound (ca. 1850s–1880s). This period became our baseline primarily because it was the timeframe of the first systematic land and water surveys, but was also coincident with the initial development of the region's shore (e.g., Prosser 1903; Chasan 1981; Klingle 2007). Because historical documentation of nearshore ecosystem processes does not exist per se, we used our conceptual model and other sources of understanding about the relationship among nearshore ecosystem processes, structures and functions (see Nearshore Ecosystems and Processes, above) to interpret the level and types of impairment of nearshore ecosystem processes based on observed physical changes to the shoreline between two snapshots in time (late 1800s and the present decade). Because even the record of physical changes is limited, this interpretation must also rely on the type, location, and extent of anthropogenic modifications that now constitute alterations of original, natural shoreline features.

Role of Change Analysis in the Project

Change Analysis provides a quantitative assessment of historical change and a qualitative interpretation of relative impairment of nearshore ecosystem processes that in turn supports the Strategic Needs Assessment of restoration and preservation needs along the breadth of the Puget Sound shoreline (Fig. 3). This analysis was not predicated on restoring Puget Sound to pre-1900s conditions. Although we have designed the Change Analysis to be a tool for planning restoration and preservation of the Sound's nearshore ecosystems, historical conditions are not necessarily appropriate or feasible goals for restoration. Returning damaged ecosystems to historical targets is often anachronistic, given the depth of human imprints and long-term legacies that may be difficult or impossible to override (Jackson and Hobbs 2009). However, historical conditions can provide valuable reference or baseline conditions from which we can

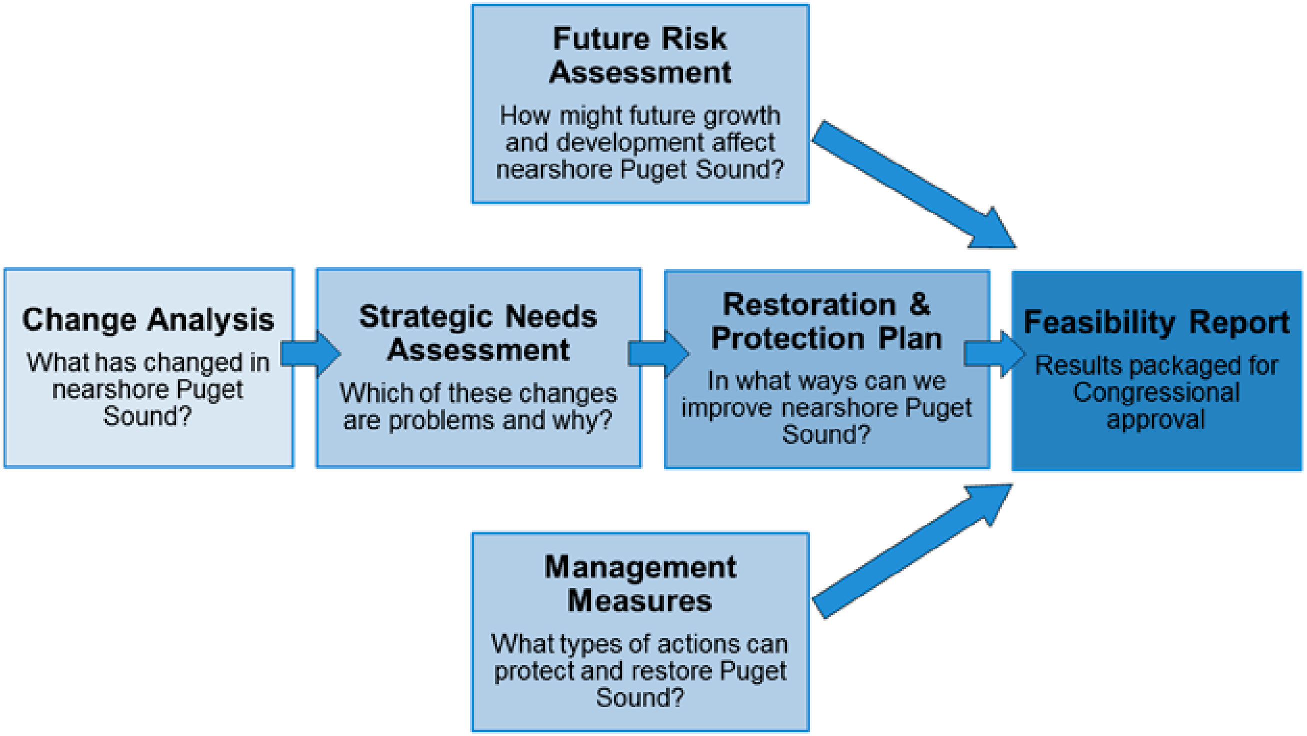


Figure 3. Relationship of Change Analysis to other components of PSNERP process to plan restoration and protection strategies for Puget Sound nearshore ecosystems.

both understand relationships among natural, functioning ecosystem processes and nearshore structure. They also help us interpret the Project's goals and objectives in the context of current constraints. Accordingly, a major objective was to identify changes to the shoreline that could ultimately be evaluated for management measures that would restore or significantly improve important nearshore ecosystem processes, preferably in conjunction with associated preservation actions.

In addition to contributing directly to the Strategic Needs Assessment, Change Analysis also provides a tractable template that could potentially aid other analyses in the PSNERP procedures to develop a restoration and preservation plan. For example, the metrics, data architecture, and impairment assessment process could be applied to the results for the Future Risk Assessment to reflect risk to proposed restoration and preservation actions of future nearshore and upland change (Fig. 3). Similarly, the Stakeholder Involvement process could be facilitated by using the relative impairment matrix as one qualitative indicator of the effect of shoreline change on Ecosystem Functions, Goods and Services that benefit human beings (see Scaling Impairment, below). While the NST did not distinguish any categories of Ecosystem Functions, Goods and Services as being more or less important than others, the ranking template would allow stakeholders to incorporate their assessment of social, cultural and economic importance and modify the Change Analysis impairment scores accordingly.

Approach

The PSNERP NST designed an analytical approach to systematically quantify historical change over the last approximately 150+ yr, between the earliest land surveys of the General Land Office and U.S. Coast and Geodetic Survey (1850s–1890s) and present conditions (2000–2006). The two timepoint data and resulting change data are documented in a geospatial template (Schlenger et al. 2009) that locates structural change and the presence and quantity of stressors on nearshore ecosystems in the context of dominant ecosystem processes. Furthermore, this template provides the mechanism to qualitatively interpret the spatially-explicit significance of these various changes and stressors in terms of the current impairment of Ecosystem Functions, Goods and Services that natural nearshore ecosystems could provide.

Methods

Concept Development

The Change Analysis was developed by the authors, based as a NST working group, and a number of collaborators from partner institutions (see Acknowledgments). We designed an analytical approach to systematically quantify historic change over the past approximately 150+ yr, between the earliest land surveys of the General Land Office (GLO) and U.S. Coast and Geodetic Survey land surveys between 1850s–1890s and present conditions (2000–2006). The historical datasets were initially developed by the Puget Sound River History Project at the University of Washington (Collins et al. 2003; Collins and Sheikh 2005), and augmented for the use of this project (Schlenger et al. 2009). Employing these initial data, a pilot project based on initial data for Washington Water Resource Inventory Area (WRIA) 9 was conducted by Fung and Davis (2005). Subsequent support of the Change Analysis has been provided by Anchor Environmental, and is described further in the Geospatial Methodology document (Schlenger et al. 2009).

Data Acquisition

The PSNERP conceptual and analytical approach (Fig. 4) expended substantial effort to locate data on historical and current conditions that met the requisite criteria of being:

1) related directly to (documented change) nearshore ecosystem processes
2) spatially explicit
3) comprehensive, complete and of uniform resolution and quality Sound-wide
4) well documented
5) in, or readily convertible, to GIS format

Documentable change was based on the comparison of historical shoreform classification and estuarine wetland delineations developed from GLO, T- and H-sheet surveys (1852–1926) with contemporary (ca 2000–2006) shoreform (Fig. 4 #1) and anthropogenic features present along Puget Sound's shoreline (Fig. 4 #3). Georeferenced spatial data from the GLO and T-sheet survey were used to characterize and delineate historic estuarine wetlands, T-sheet data were used to classify shoreline structure (see below), and H-sheets were used to delineate delta features that were missing from the other sources. Details for the methods associated with these spatial analyses are described in Schlenger et al. (2009), and can be further found in Collins et al. 2003, Collins and Sheikh (2005), and with further descriptions, examples and metadata for development of the GLO (*http://riverhistory.ess.washington.edu/glo.php*) and T-sheet geodatabases at the University of Washington's Puget Sound River History Project, *http://riverhistory.ess.washington.edu/research/data/sps_nad83/mega_t_metadata_html/*).

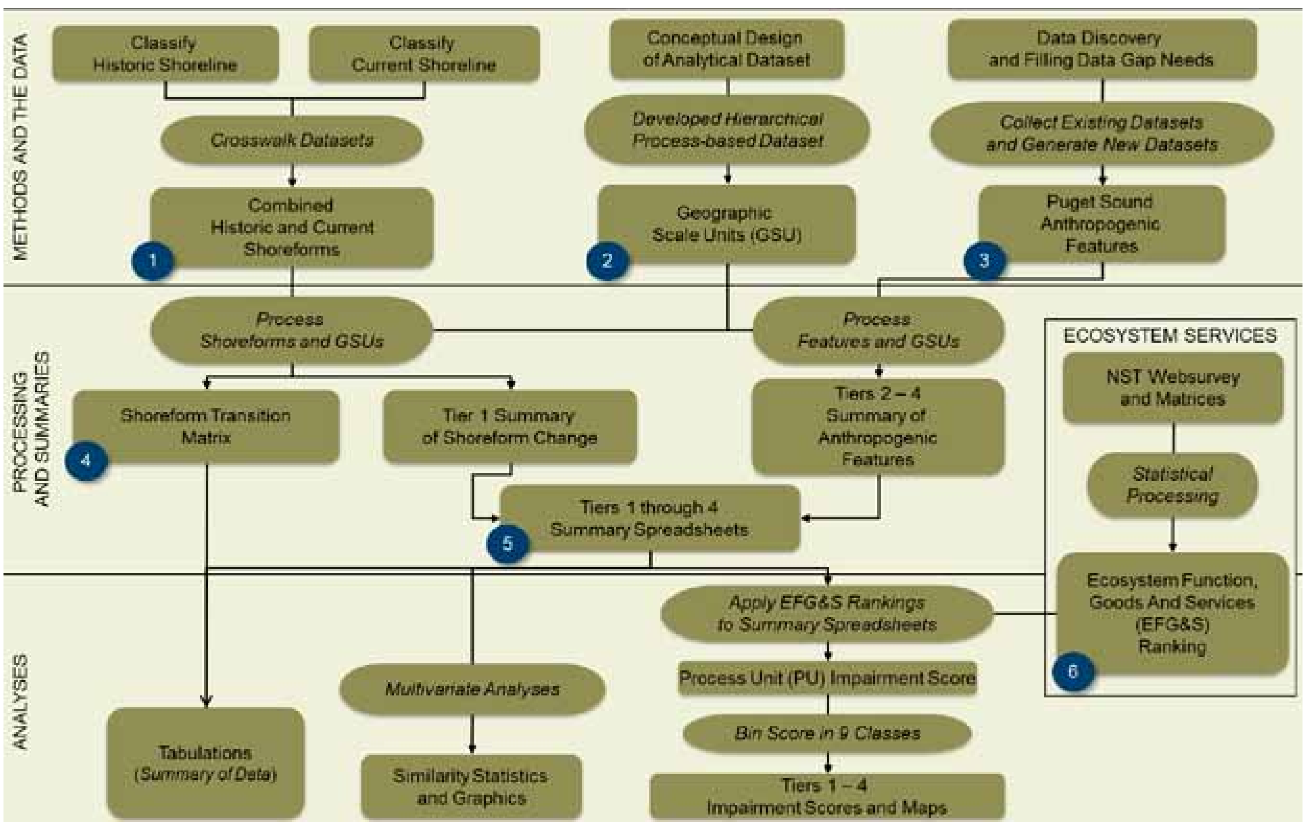


Figure 4. Flowchart of the analytical process for PSNERP Change Analysis. Numbers refer to specific text references.

In all cases, for both historical and current data, we adhered to maximum uniformity in spatial data that was mappable over the entire Puget Sound shoreline. Thus, our historical analysis was confined to these datasets by our need to characterize the structure of the entire shoreline of Puget Sound with spatially-explicit data; while other historical accounts from early explorers and pioneers provide further insight, they did not provide spatially-explicit information or comprehensive information for all of Puget Sound.

Extensive data discovery was required on the part of the NST Change Analysis Working Group and support contractors (Anchor Environmental QEA, L.L.C. 2008). Although several datasets that were considered desirable for inclusion in Change Analysis were evaluated, many (e.g., nearshore dredging) had to be rejected because they did not meet the evaluation criteria. In cases where contemporary datasets were not spatially complete and otherwise met the criteria, PSNERP partners (e.g., Salmon and Steelhead Habitat Inventory and Assessment Program, SSHIAP) or contractors (i.e., Anchor QEA) acquired data for the required spatial extent and integrated it into the project.

Data Architecture

The NST's analytical template underlying the Change Analysis is based on the spatial arrangement of the dominant ecosystem processes along Puget Sound's beaches, estuaries, and river deltas. In order to meet this need for a spatially-explicit accounting of changes to Sound-wide nearshore ecosystem processes, we delineated the Puget Sound shoreline into broad geomorphic features or coastal landforms (hereafter referred to as "shoreforms") that occur on the scale of hundreds to thousands of meters in scale, such as coastal bluffs, estuaries, barrier beaches, or river deltas. Because shorelines with the glacial history such as Puget Sound's have not been systematically classified elsewhere, we adopted the PSNERP Geomorphic Classification (Shipman 2008) (Table 2).

This classification system provided us with the basis for independently and consistently classifying historical and current shoreforms (Fig. 4 #1) that reflect varying sedimentation processes (beaches) and freshwater inflow and tidal mixing (large estuaries/deltas) as the dominant controlling factors.

The Puget Sound geomorphic shoreforms became one of the primary units in a geospatial hierarchy of data organized in four Geographic Scale Units (GSUs; Fig. 4 #2):

1) shoreforms
2) shoreline drainage units
3) process units (drift cell or delta hydrogeomorphic components)
4) various larger ("user defined") scales of shoreline-delta organization, such as large embayments or sub-basins of Puget Sound.

The hierarchy is structured upon two prominent processes that structure Puget Sound's nearshore ecosystems: littoral sediment drift along the shoreline and tidal hydrology and mixing with fluvial inflow in large estuaries and deltas. The primary analytical GSUs are Shoreline Process Units (SPU) and Delta Process Units (DPU), respectively. Shoreline Process Units (SPU) are areas associated with individual littoral drift cells that consider the "compartmentalization" of sediment delivery and transport along the shore, but also include the adjacent upland drainage area. A drift cell, or littoral cell, is a length of beach within which longshore sediment transport is confined to "along- shore transport of sediment, in both the swash- backwash zone and the surf zone, under the influence of wave refraction" (Schwartz 1986). Drift cells will typically include sediment sources, sediment sinks, and transport segments; two adjacent drift cells will often share a common sediment source (referred to as a divergence zone, DZ).

The coastal marine drift cell concept and resulting mapping methodology, often attributed initially to Stapor (1971) (Lowry and Carter 1981), has been applied extensively to characterizing the cellular structure of marine coast and large lake shorelines (e.g., Clayton 1980; Stapor Jr. and May 1983; Chrzastowski et al. 1994; Bray et al. 1995), and has since become a major tool in shoreline management planning where different geomorphological states of the coastline are distinguished by distinct fauna and ecological functions (Valesini et al. 2003; Cooper and Pontee 2006). Drift cells and, to some degree, sediment transport rates, have been cumulatively mapped for the inland sea shorelines of Puget Sound (Keuler 1979; Jacobsen 1980; Chrzastowski 1982; Blankenship 1983; Harp 1983; Hatfield 1983; Taggart 1984; Bubnick 1986; Wallace 1988), resulting in one of the exceptional examples of drift cell characterization along extensive lengths of shoreline (Rosenfield et al. 1991; Bray et al. 1995). Thus, the SPU is composed of a sediment transport zone and adjacent divergence and convergence zones, or areas of no appreciable drift. The DPU is characterized by the large riverine drainages and associated deltas that encompass varying salinity and flooding regimes (Fig. 5), both of which we believe capture the appropriate scales, structures, and processes of Puget Sound's nearshore ecosystems.

Commensurate with our intent to capture the full spatial and temporal scale of nearshore processes, we specifically decided to incorporate into the geospatial data structure the natural continuity, scale, and variation of processes that were compartmentalized in the process units. Specifically, SPU may overlap one another at littoral cell divergence, convergence zones, or no appreciable drift, and SPU and DPU may overlap at the outer (Sound-ward) margins of deltas where riverine deposition was concurrent with littoral cells that were actively transporting sediment (see areas of overlap, Fig. 5). Although this might result in some "double counting" confusion, where process units and their associated attributes (e.g., process unit length) should not be

Table 2. Geomorphic units, including systems, shoreforms (landforms) and components of Puget Sound shorelines; landforms do not necessarily include all potential components (adapted from Shipman 2008).

Systems	Shoreforms	Components
Beaches -- Shorelines consisting of loose sediment and under the influence of wave action	Bluffs -- Formed by landward retreat of the shoreline	Bluff face Backshore Beach face Low tide terrace
	Barriers -- Formed where sediment accumulates seaward of earlier shoreline	Backshore Beach face Low tide terrace
Rocky Coast -- Resistant bedrock with limited upland erosion	Plunging -- Rocky shores with no erosion/deposition and no erosional bench or platform	Cliff/slope
	Platform -- Wave-eroded platform/ramp, but no beach	Cliff Ramp/platform
	Pocket Beaches -- Isolated beaches contained by rocky headlands	Cliff Backshore Beachface Low tide terrace
Embayments -- Protected from wave action by small size and sheltered configuration	Open Coastal Inlets -- Small inlets protected from wave action by their small size or shape, but not significantly enclosed by a barrier beach	Stream delta Tide flats Salt marsh Channels
	Barrier estuaries -- Tidal inlet largely isolated by a barrier beach and with a significant input of freshwater from a stream or upland drainage	Stream delta Tide flats Salt marsh Channels Tidal delta
	Barrier lagoons -- Tidal inlet largely isolated by a barrier beach and with no significant input of freshwater	Tide flats Salt marsh Channels Tidal delta
	Closed lagoons and marshes -- Back-barrier wetlands with no surface connection to the Sound	Salt marsh Pond or lake
River Deltas -- Long-term deposition of fluvial sediment at river mouths	River-dominated deltas Wave-dominated deltas Tide-dominated deltas Fan deltas	Alluvial floodplain Tidal floodplain Salt marsh Tide flats Subtidal flats Distributary channels Tidal channels

added if the desire is to know the absolute or proportional distribution of an attribute, the NST preferred to capture the continuum of hydrological, physical, and ecological process among these physiographic units of the Sound's shoreline. Accordingly, in providing the following summaries, we specifically noted where process units overlap or have eliminated potential double-counting where feasible.

The boundary of a PU encompasses the upland drainage (catchment) area(s) and extends from shore to the 10-m depth contour (NAVD88), referred to as the aquatic zone (Fig. 6). These zones provided the spatial framework (Tiers) to summarize change and provide interpreted categories of impairments for each PU. A PU comprises three additional geographic scales: shoreforms as linear features, adjacent upland zones (within 200 meters of shoreline), and drainage units (DUs) as area features. A single PU may include in a nested structure of one or more shoreform types and one or more drainage units, all associated with a single drift cell unit. Thus, data on nearshore ecosystem changes could be assessed at various geospatial scales. The NST chose to compile and compare the Change Analysis data by the seven Puget Sound sub-basins (Fig. 1).

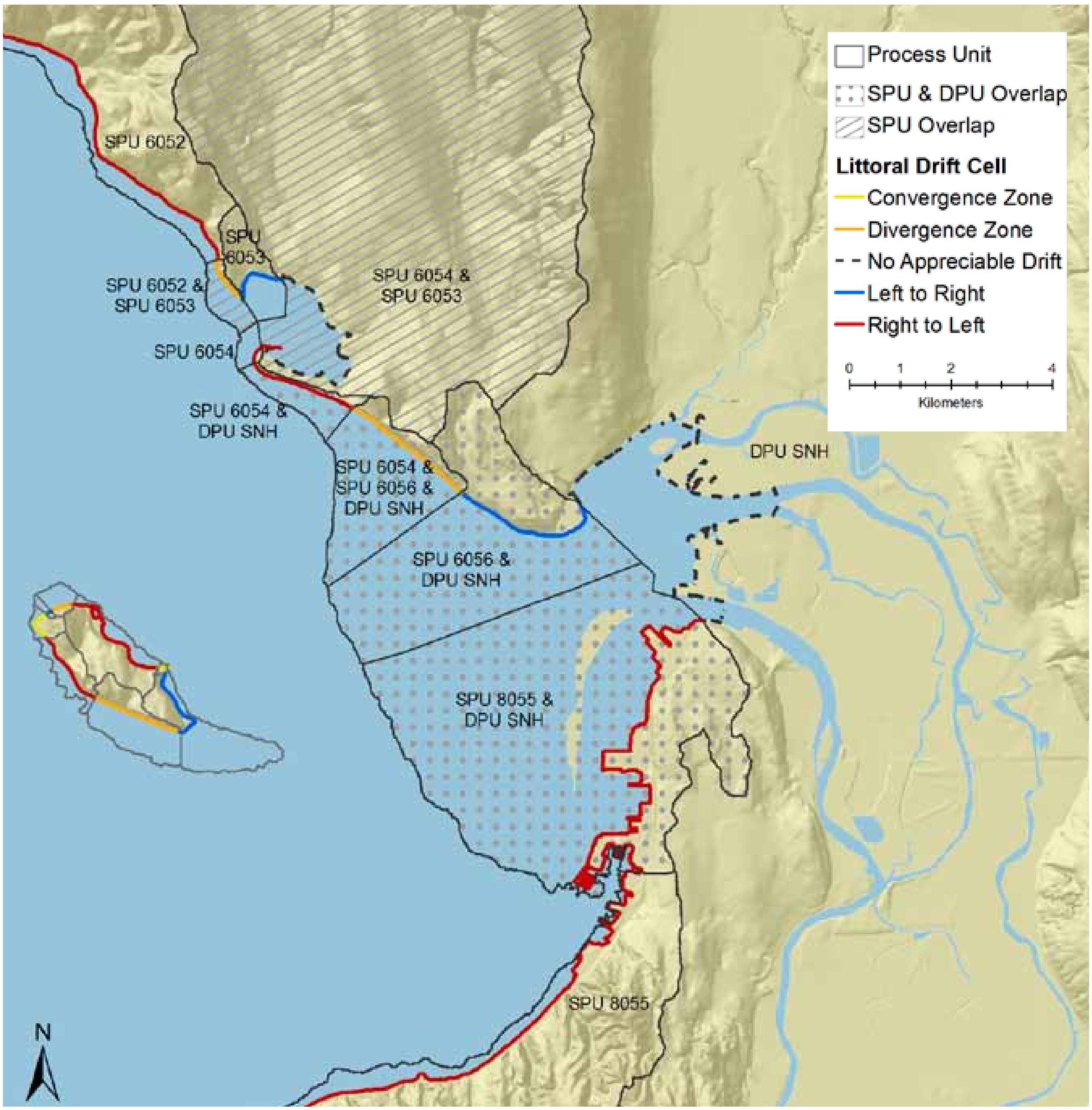


Figure 5. Example of PSNERP geographic scale units (GSU) for shoreline process unit (SPU), delta process unit (DPU), and components of littoral drift cells (Drift Cell Type), for which directional drift is viewed shoreward, at the Snohomish River estuary. Note drift cell component types where the SPU and DPU overlap (stippling), and where SPU 6053 overlaps with SPU 6054 (cross-4 hatching) where there is No Appreciable Drift.

Assessing Change

Historical change was tabulated and illustrated in a variety of analytical outputs at the individual PU level and summarized within Puget Sound sub-basins, among sub-basins, and Sound-wide (Fig. 4 #4&#5).

Tiers of Change

Historical change was analyzed for each PU in Puget Sound, and at the PSNERP sub-basin scale, in four categories, also referred to as "tiers" (Fig. 7):

- Shoreform Transition (Tier 1): changes from one shoreform type to another
- Shoreline Alteration (Tier 2): changes in historical attributes, such as wetlands, or presence and dimensions of anthropogenic modifications (considered "stressors") along the shoreline
- Adjacent Upland Change (Tier 3): anthropogenic changes as suggested by current land use/land cover within 200-m[1] of the adjacent uplands
- Watershed Change (Tier 4): anthropogenic changes as suggested by current land use/land cover in the drainage area

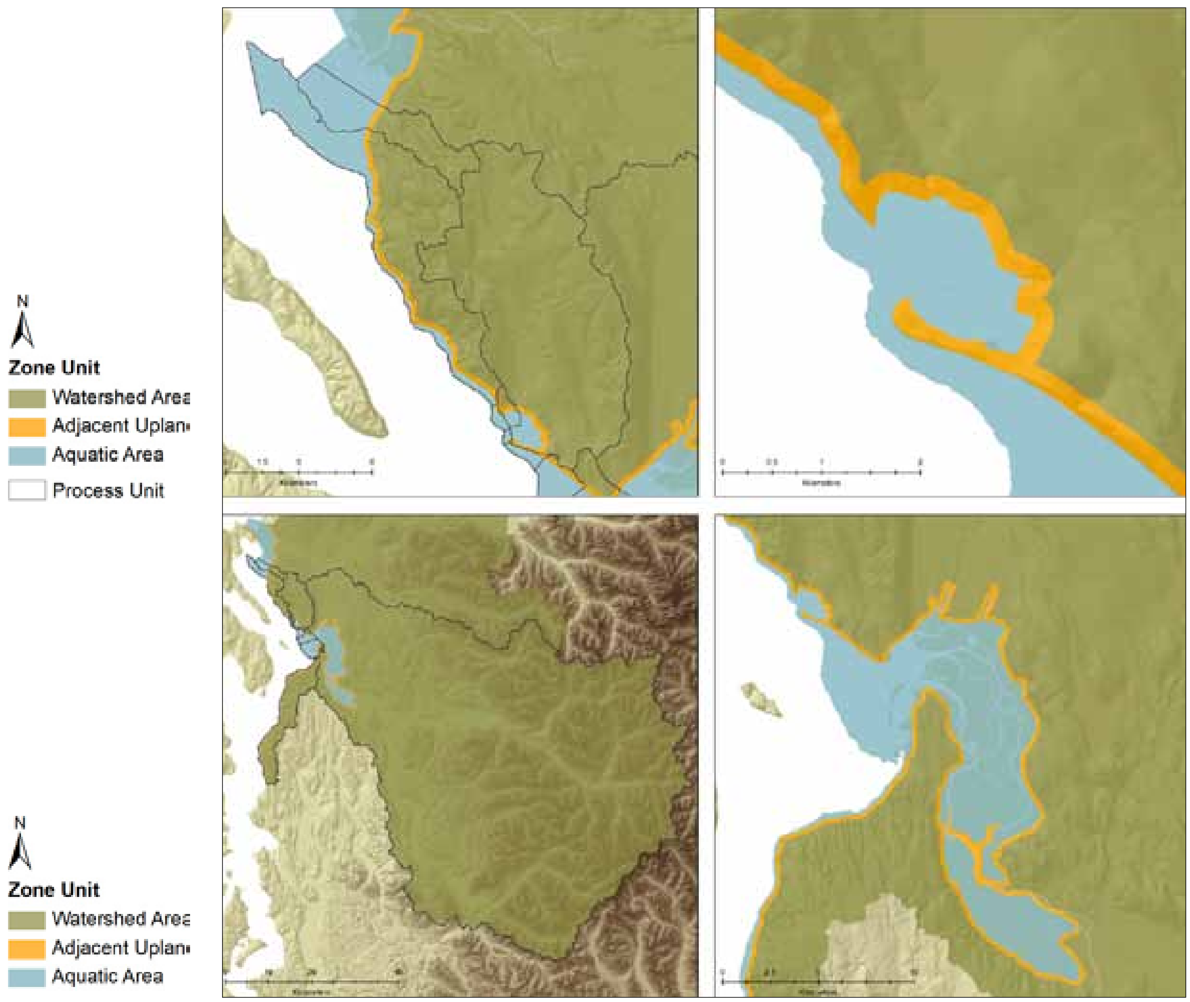


Figure 6. Zone unit delineation for shoreline process units (SPU, top) and delta process units (DPU, bottom). In SPU, the Aquatic zone is the area from the Shorezone Shoreline out to the 10-m bathymetric contour. In DPU, the Aquatic zone is the area from the outer landward boundary of historic intertidal wetlands out to the 10-m bathymetric contour. In most cases, the Shorezone shoreline and the outer landward boundary of the intertidal wetlands were not coincident.

[1] The 200 m width of the Nearshore Zone was determined from LiDAR imagery as the maximum distance from the shoreline to the top of the largest bluffs along the Puget Sound.

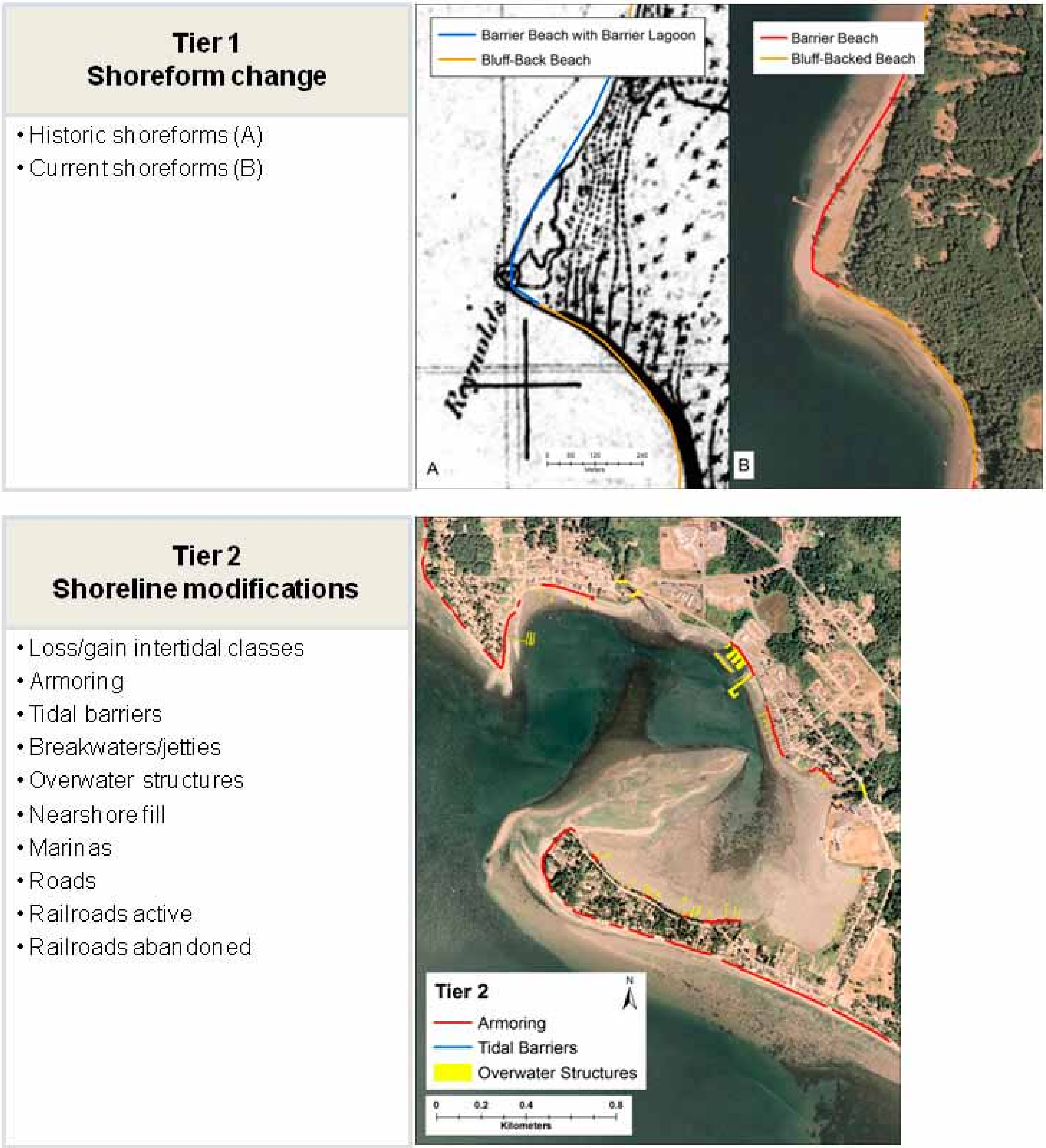


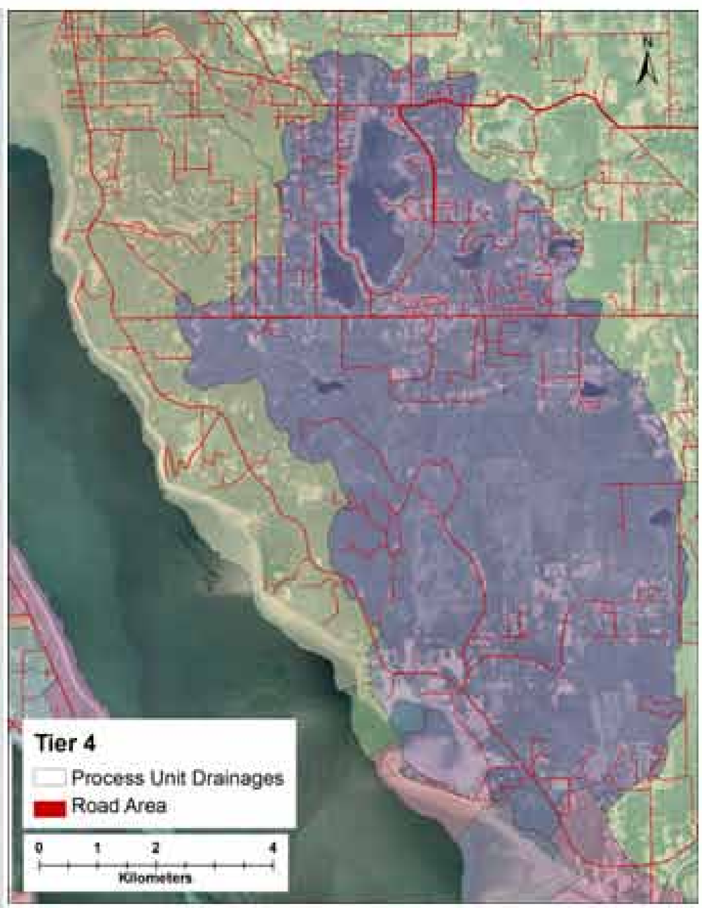
Figure 7. Four categories (tiers) and associated metrics used to describe nearshore ecosystem change by PSNERP: a) Tier 1—shoreform change or "transition" and Tier 2—shoreline alterations, and b) Tier 3—adjacent upland modifications, and Tier 4—watershed area modifications.

Tier 3
Nearshore Zone modifications

- Roads
- Railroads active
- Railroads abandoned
- Land cover
- Impervious surface

Tier 4
Drainage Area modifications

- Roads
- Railroads active
- Railroads abandoned
- Land cover
- Impervious surface
- Impounded drainage area (dams)
- Change in drainage extent



For each of the four tiers, the documented changes among SPU and DPU were standardized (e.g., to relative percent) using shoreline length or area based on the aquatic zone and two upland zones (adjacent and watershed). Although some concern is warranted when comparing line features, such as shoreline length, generated from different historical and current mapping scales (1:10,000 and 1:24,000, respectively), we believe that standardization by the proportion of the total process unit shoreline minimizes potential bias.

The NST determined that, at the Change Analysis stage of the PSNERP restoration/preservation planning, none of these categories or "tiers" of changes should be considered more important than any other in terms of impairment or loss of nearshore ecosystem function. However, it is important to recognize that a transition (change in shoreform) or elimination (e.g., anthropogenic artificial structure such as fill) of a shoreform (Tier 1 shoreform transition) is a dramatic change in nearshore ecosystem composition, especially when a natural shoreform is converted to an artificial or unrecognizable shoreform. Artificial shorelines are areas where the shape and location of the shoreline has changed so significantly due to dredging or fill that it is no longer recognizable as a shoreform defined by Shipman (2009). Artificial shorelines are typically heavily armored throughout the intertidal zone; therefore, the intertidal substrate provided is either large riprap (rock) or a vertical seawall of concrete or wood. These shorelines are also steeply sloped, which reduces the width of the intertidal area. Shoreline alterations (Tier 2) represent many of the potential candidates for nearshore restoration by PSNERP. Conversely, changes that have occurred in the Nearshore Zone (Tier 3, adjacent upland) or the entire Drainage Area (Tier 4, local watershed of process unit) may have major impacts to nearshore ecosystems and processes, but may be significant more for their potential constraints on the long-term effectiveness of nearshore restoration or preservation actions.

We quantified and mapped shoreform transitions (Tier 1) between natural shoreform types and between natural and artificial shoreforms for each PU (Fig. 8). Shoreline alterations (Tier 2) were documented quantitatively as percent of linear shoreline length for linear features (e.g., shoreline armoring, tidal barriers[2]) or area of aquatic zone for area features (e.g., overwater structures) (Fig. 9).

[2]Change in tidal barriers (i.e., dikes, embankments and other man-made features that eliminate or extensively restrict tidal inundation of former tidal wetlands) was measured as the length of the feature, although the actual area of historical wetland now restricted from tidal inundation is perhaps a superior measure, but was not available at the time of compiling the Change Analysis data. However, changes in tidal wetlands, also documented as Tier 2 change, capture that scale of effect.

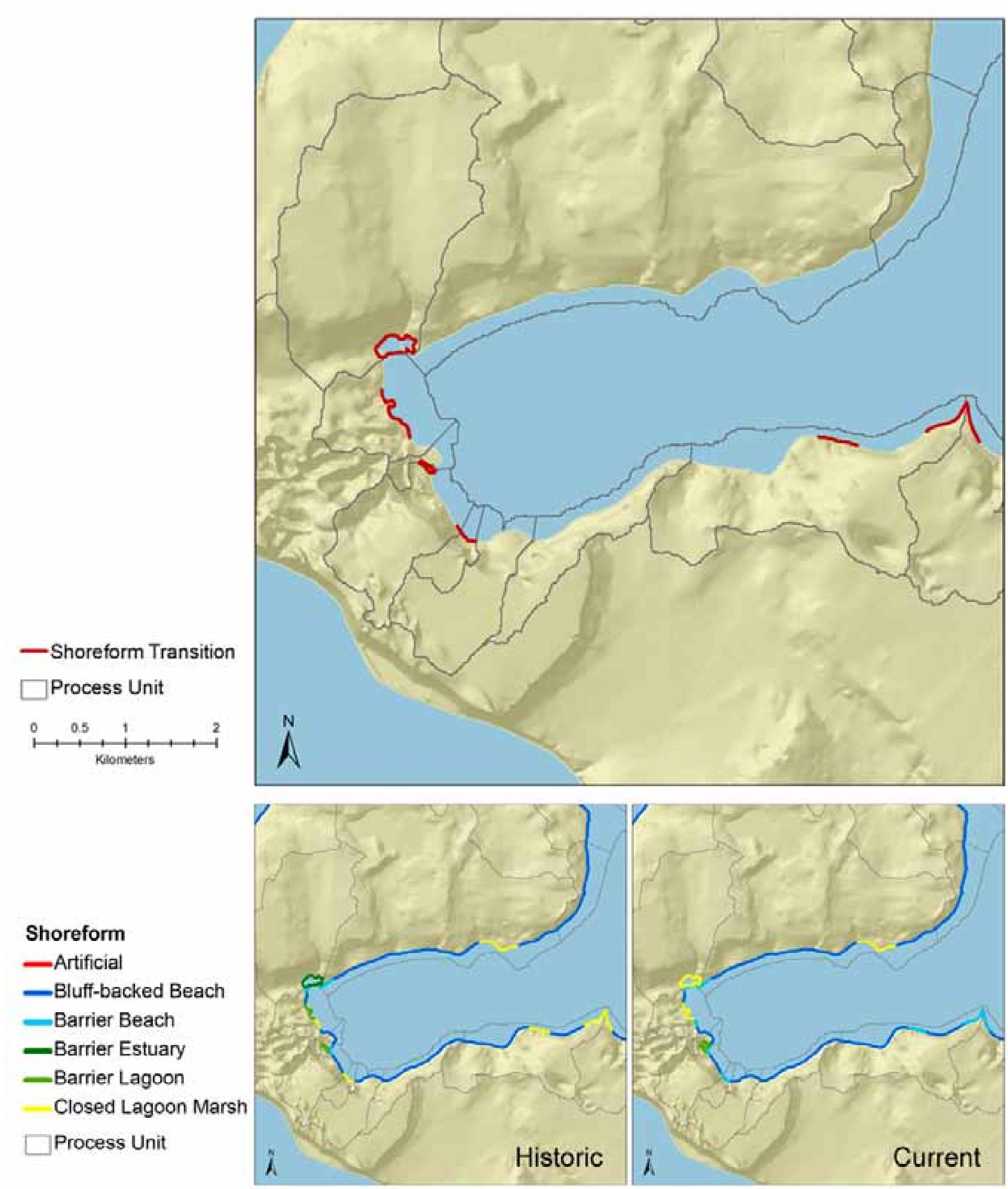


Figure 8. Example of shoreform transitions mapped for a segment (Penn Cove, Whidbey Island) of the Whidbey Sub-Basin (above); shoreform type historically (left) and currently (right) shown below.

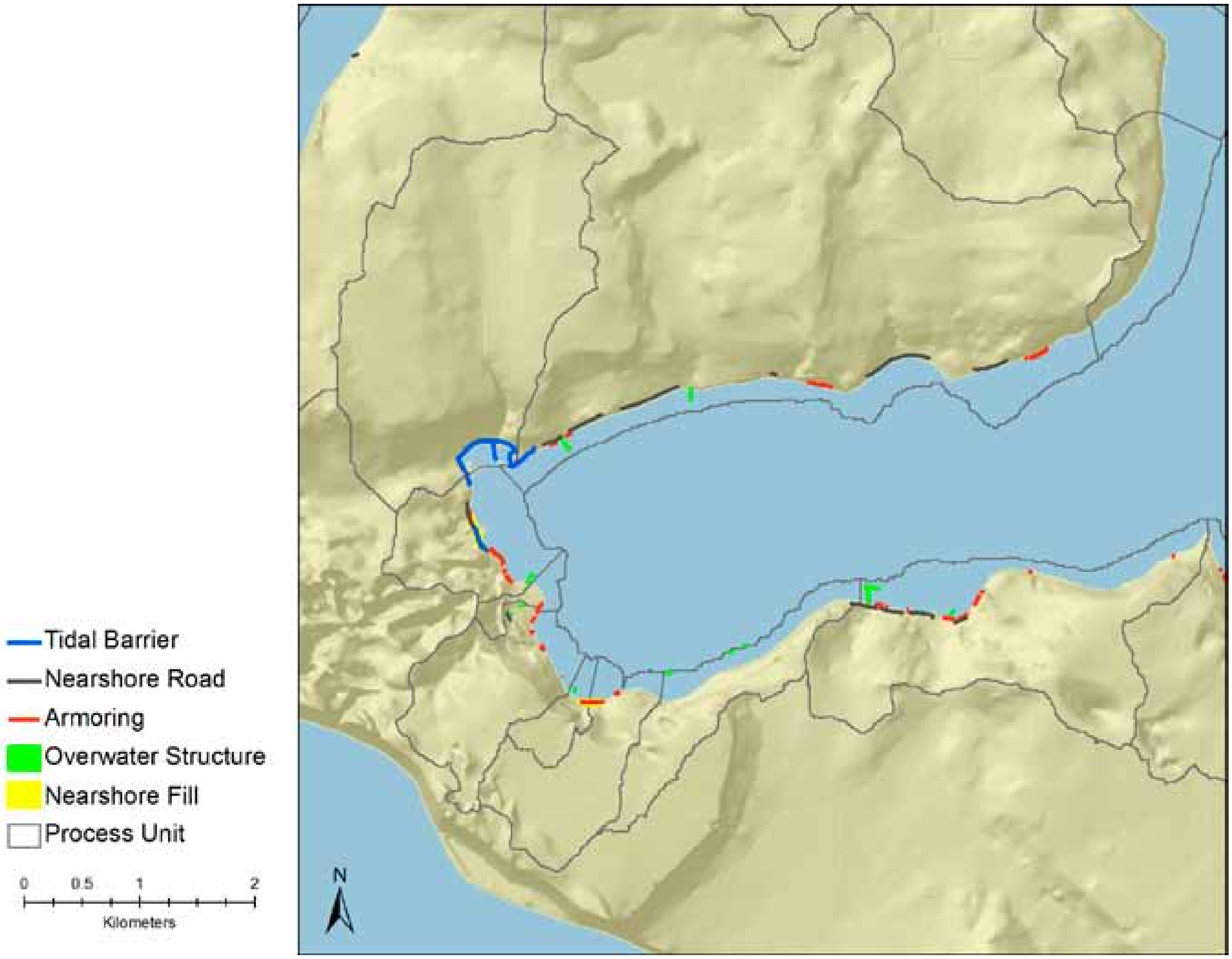


Figure 9. Examples of shoreline alterations (Tier 2) changes mapped for a segment (Penn Cove, Whidbey Island) of the Whidbey Sub-Basin; other features not shown, but analyzed in this category of the Change Analysis included nearshore railroads (active and abandoned), marinas, breakwaters/jetties, and percent change in wetland classes.

Additionally, we documented changes in type and occurrence of historical to current estuarine wetlands (Fig. 10). Because of the limited interpretation of their symbology, estuarine wetlands were classified into four broad categories that could be interpreted from the historic T-sheets: 1) euryhaline unvegetated (high salinity [>18 psu] mudflats, sandflats), 2) estuarine mixing (mid-salinity [5–18 psu] emergent marsh), 3) oligohaline transition (low salinity-brackish [0.5-5psu] scrub-shrub wetlands), and 4) tidal freshwater (salinity <0.5 psu; tidal freshwater forested swamps). In addition, euryhaline unvegetated wetlands could only be delineated for the DPU (where we used the historic H-sheet data) because the deeper edge of mud- and sandflats was inconsistent for the SPU (Schlenger et al. 2009). Changes in adjacent land cover/land use of upland (Tier 3) and watershed area (Tier 4) were based on proportion of area within an individual PU (Fig. 11).

Multivariate Analysis

The diversity, permutations and magnitudes of changes along the beaches, estuaries, and deltas vary amazingly across Puget Sound. It would be almost bewildering without some systematic organization to sort out how and where the structure, types, and magnitudes of changes in PU are comparable. In order to organize these diverse changes, relate their occurrence and the implications to desired nearshore functions, and categorize the types, magnitude, and management measures that would need to be addressed for restoration and conservation, we chose to quantitatively classify or group the process units into more convenient categories. For each type (tier) of nearshore change, we conducted a sequence of multivariate analyses to group the PU by their compositions (percentages) of shoreform types (Tier 1), nearshore alterations (Tier 2), and land cover and land use in adjacent upland and watershed areas (tiers 3 and 4).

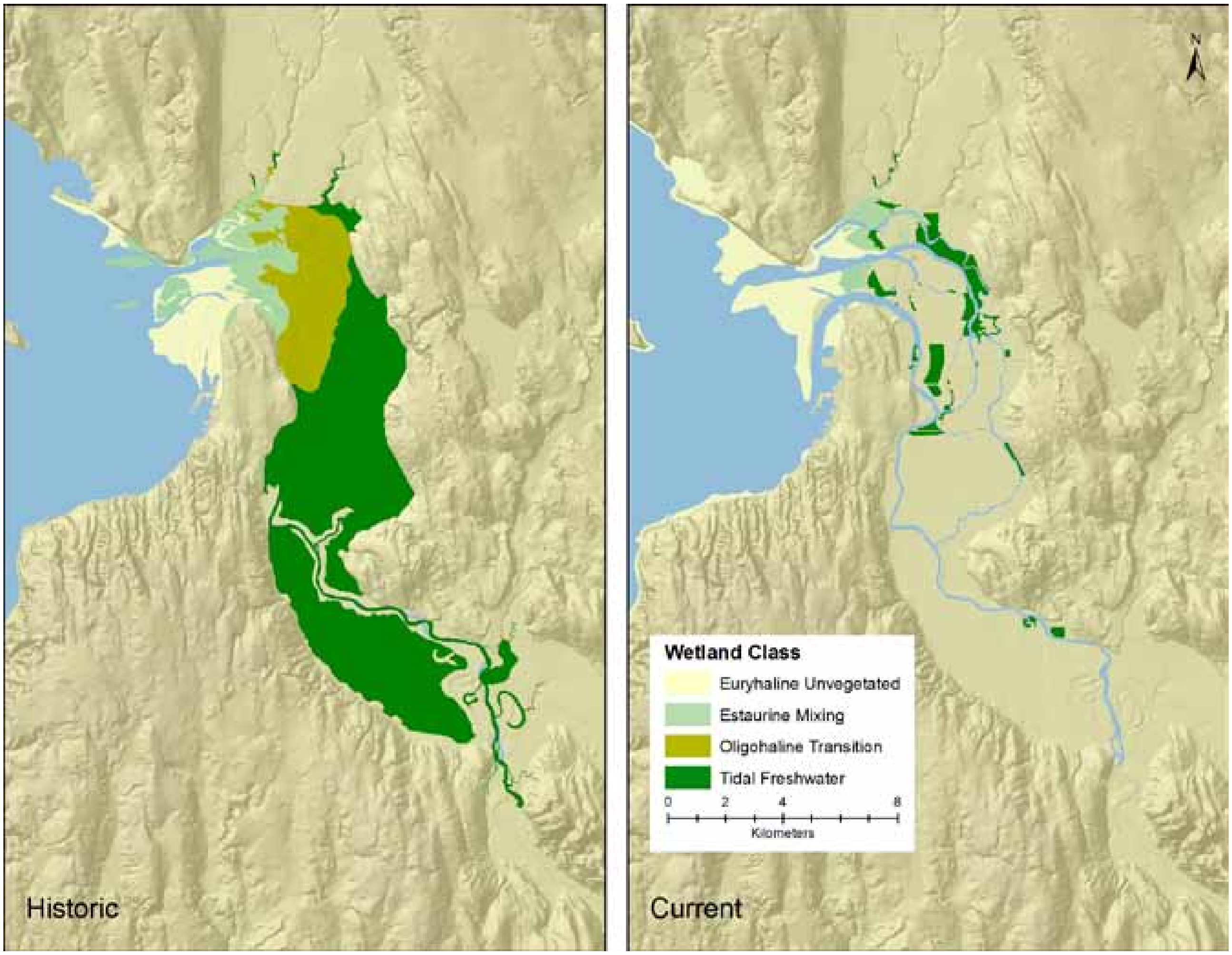


Figure 10. Examples of changes in wetland classes from historical to current conditions in the Snohomish River delta.

To perform this "grouping," we used several multivariate analysis tools to organize nearshore ecosystem change (e.g., groups of PU having similar shoreform compositions or types or types and magnitudes of change) into statistically distinct categories. All statistical analyses were performed using the PRIMER v6.0 multivariate statistics analysis package (Clarke and Gorley 2006). These analytical tools, and the PRIMER package in particular, are used extensively in applied ecology and other scientific inquiries where the degree of similarity in organization of multivariate data (e.g., species, ecosystem attributes) is of interest. Similar multivariate techniques have been used by Valesini et al. (2010) and Edgar et al. (2000) in their analyses of large-scale habitat classifications of estuaries.

Cluster Analysis

We initially performed hierarchical clustering based on the Bray-Curtis resemblance matrix to separate PU into distinct groups. The output is a dendrogram, or tree diagram, displaying the grouping of samples (usually) into successively smaller numbers of clusters, of ever-larger size, as the threshold level of similarity at which two groups are considered to merge into one is steadily decreased (see example for shoreline alterations [Tier 2] from South Puget Sound Sub-Basin, Fig. 12). Because these groups are reflected in subsequent data displays (Non-Metric Multidimensional Scaling, SIMPER), we have not included the individual dendrograms in this report.

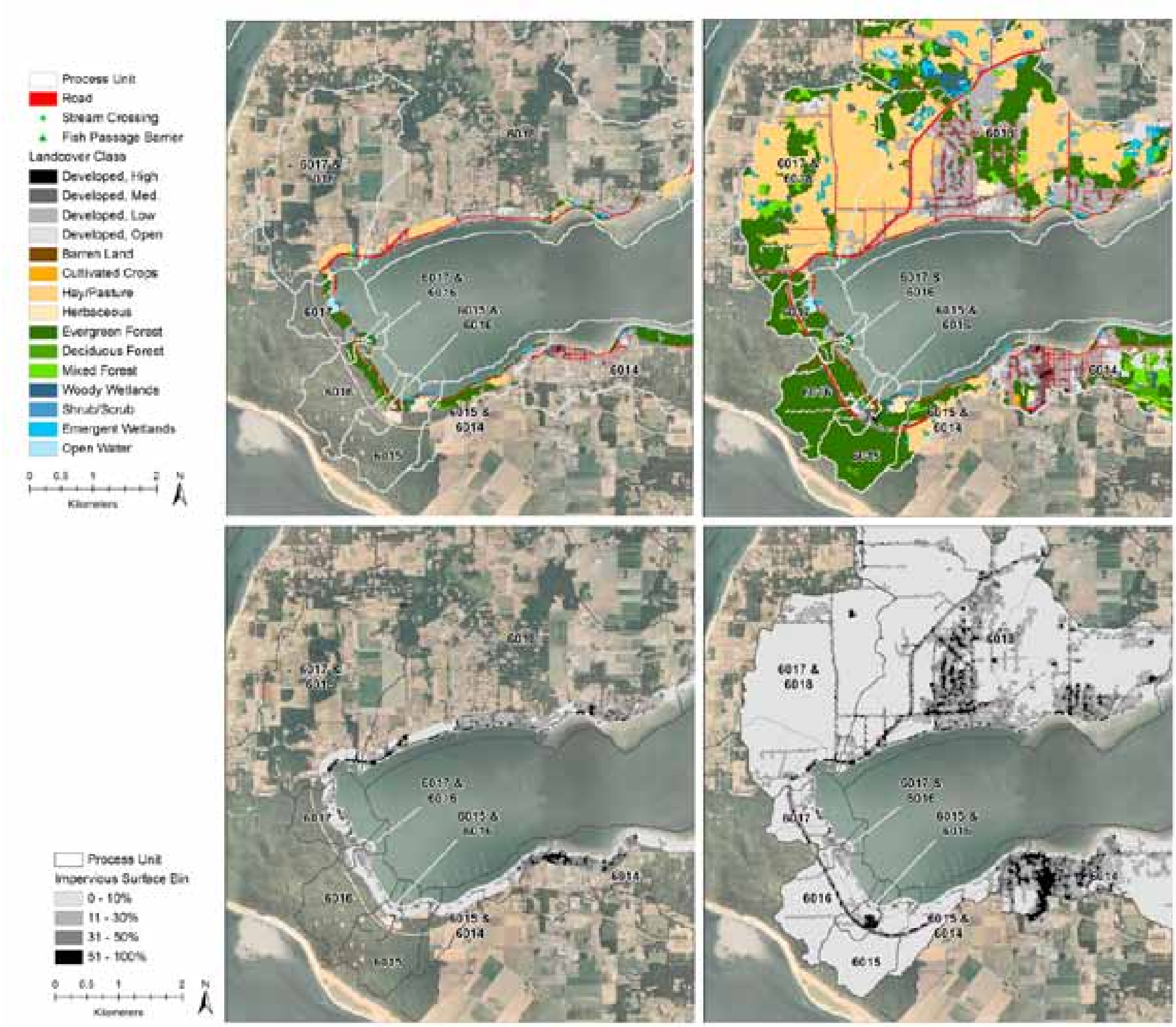


Figure 11. Examples of land cover/land use and anthropogenic features/stressors in the adjacent upland area (left) and the watershed area (right) for a region (Penn Cove, Whidbey Island) of the Whidbey Sub-Basin. Features analyzed in the Change Analysis but not shown here include: railroads (active and abandoned), dam locations (Tier 4 only), impounded drainage area (Tier 4 only), and percent change of historic drainage area (Tier 4 only).

We used the Bray-Curtis similarity coefficient as opposed to more strict distance measurements such as Euclidean. Bray-Curtis was a preferred technique for our dataset due to the following: 1) all values were in percentages (same scale), 2) all values were positive, and 3) there were many zero values with zero playing a special role. Thus, a more community-based measurement was required, differing from most environmental datasets that measure continuous variables across different scales (e.g. temperature, dissolved oxygen). Data was square root (SQRT) transformed before analysis, as is suitable for percentage data.

Similarity Profile Permutation

We used the "Similarity Profile" permutation test (SIMPROF) to identify statistically similar clusters or groups among all samples (samples in that group appear to show evidence of multivariate pattern). Significant groups resulting from the test are color coded in the dendrogram. If more than nine significant groups were identified, we decreased the threshold level of similarity so that some groups would merge and we would retain at most nine significant groups. We chose nine groups based on principles of information theory, that the number of separate bits of multidimensional information that people can keep straight is 7±2 (Miller 1956).

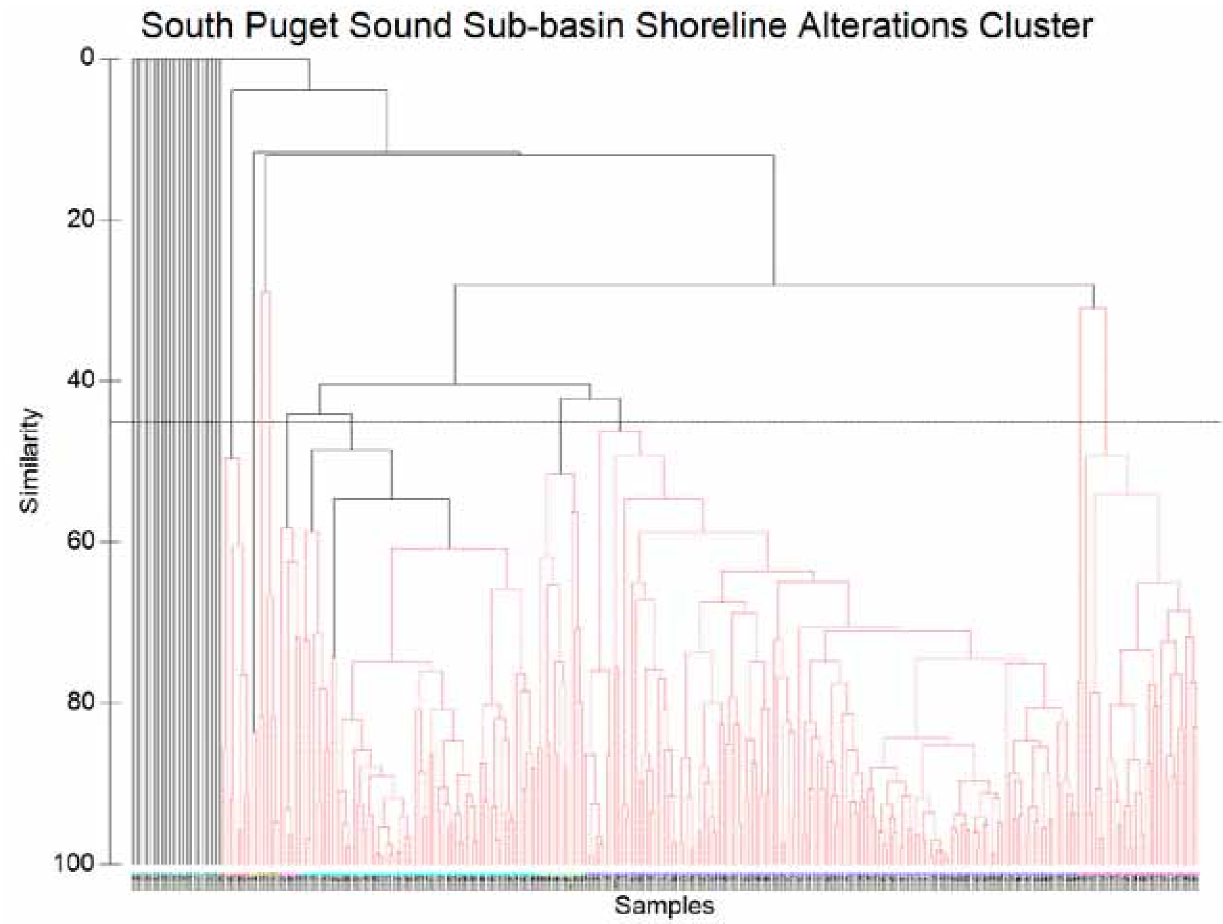


Figure 12. Example of a clustering dendrogram that illustrates the grouping of shoreline process units with the most similar (approaching similarity of 100) characteristics, which in this example is shoreline alterations (Tier 2) in the South Puget Sound Sub-Basin; the nine major significant groups are designated by the color code for each process unit (PU) at the bottom of the dendrogram.

Non-Metric Multi-Dimensional Scaling

The interpretation of a Non-Metric Multi-Dimensional Scaling (NMDS) plot (example, Fig. 13) is relatively straightforward: points that are close together represent samples that are very similar in relative (percentage) composition, and points that are far apart correspond to very different compositions among the variable set. Samples are coded by the significant groups identified by the SIMPROF test (see page 22).

The test statistic of the adequacy of NMDS representation is called the "stress level" and ranges from 0 to 1 (see "2D Stress" level in upper right corner of NMDS plot, Fig. 13). The level of stress describes how well the multi-dimensional data was represented in the 2-dimensional (or in a few cases 3-dimensional) ordination. Stress increases with reducing dimensionality and also with increasing quantity of data. A general guide for reading stress levels is as follows (Clarke and Warwick 2001):

1) <0.05 gives an excellent representation with no prospect of misinterpretation;
2) <0.1 corresponds to a good ordination with no real prospect of a misleading interpretation;
3) <0.2 still gives a potentially useful 2-dimensional picture, though for values at the upper end of this range too much reliance should not be placed on the detail of the plot; and,
4) >0.3 indicates that the points are close to being arbitrarily placed in the 2-dimensional ordination space.

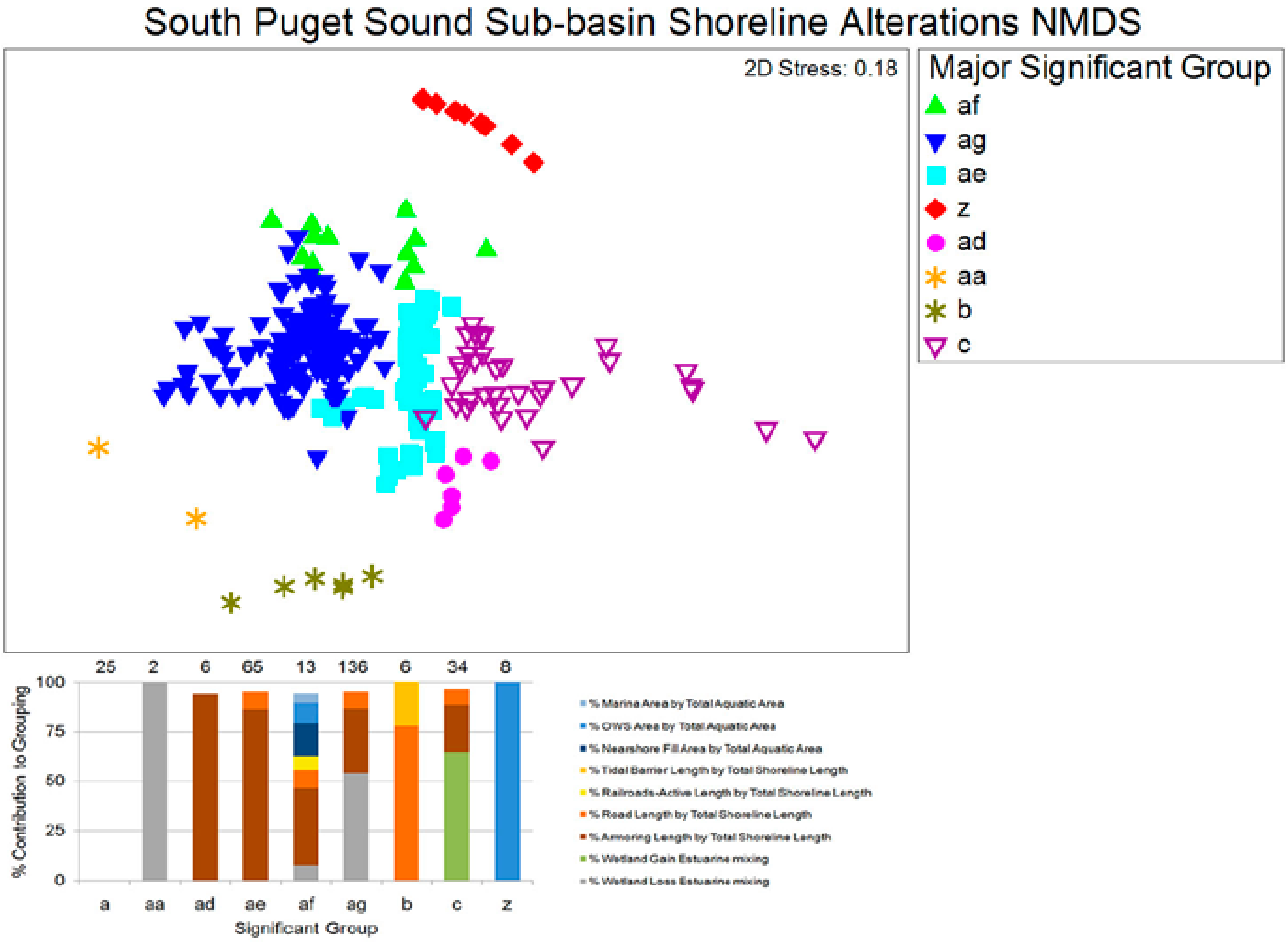


Figure 13. Example of results from Non-Metric Multidimensional Scaling (NMDS; plot, top) and SIMPER analysis (bottom) of shoreline alterations in Process Units (PU) for the South Puget Sound Sub-Basin. Each symbol represents one PU, where the symbol and color distinguishes PU groups with significantly similar shoreform compositions. Number above stacked histograms indicates the number of PU in each group. Groups composed of one PU show the descriptive composition of the PU.

SIMPER Analyses

We used SIMPER analysis to interpret differences between groups when they have been shown to exist (in our case by the SIMPROF test) by identifying discriminating variables that contribute to similarity within a group and dissimilarity among groups. Grouping similar PU, and understanding their clustering patterns, organizes the landscape into discreet units that may benefit from similar management measures. As we described earlier, we have chosen to limit the maximum number of groups to nine, which means that some subtle within-group differences (e.g., not all discriminating variables will necessarily be represented in all PUs in a group) may not be represented by this somewhat coarse grouping; however, the dissimilarity among PUs is still valid. For each multivariate NMDS analysis, we have generated histogram (bar) graphs that show the discriminating variables that contribute to the similarity within groups; there the relative contribution is expressed as percent. For all these plots, the numbers above the histogram bars indicate the number of PU in the group.

An example of our use of these basic NMDS and SIMPER analyses to identify the statistically similar groups is illustrated (Fig. 13) for similarity in shoreline alterations of PU in the South Puget Sound Sub-Basin is illustrated in a 2-D multi-dimensional plot of eight significant groups (one group, a, identified in the clustering dendrogram [Fig. 12] does not appear in the NMDS analysis because these PU have only one alteration, thus no statistical “group” can be distinguished). The histogram (bar) graph below the NMDS plot illustrates the percent contribution that each shoreline alteration contributes to distinguishing the similarity within each group and how these proportions may explain the strength in similarities or differences displayed in the 2-D plot. Some groups, such as ad and ae, represent PU with very similar shoreline alterations, in this case just shoreline armoring (six PU, comparatively rare) or shoreline armoring with some shoreline roads (65 PU, more common), respectively. Other groups, such as c, are more dissimilar (less cohesive grouping), here characterized by 34 PU with a combination of gains in estuarine mixing wetlands and some occurrence of shoreline armoring and roads.

Scaling Relative Impairment of Nearshore Ecosystem Processes over Puget Sound and Sub-Basins

The Change Analysis provides a spatially-explicit basis for relating changes in the nearshore structure of Puget Sound to altered nearshore ecosystem processes. Understanding the potential effects of these changes in nearshore structure and processes on ecological and other functions valued by the region's inhabitants is more challenging, but can potentially provide useful scientific guidance for shoreline management of the Sound. However, because we had no Sound-wide historical information on shoreline functions, and actually very incomplete information for even their current contributions to the Puget Sound populace, we were confined by our conceptual models and scientific expertise to merely hypothesize changes in nearshore ecosystem function and categorize their relative impairment due to the observed physical changes. Therefore, as a demonstration of how our documented changes in nearshore ecosystems might be qualitatively associated with potential changes of ecological, social and cultural importance, we hypothesized relative ranks of Ecosystem Functions, Goods and Services that would be affected by changes at each level (tier) of change (Fig. 4 #7) using a modified Delphi process. This was an exercise to explore the scale of potential effects on nearshore ecosystem processes and functions, goods, and services due to the variability in nearshore ecosystem change that we documented among shoreforms, process units, and sub-regions Sound-wide. It will not necessarily form an analytical basis for setting restoration and conservation priorities for PSNERP. Approaches to interpreting and building on these Change Analysis data, are described in the PSNERP Strategic Assessment (Schlenger *et al.* in prep.) and Cerighino *et al.* (in prep.) documents.

The first step in this process, once we had characterized spatial change for each shoreline process unit and delta process unit, involved establishing a link between changes in shoreforms and changes in Ecosystem Functions, Goods and Services (EFG&S) that are associated with those changes. As a template for qualifying the level of cumulative impairment to nearshore ecosystem processes from changes in attributes of SPU and DPU at each category (tier) of change, we adapted the Millennium Ecosystem Assessment (MEA 2005; WRI 2005) and more recent applications (Leslie and McLeod 2007; NAS 2007; Halpern et al. 2008) of the concept that ecosystems function to provide goods and services (provisioning, regulating, cultural and supporting) to support human well being. "Ecosystem Functions, Goods, and Services" is a common concept and terminology to describe the diverse benefits that humans derive from natural ecosystems. These EFG&S have increasingly served as assessment criteria for a variety of analyses of human impacts on natural ecosystems, from comparing natural and engineered shorelines (NAS 2007) to assessing the need for marine ecosystem management (Leslie and McLeod 2007; Halpern et al. 2008). Renayas et al. (2009) and Duffy (2009) argued that high local and regional diversity enhances the maintenance of multiple ecosystem services in a changing world.

De Groot et al. (2002) listed four categories of ecosystem functions—regulation, habitat, production, and information—wherein 23 functions tie ecosystem processes to goods and services. Subsequently, the Millennium Ecosystem Assessment [MEA] (MEA 2003; World Resources Institute 2005) reclassified ecological goods and services into four categories and related these to both indirect and direct drivers for change and to the response in human well-being and poverty: 1) ***provisioning services*** such as food, water, timber, fuel, and fiber; 2) ***regulating services*** such as the regulation of climate, floods, disease, wastes, and air and water quality; 3) ***cultural services*** such as educational, recreational, aesthetic, and spiritual benefits; and 4) ***supporting services*** such as soil formation, photosynthesis, and nutrient cycling.

We adapted definitions and lists of EFG&S modified for Puget Sound by World Resources Institute (WRI 2007) and Earth Economics (Batker et al. 2008) to specifically address how changes in Puget Sound's nearshore ecosystems have altered their ability to deliver EFG&S. Thus, we adopted a broad perspective on functions that support, regulate, and provide goods and services (e.g., all EFG&S on the list were ranked), while being focused on changes in nearshore attributes that impair those functions.

Using a modified Delphi process for reaching group consensus, the NST assigned relative ranks of impairment to EFG&S by changes at each category (tier). Originally developed at the Rand Corporation as a means of extracting opinion from a group of experts, the Delphi process is often used by the applied research community (Adler and Ziglio 1995; Linstone and Turoff 2002). A Delphi processes is intended to gain the advantages of groups of individuals working together, while overcoming their disadvantages. Conventional Delphi has three characteristics that distinguish it from conventional group interaction: anonymity, followed by iteration with controlled feedback, and response. A complete description of the EFG&S ranking process is provided in Appendix C.

Impairment Calculation

Within each category of change (tier), the NST-assigned EFG&S ranks were multiplied by the value of proportional change (ranging from 0 to 1) for each attribute within each process unit. The resulted values of all attributes were summed within a PU to generate a composite Impairment Score for each PU.

It is important to recognize two significant attributes of this analytical approach when interpreting the results:

1) The Impairment Score represents a sum rank over all EFG&S, and thus the diverse combination of EFG&S attributable to each change may play just as large a role in the sum total rank as a high proportional change of a highly ranked change
2) Positive impairment (improvement) scores may occur where changes involve a shift (particularly in shoreform transitions) from a lower to a higher ranked category. For example, a transition from a Closed Lagoon/Marsh (EFG&S Rank of 205) to a Barrier Estuary (EFG&S Rank of 242) would result in a net increase in the ability to provide or support ecosystem function goods and services.

In order to classify levels of impairment, the Impairment Scores calculated for individual PU were assigned to one of nine bins using the Natural Breaks classification scheme. This method identifies break points in the distribution of continuous data, groups similar values, and maximizes differences between classes. PU impairment scores were binned relative to all of the scores within their respective sub-basin as well as all of Puget Sound. In this way, a PU that is "highly impaired" relative to others within its sub-basin, may be only "moderately impaired" at the Puget Sound scale.

Figure 14 illustrates an example of calculation of ecosystem impairment resulting from shoreform change (tier 1) for two SPU. The EFG&S rank for each shoreform type is multiplied by the proportional change observed for that shoreform; these values are then summed within each PU. In the example, both SPU show an increase in Barrier Beach length, which contributes positively to the final impairment score. SPU 6012 also shows an increase in Barrier Lagoon length, which, combined with the increase in Barrier Beach, outweighs the negative impact to the provision and support of EFG&S associated with the loss of Bluff-backed Beach. This PU therefore results in a positive Impairment Score (47.64). Conversely, the complete loss of a Closed Lagoon/Marsh in SPU 6013 offsets the positive impact of gain in Barrier Beach, with a resulting Impairment Score of −174.25. These scores are then binned from 1 (least impaired) to 9 (most impaired) relative to the range of all scores within Puget Sound and their sub-basin. In the example, SPU 6012 is more impaired relative to the other PU within its sub-basin than it is relative to all PU within Puget Sound.

The NST used these Impairment Scores to compare the status of each SPU and DPU and generate aggregate maps scaled across each Puget Sound sub-basin as well as Sound-wide.

Ecosystem Function, Goods, and Services Rank

	Barrier Beach	Barrier Estuary	Barrier Lagoon	Bluff-backed Beach	Closed Lagoon/ Marsh
EFG&S Rank	211	242	208	231	205

× Proportional Change in the Data

	Proportional Change from Historic Shoreline Length				
	Barrier Beach	Barrier Estuary	Barrier Lagoon	Bluff-backed Beach	Closed Lagoon/ Marsh
SPU 6012	0.30	0	0.13	–0.18	0
SPU 6013	0.16	0	0	–0.01	–1

= *Impairment Score Summed for each Process Unit*

	Proportional Change * EFG&S Rank						Impairment Bin	
	Barrier Beach	Barrier Estuary	Barrier Lagoon	Bluff-backed Beach	Closed Lagoon/ Marsh	Impairment Score	Puget Sound	Sub-Basin
SPU 6012	63.34	0	26.44	–42.13	0	47.64	7	8
SPU 6013	33.63	0	0	–2.89	–205	–174.25	4	4

Figure 14. Example calculation for two shoreline process units (SPU 6012 and 6013) of nearshore ecosystem impairment caused by shoreform change (Tier 1).

Data Uncertainty

The historical T- and H-sheet surveys provide a wealth of information that allow for a systematic analysis of nearshore change over the last century. While generally considered highly reliable data sources, their use requires an acceptance of potential uncertainty that cannot be validated with other datasets as a part of this project. In addition, absence of evidence is not necessarily evidence of absence: in many cases, features that were actually historically present were not mapped on the T-sheets. For example, this occurred 40 times in the Puget Sound Basin, where a current Rocky Platform shoreform was not mapped historically, but has transitioned to that shoreform in the current dataset and is associated with rocky outcrop islands just offshore. However, other omissions or positional inaccuracy in the historical dataset may not be as evident.

Similarly, we must accept a level of uncertainty with the current data, including wetland delineation, which remains problematic in assessing accurate and comprehensive regional coverage. Positional accuracy is also low for the railroad dataset, which becomes apparent when evaluating nearshore railroads (Shoreline Alterations, Tier 2), a subset that includes railways within 25 meters of the ShoreZone shoreline. When a railroad is digitized inaccurately (at times more than 50 meters from the actual location) it is often improperly excluded from the nearshore category. This is commonly observed along the stretch of shoreline from Seattle to Everett. Finally, the nearshore fill (Shoreline Alterations, Tier 2) dataset is known to underestimate the occurrences and areas of nearshore ecosystems that are covered and converted to upland in Puget Sound.

We relied on proportional change in the analysis of shoreforms (impairment and multivariate analyses), which allows comparison between PU that vary significantly in size. However, using proportional data leads to potential misinterpretation when subtle changes become magnified. A small absolute change may be proportionally equivalent to or greater than a large absolute change. Additionally, a percent change in shoreline length will always be quantified even when the shoreform stays the same because either the shoreline has been modified (a simplified or reduced shoreline is often apparent, as in many deltas, for example) or there was an inconsistency between the measurements taken historically and currently at two different scales (1:10,000 and 1:24,000, respectively). While pervasive, these measurement inconsistencies are expected to be minor; on average the proportional change in shoreline length of a non-transition shoreform was approximately –0.07, and consequently they carry little weight through subsequent analyses.

Data Availability

The Change Analysis geodatabase, and associated metadata and methodology (described in the following document) are available to the public for download after November 2011 at the following website: *http://wagda.lib.washington.edu/*

Questions about these data and their use should be directed to Mr. Scott Campbell at the U.S. Army Corps of Engineers, Seattle District (*scott.w.campbell@usace.army.mil*).

Results

In the following, we have described the Change Analysis results based on tabular and graphical summaries of nearshore change according to: 1) Sound-wide and sub-basin and, within each, 2) the four categories of change (tiers).

Puget Sound Basin

The Nearshore Dimensions of Puget Sound

Among the seven Puget Sound sub-basins around which the PSNERP Change Analysis data is organized (Fig. 1), the Whidbey Sub-Basin dominates (40.7 percent) the 36,080 km2 total drainage area (Fig. 15, Table 3). However, the San Juan Islands–Strait of Georgia Sub-Basin dominates in terms of nearshore area (28.5 percent) and shoreline length (29.9 percent). The North Central Sub-Basin ranks the lowest in each of the above categories. Stream confluences are most abundant in the Hood Canal and South Puget Sound sub-basins, least in the North Central Sub-Basin.

Change is documented for each of 828 process units (PU): 812 shoreline process units (SPU) and 16 delta process units (DPU). The shoreline length of the vast majority of process units is less than 10 km (median 3.1 km, minimum <0.1 km maximum 96.2 km), including DPU from ~3 to almost 100 km shorelines (Fig. 16a). Including the shoreline zone and the total watershed area, the mean PU area is almost 50 km2, but the vast majority of process units are smaller than 10 km2 (Fig. 16b). The mean area of the 812 SPU is 18.6 (median 3.3 km2; minimum <0.1 km2; maximum 1562.0 km2); the mean area of the 16 DPU is 1619.5 km2 (median 745.7 km2; min 204.0 km2; maximum 7,300.6 km2).

Among the seven sub-basins, South Puget Sound has the greatest number of process units (295, followed by the San Juan Islands–Strait of Georgia (180) and South Central sub-basins, with the fewest located in the Strait of Juan de Fuca (31), and North Central (40) sub-basins. The mean length ranges between ~3 and 12 km, with most PU being ≤20 km long but with notably longer PU in the Whidbey Sub-Basin (associated with the three deltas; maximum 96.2 km), the Strait of Juan de Fuca (maximum 59.4 km), South Central (also associated with deltas; maximum 45.7 km) and San Juan–Strait of Georgia (maximum 21.1 km) sub-basins (Fig. 17). The total nearshore area of process units in each sub-basin is influenced by the occurrence of deltas. Where the three deltas in the Whidbey Sub-Basin generate the highest maximum and mean area (7300 and 226.6 km2, respectively) of the seven sub-basins and are the largest contributing PU for the other sub-basins but North Central Sub-Basin (Fig. 18). However, the distribution of the largest SPU areas is in the Strait of Juan de Fuca Sub-Basin.

The proportions of each PU that fall into different segments of the drift cell are quite similar among the sub-basins: 2–10 percent of the length of each drift cell is classified as divergence zones, serving as the source of beach sediments; the sediment transport zone is 35–74 percent; the convergence zone, where most sediments either accumulate or are transported into deep water, is 1–3 percent of the total drift cell (SPU) length; and "no appreciable drift" is the most variable component, comprising between 13 and 62 percent of the SPU (Table 3).

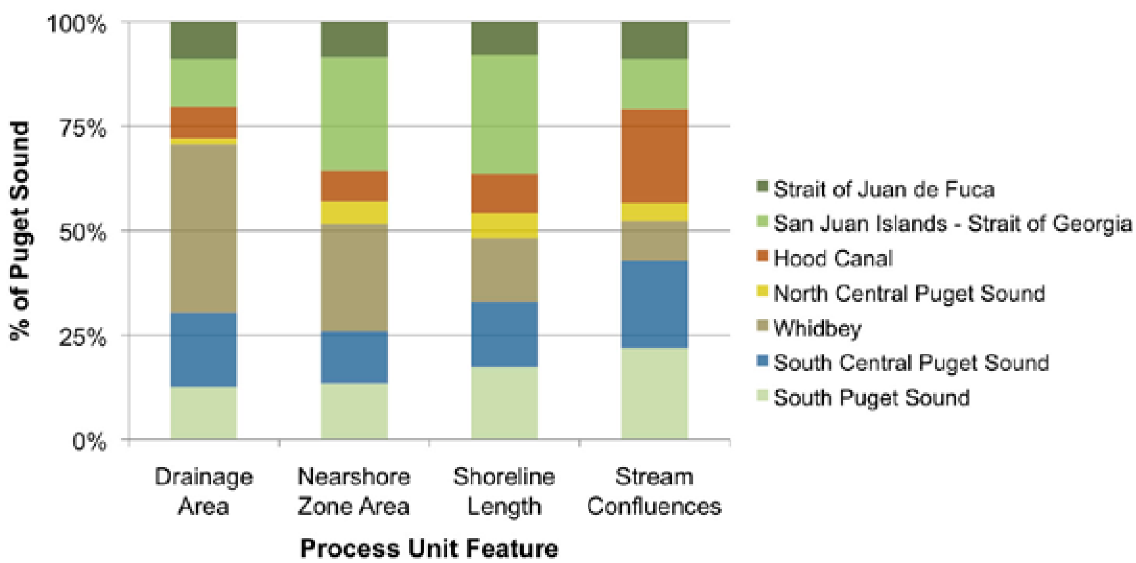
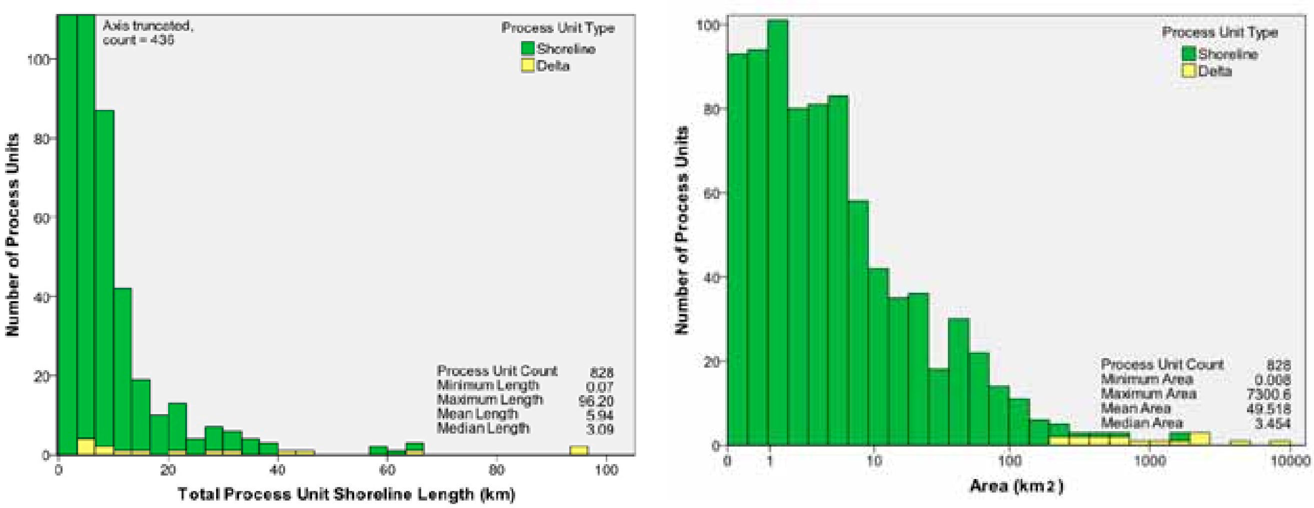


Figure 15. Puget Sound sub-basin composition by Process Unit features.

[3]Where necessary, sub-basins and the comprehensive basin are abbreviated as: JF = Strait of Juan de Fuca; SJ = San Juan Islands–Strait of Georgia; HC = Hood Canal; WH = Whidbey; NC = North Central Puget Sound; SC = South Central Puget Sound; SP = South Puget Sound; and, PS =Puget Sound (entire basin).

Table 3. Summary statistics for Puget Sound and sub-basins.

	Process Unit Features				Drift Cell Summary (%)			
	Drainage Area (km^2)	Nearshore Zone Area (km^2)	Shoreline Length (km)	Stream Confluences	Convergence Zone	Divergence Zone	No Appreciable Drift	Transport Zone
Strait of Juan de Fuca	3231	181	329	259	2.5	5.4	30.9	61.2
San Juan Islands-Strait of Georgia	4176	580	1187	356	1.2	2.1	61.5	35.3
Hood Canal	2790	155	395	656	0.6	6	21.9	69.2
North Central Puget Sound	502	113	249	126	3	9.6	13.2	74.2
Whidbey	14687	550	634	277	1	4.6	43.2	51.2
South Central Puget Sound	6459	263	648	611	1	5.6	23.1	70.4
South Puget Sound	4610	287	725	641	0.7	7.4	29	62.9
Puget Sound Basin	36080	2036	3969	2810	1.1	5.1	39.2	54.6



A

B

Figure 16. Frequency distribution of current process unit size (a-length, km; b-area; km2) used to characterize nearshore ecosystem change in Puget Sound.

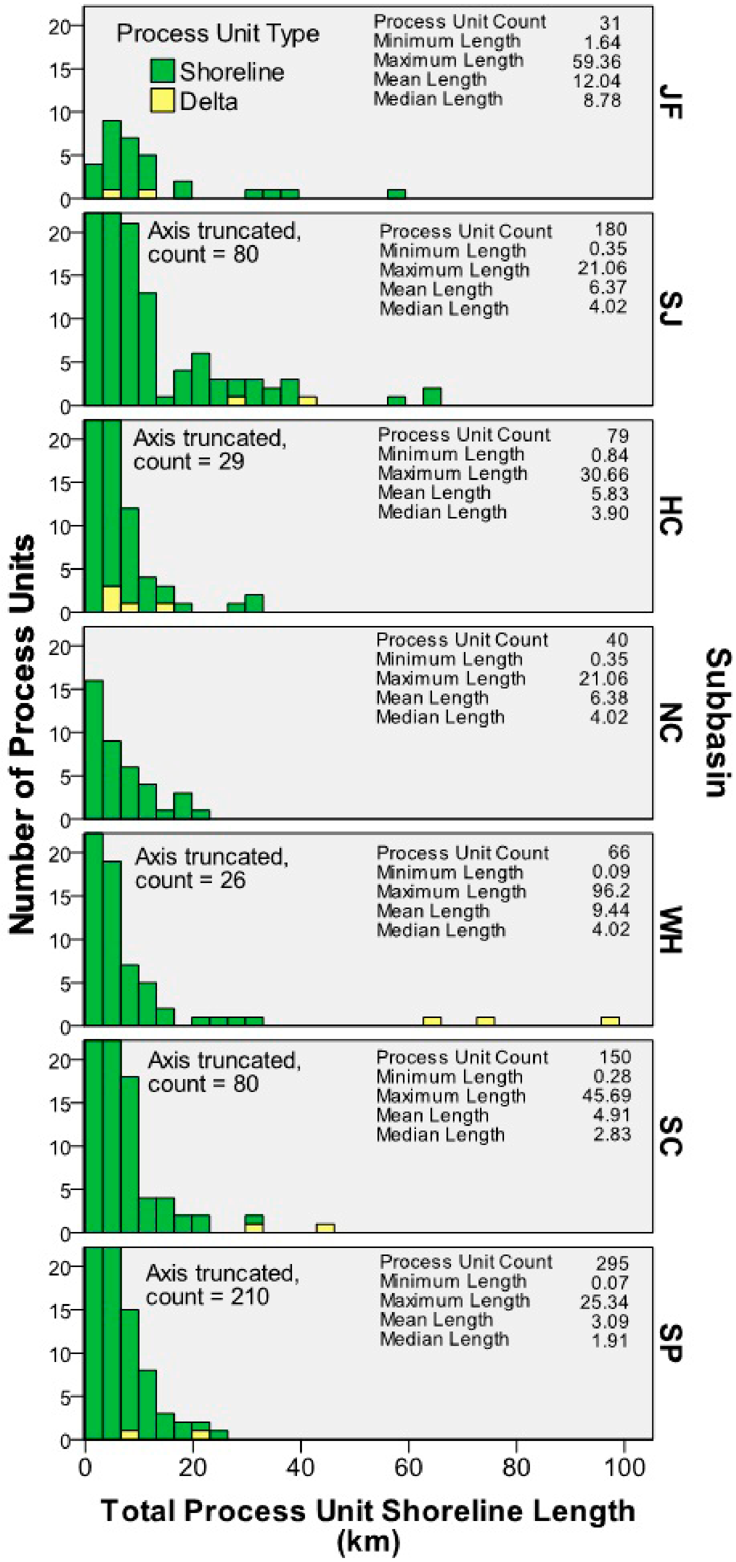


Figure 17. Frequency distribution of process unit shoreline length by Puget Sound sub-basin.

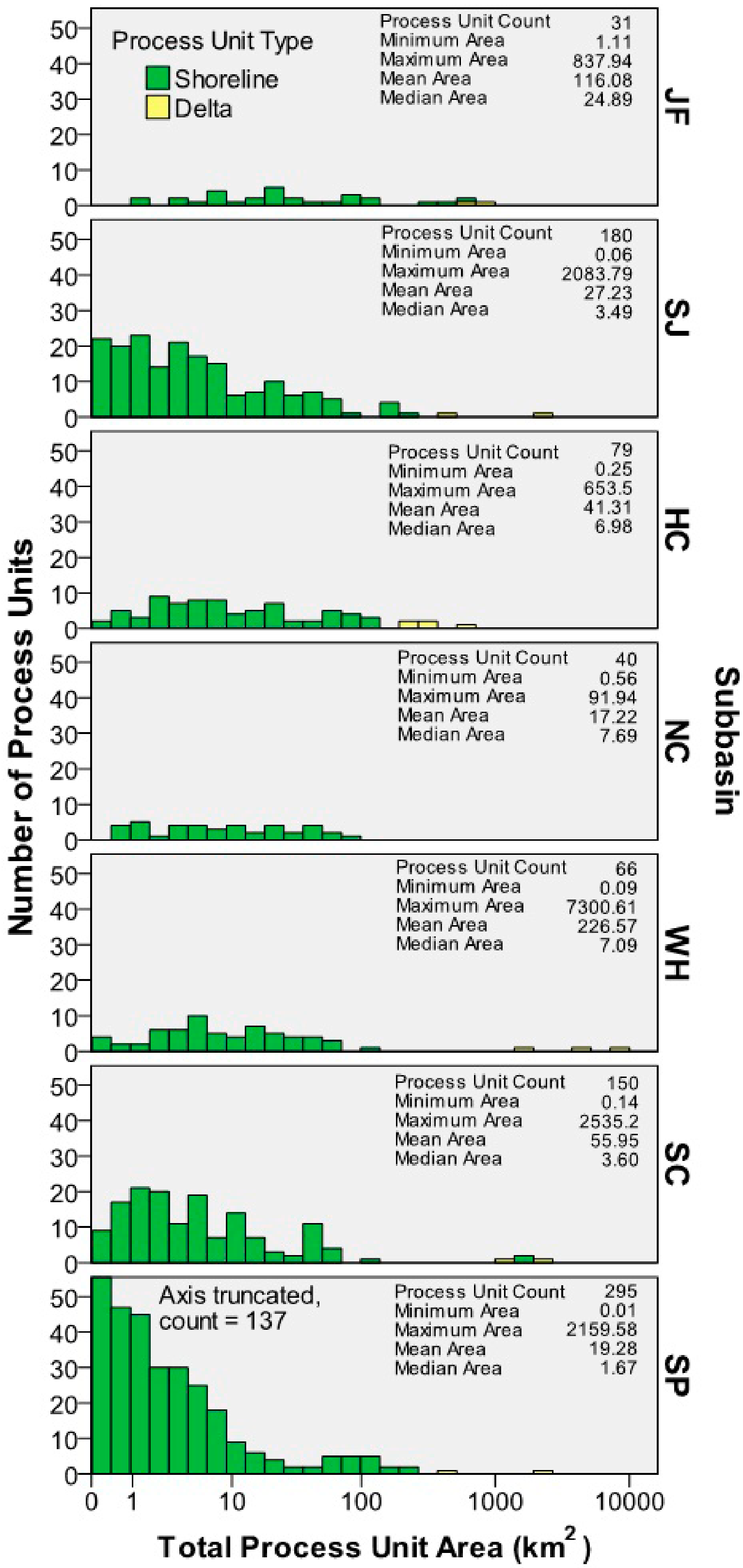


Figure 18. Frequency distribution of process unit total nearshore area by Puget Sound sub-basin; note logarithmic scale for the total process unit area.

Shoreform Change and Transition

The magnitude and variation in the changes of shoreform type and complexity along Puget Sound's shoreline, indicated by the PSNERP Change Analysis, is due predominantly to either one or the combination of the following: 1) the loss or change (in shoreline length or area) in the different shoreforms that still identifiably meet the definition of a geomorphic shore type (not Artificial), 2) the effect of other direct modifications to beaches and embayments (see Shoreline Alterations below), and 3) geospatial mapping error. Because we have found mapping errors to be variable, but typically small, between historical and current geospatial datasets, we believe that relative changes (percent) in shoreline length are real. However, because of the differences between historical and current mapping scales (1:10,000 and 1:24,000, respectively), we emphasize that, in interpreting these results, the shoreform (count) transitions and relative change in shoreline length should be given more attention than absolute shoreline length or area changes, especially where those differences are small.

Descriptive

The shoreline of Puget Sound has declined measurably (Fig. 19, Table 4). Total shoreline length of all shoreforms combined, including deltas, declined by approximately 15 percent Sound-wide (Figs. 20 & 21). Shorelines declined the least in the Strait of Juan de Fuca and South Central Puget Sound and considerably more in the Whidbey and South Puget Sound sub-basins. Because of the size of the deltas, the 47 percent decrease in length of that shoreform alone accounted for much of the observed simplification of the nearshore Puget Sound overall. Through transitions to artificial, the South Central Puget Sound Sub-Basin saw a complete loss of the delta shoreform (Fig 21).

The vast majority of transitions in shoreform type were attributable to changes to an artificial (primarily nearshore fill) shoreform; other types completely disappeared as a recognizable shoreform (Tables 5 & 6). Some 80–100 percent of the transitions (Table 6) involved such anthropogenic changes. Because some differences in mapping or actual mapping error could be involved in the "shoreform absent" category (e.g., the diagnostic attributes may not have been as evident in the historical surveys as in the current data), we can only ascertain with any certainty that approximately 400 shoreforms changed in character. Where transitions occurred from one shoreform to another, this usually could be ascribed to either a loss or addition of one feature of a complex shoreform (e.g., change from a barrier beach to a barrier estuary) or, more typically, a change in the character of the hydrologic connectivity (e.g., barrier lagoon to closed lagoon/marsh or open coastal inlet to barrier estuary). Further examination of each transition will be required to interpret whether these were natural transitions from normally dynamic nearshore geomorphology, or if they involved an anthropogenic modification, such as a dredged channel. Other transitions, such as between bluff-backed beach and barrier beach (82-83 percent of transitions for those two shoreforms), likely involved small mapping errors or natural changes in the diagnostics for the two closely related shoreforms (Table 6).

Some shoreform transitions will require more detailed examination to determine whether they were valid or mapping errors. For example, transitions of rocky platform to barrier lagoon (1 occurrence) or bluff-backed beach to barrier estuary (2) do not typify natural nearshore geomorphic changes and will require verification.

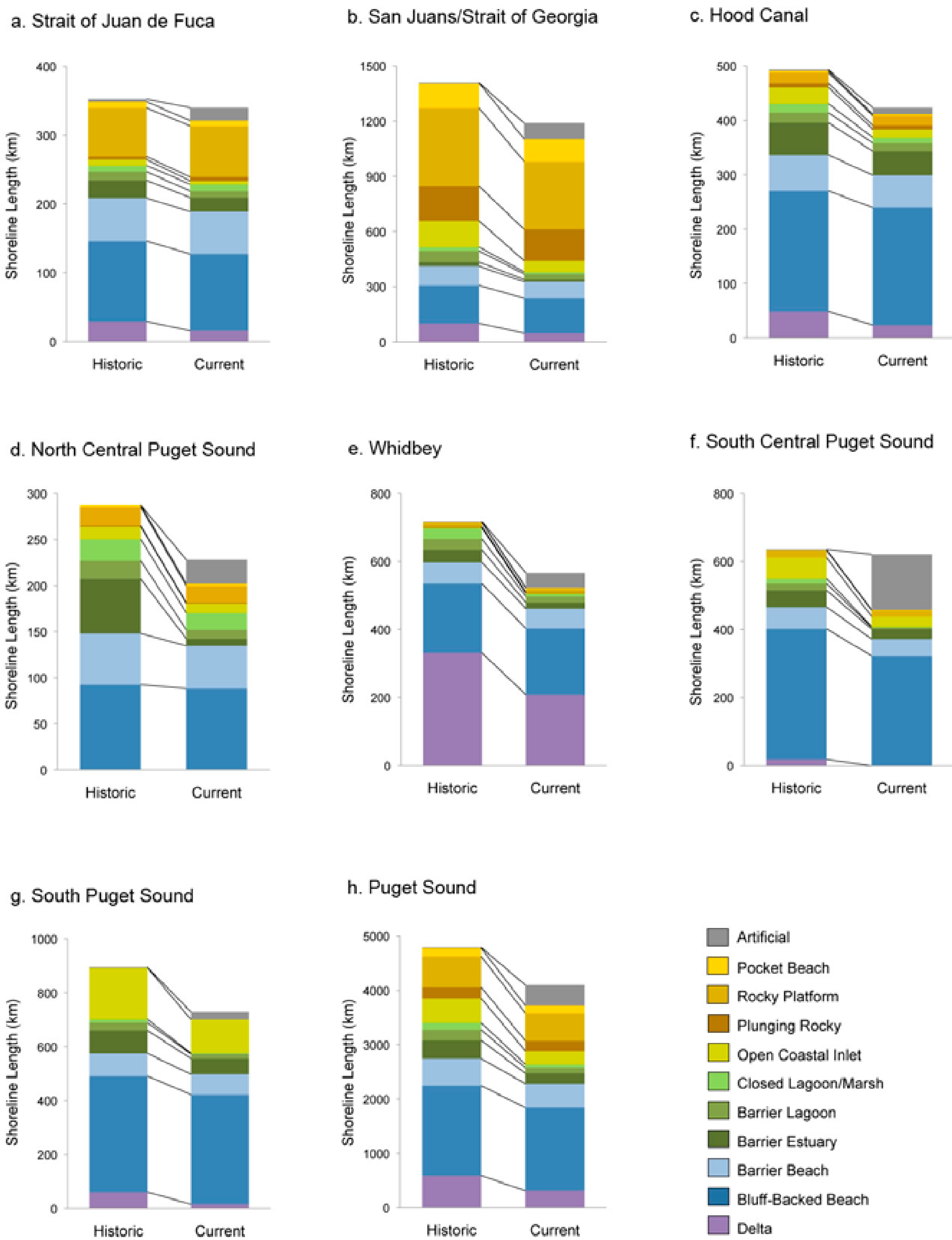


Figure 19. Sub-basin (a-g) and Sound-wide (h) shoreform composition change (length, km) from historical to current conditions.

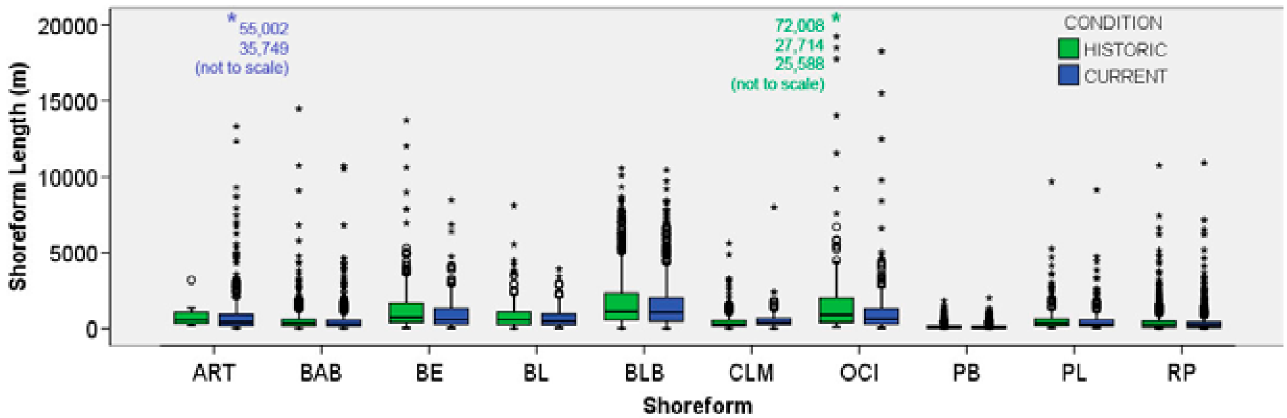


Figure 20. Historical and current contiguous shoreline length of Puget Sound shoreforms in PU (excludes delta shoreform): ART = artificial, BLB = Bluff-Backed Beach, BAB = Barrier Beach, BE = Barrier Estuary, BL = Barrier Lagoon, CLM = Closed Lagoon Marsh, OCI = Open Coastal Inlet, PL = Plunging Rocky, RP = Rocky Platform, and PB = Pocket Beach. The box represents the median and upper and lower quartile of the data. The 'whiskers' (lines that extend out of the top and bottom of box) represent the highest and lowest values that are not outliers or extreme values. Outliers (values between 1.5 and 3 times the interquartile range) are marked with a circle and extreme cases (values more than 3 times the interquartile range) with an asterisk. Extreme cases not shown to scale are indicated with the shoreform length (m) measurement.

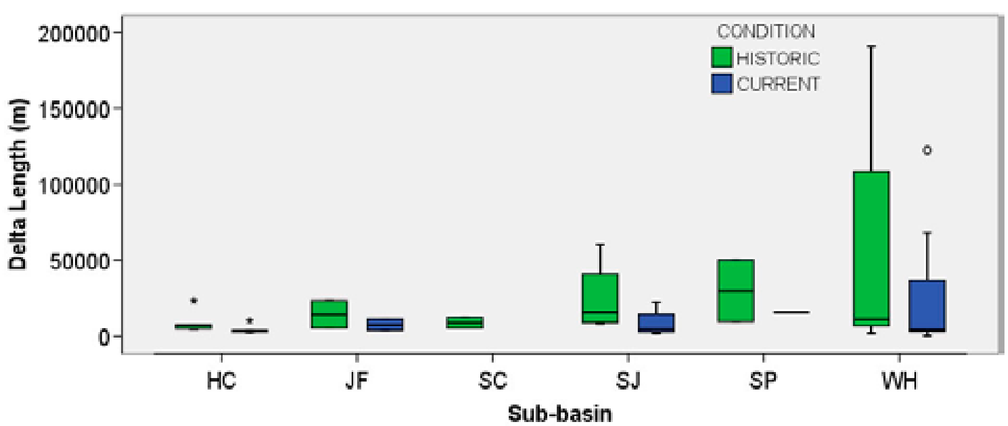


Figure 21. Historical and current contiguous shoreline lengths of the delta shoreform in six of the Puget Sound sub-basins in which they occur. A complete loss of the delta shoreform is observed in the South Central Puget Sound Sub-Basin. Refer to Fig. 18 for an explanation of box and whisker components, including outlier definitions.

Table 4. Relative change (% gain/loss from historical length) in shoreform composition in Puget Sound and sub-basins.

	Delta	Bluff-backed Beach	Barrier Beach	Barrier Estuary	Barrier Lagoon	Closed Lagoon/ Marsh	Open Coastal Inlet	Plunging Rocky	Rocky Platform	Pocket Beach	Artificial
Strait of Juan de Fuca	-46.5	-4.2	-2.4	-20.7	-22.8	8.4	-44.6	29	4.8	-11.9	403.1
San Juan Islands-Strait of Georgia	-53.3	-7.6	-13.8	-63.6	-50.6	-9.5	-57.2	-10.3	-13	-9.8	5118.5
Hood Canal	-50.6	-2.9	-9.8	-25.2	-21.2	-36.3	-48.9	-10.5	-8.3	-8.5	491.5
North Central Puget Sound	--	-3.6	-14.4	-88.2	-52.8	-22.3	-27.2	2.6	-10	14.2	100
Whidbey	-37.2	-8.1	-6.4	-62.3	-50	-64.1	-13.2	-12.4	-4.1	-5.8	4394.1
South Central Puget Sound	-100	-16.6	-24.8	-41.9	-78	-89.1	-52.1	0	-16.9	-8.5	21021.1
South Puget Sound	-73.6	-5.7	-11	-30.1	-43.3	-74.9	-35	0	0	0	2574.1
Puget Sound Basin	-47.1	-7.7	-11.9	-44.4	-46.1	-48.4	-45.3	-9.3	-10.4	-9.5	3443

Table 5. Relative change in shoreform count between historical (H) and current (C) conditions in Puget Sound and sub-basins.

	Delta		Bluff-backed Beach		Barrier Beach		Barrier Estuary		Barrier Lagoon		Closed Lagoon/ Marsh		Open Coastal Inlet		Plunging Rocky		Rocky Platform		Pocket Beach		Artificial	
	H	**C**	**H**	**C**	**H**	**C**	**H**	**C**	**H**	**C**	**H**	**C**	**H**	**C**	**H**	**C**	**H**	**C**	**H**	**C**	**H**	**C**
Strait of Juan de Fuca	2	2	43	42	51	49	15	13	9	8	12	13	3	3	13	23	53	64	17	17	2	20
San Juan Islands-Strait of Georgia	2	2	134	130	117	112	14	6	49	39	42	28	29	28	315	315	1204	1232	944	939	5	74
Hood Canal	5	5	146	145	147	143	49	37	23	13	46	23	11	8	22	22	38	38	24	24	2	33
North Central Puget Sound	0	0	63	62	70	64	17	6	17	8	30	18	9	9	3	3	40	40	19	19	0	17
Whidbey	3	3	91	90	96	99	14	7	24	13	32	13	2	2	23	23	56	57	30	30	1	31
South Central Puget Sound	2	0	170	163	160	136	39	27	31	10	41	5	31	24	0	0	22	21	10	10	2	113
South Puget Sound	2	1	324	326	306	296	100	84	75	52	61	11	90	85	0	0	0	0	0	0	1	46
Puget Sound Basin	16	13	932	921	910	867	240	179	222	142	249	101	173	157	354	364	1371	1409	1015	1010	13	326

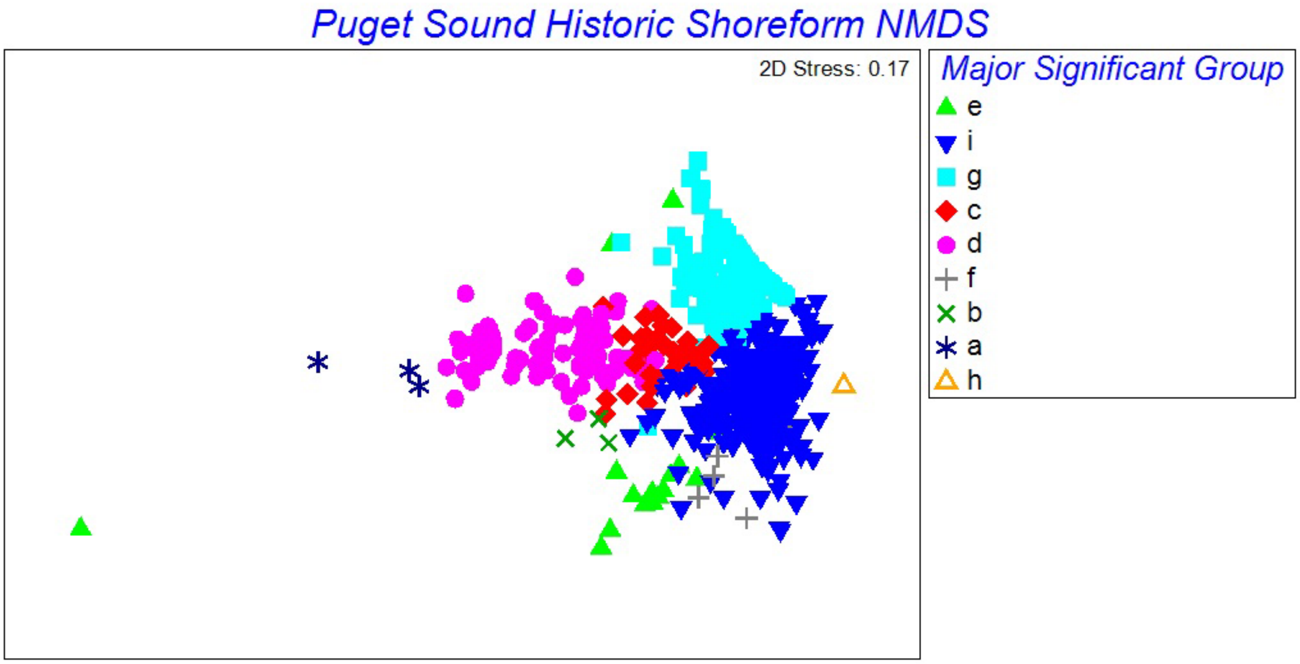
Table 6. Shoreform transitions (Tier 1) in Puget Sound. Highlighted numbers (diagonal line) represent the number that did not transition and are derived as the difference between the historical shoreform count and the total number of transitions.

Shoreform Transition	*Current* ----------------------->												
Historic	Bluff-Backed Beach	Barrier Beach	Delta	Barrier Estuary	Barrier Lagoon	Closed Lagoon/ Marsh	Open Coastal Inlet	Plunging Rocky Shoreline	Rocky Platform	Pocket Beach	Artificial	Shoreform Absent	Total Transitions
Bluff-Backed Beach	793	12		2	1						124		139
Barrier Beach	4	823			1						82		87
Delta			8								8		8
Barrier Estuary				154	1	2					21	62	86
Barrier Lagoon					126	7					16	73	96
Closed Lagoon/Marsh					1	79					5	164	170
Open Coastal Inlet				13			107				53		66
Plunging Rocky Shoreline								352			2		2
Rocky Platform					1				1349		21		22
Pocket Beach										1010	5		5
Artificial		1									12		1
Shoreform Absent					7	10		10	40		29		96
Total Transitions	10	15	0	16	13	22	0	10	40	0	366	299	791

Multivariate Analysis

Historically, the shoreline process units were dominated by three distinct shoreform groups: 1) predominantly bluff-backed beach and, to a lesser extent, barrier beach and some barrier estuary segments; 2) bluff-backed beach and open coastal inlet; and 3) plunging rocky, rocky platform, and pocket beach (Fig. 20; groups i, g, and d, respectively). Other groups, such as SPU formed entirely of the plunging rock shoreform (group a), barrier estuary, closed lagoon/marsh and rocky platform (group b), or barrier beach with a comparatively minor contribution by bluff-backed beach (group f), were represented by only three to four SPU. The 16 delta process units, and one shoreline process unit located adjacent to the Duckabush River delta, clustered into a single group (group e), distinguished by the delta shoreform.

Although associated with several east Puget Sound sub-basins (including the extensively artificial Lake-Washington/ Lake Sammamish watershed associated SPU in South Central Puget Sound), most of the group g SPU were located in the southern portion of the Hood Canal Sub-Basin and the South Puget Sound Sub-Basin and most of the group d were located in the San Juan Islands–Georgia Basin Sub-Basin (Fig. 23). The vast majority of the SPU in the central and northern Puget Sound and Hood Canal sub-basins occurred in group i.



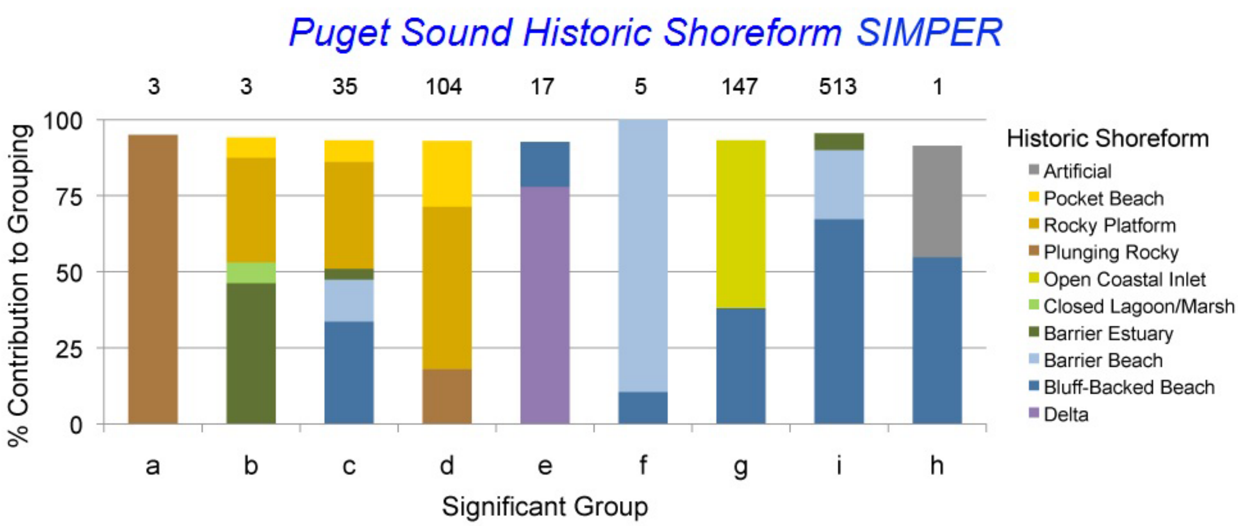


Figure 22. Non-Metric Multi-Dimensional Scaling (NMDS) plot and SIMPER multivariate analysis results for historical shoreform composition in the process units (PU) of the Puget Sound Basin. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group. Groups composed of one PU show the descriptive composition of the PU.

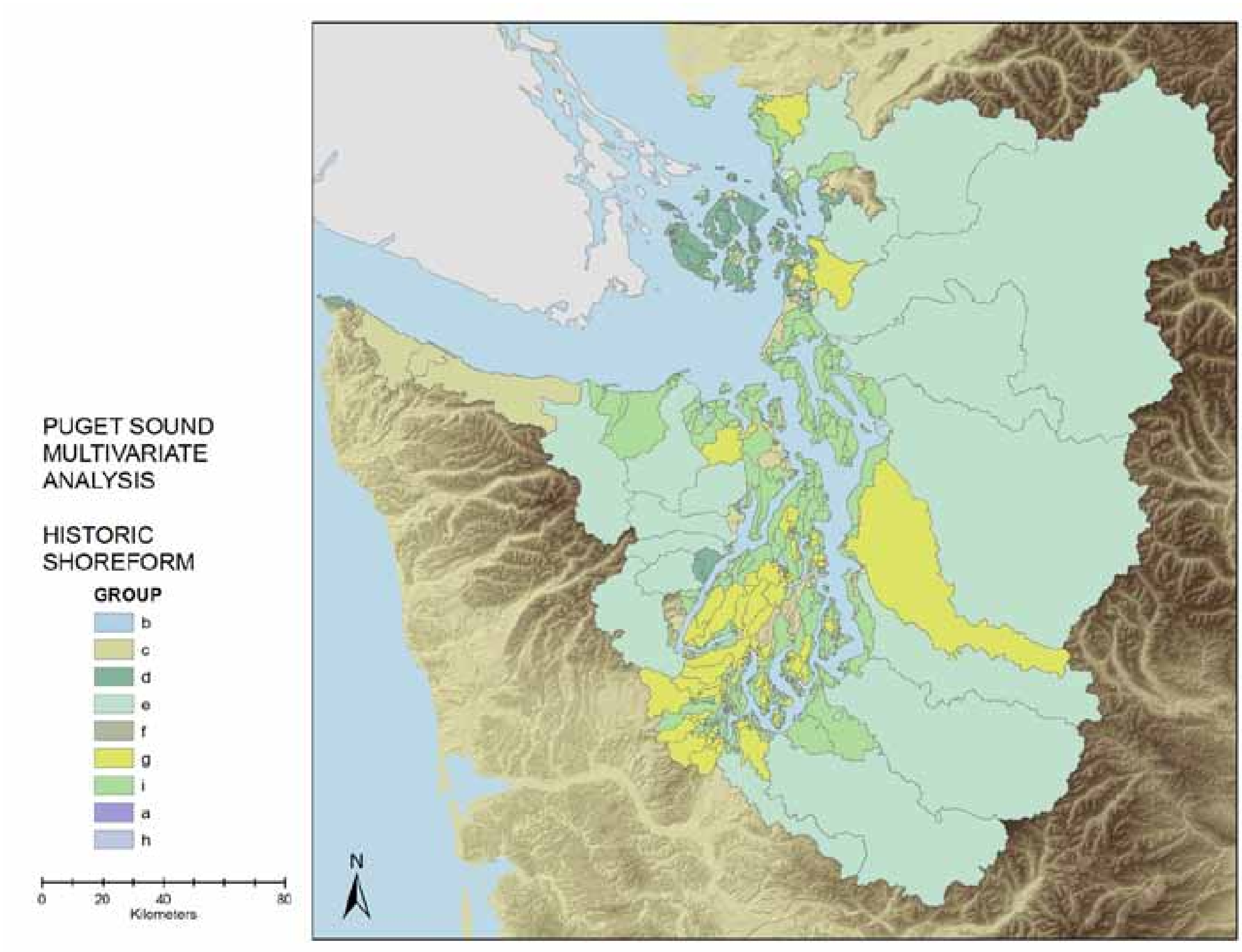
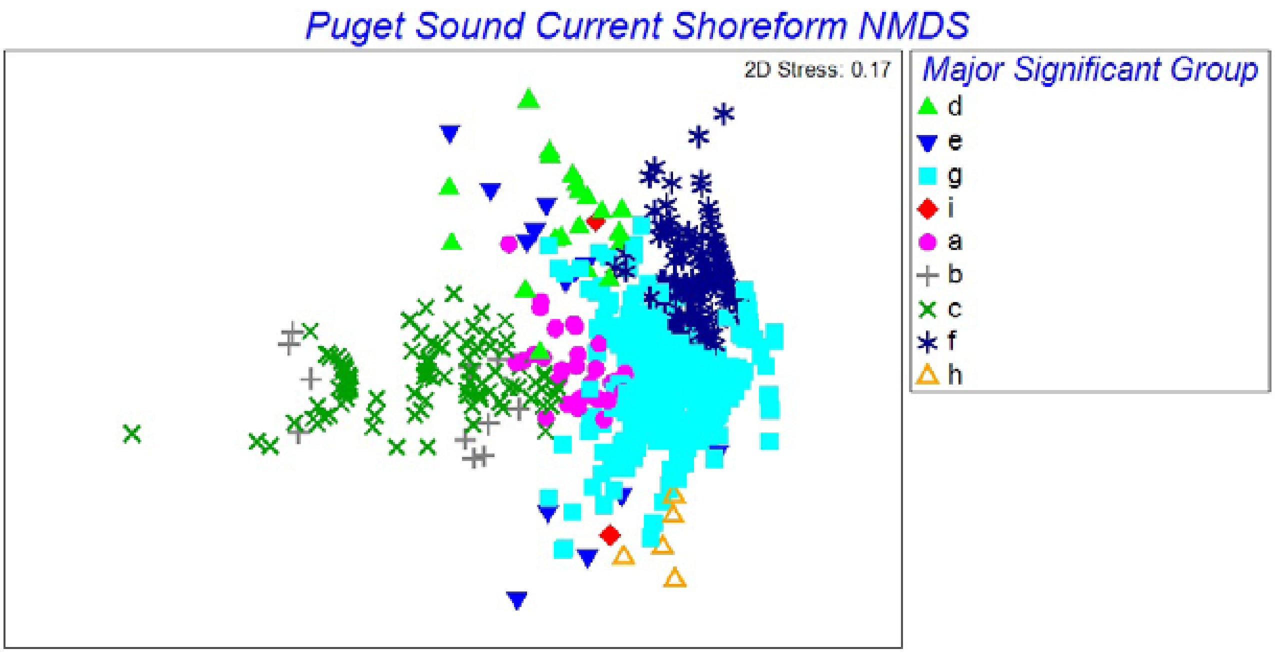


Figure 23. Map of Sound-wide distribution of process unit (PU) groups with significant similar historical shoreform composition based on multivariate analysis (see Fig. 20). Areas left blank represent the overlap of two PU that do not belong to the same group.

Similar multivariate analysis of the current shoreform composition (Fig. 24) indicates somewhat similar statistical groups but loss of complexity. SPU dominated by bluff-backed and, to a lesser extent, barrier beach still are most common, but barrier estuaries have disappeared from that group (group g). PU dominated by bluff-backed beach and open coastal inlet continue to be a cohesive group (group f), but the group dominated by rocky shoreforms (rocky plunging, rocky platform, and pocket beach: group c) is less cohesive and the contribution of rocky platform is less. The most obvious change is a group of 15 current SPU distinguished entirely by artificial shoreforms (group d). The map of current shoreform groups (Fig. 25) illustrates the occurrence of the artificial shoreform-dominated SPU in South Central, South Puget Sound and eastern San Juan Islands–Strait of Georgia sub-basins.

Analysis of the shoreform transitions suggests that the dominant shifts in PU composition between historical and current nearshore structure seldom involved just one type of shoreform change in the PU (Fig. 26). The most prominent group (g) is characterized by multiple transitions, which typically include loss of bluff-backed beach, barrier beach, barrier estuary, barrier lagoon, and/or open lagoon/marsh, in combination with replacement by artificial shoreforms. The two other prevalent SPU changes involved loss of plunging rocky, rocky platform and pocket beach shoreforms (group c) and loss of bluff-backed beaches and open coastal inlets (group i). The loss of delta shoreforms characterized only four PU. The map of these transition group PU (Fig. 27) indicates the prevalence of the complex, group g types of multiple shoreform losses. As might be expected, the bluff-backed beach and open coastal inlet losses occurred primarily in the South Central and South Puget Sound sub-basins (group i) and the loss of rocky shoreform dominated PU occurred in the San Juan Islands–Strait of Georgia Sub-Basin (group c). The delta loss (group h) PU were located in the Strait of Juan de Fuca and Hood Canal Sub-basins.



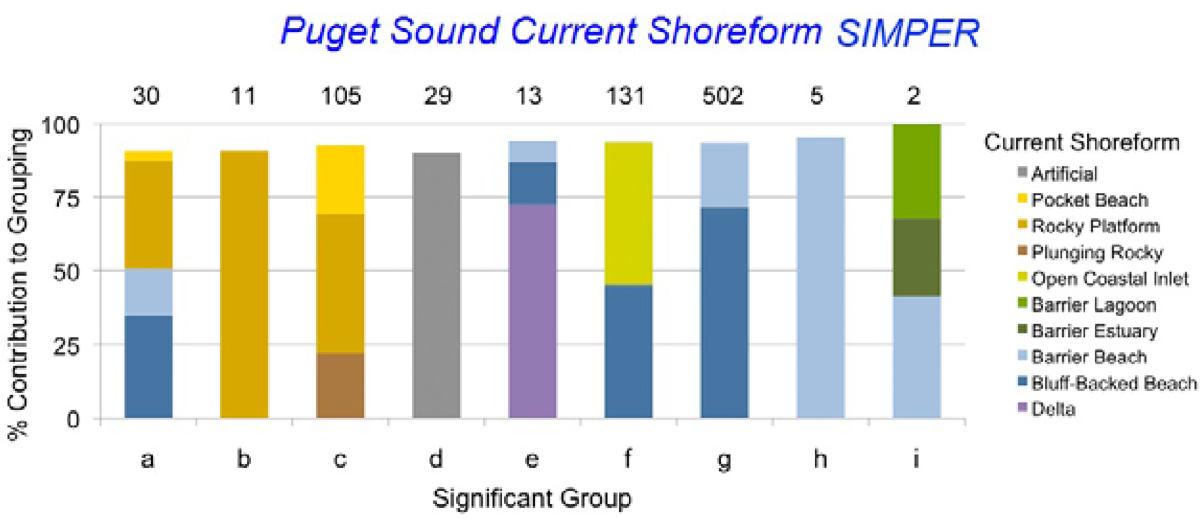


Figure 24. Non-Metric Multi-Dimensional Scaling (NMDS) plot and SIMPER multivariate analysis results for current shoreform composition in the process units (PU) of the Puget Sound Basin. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group.

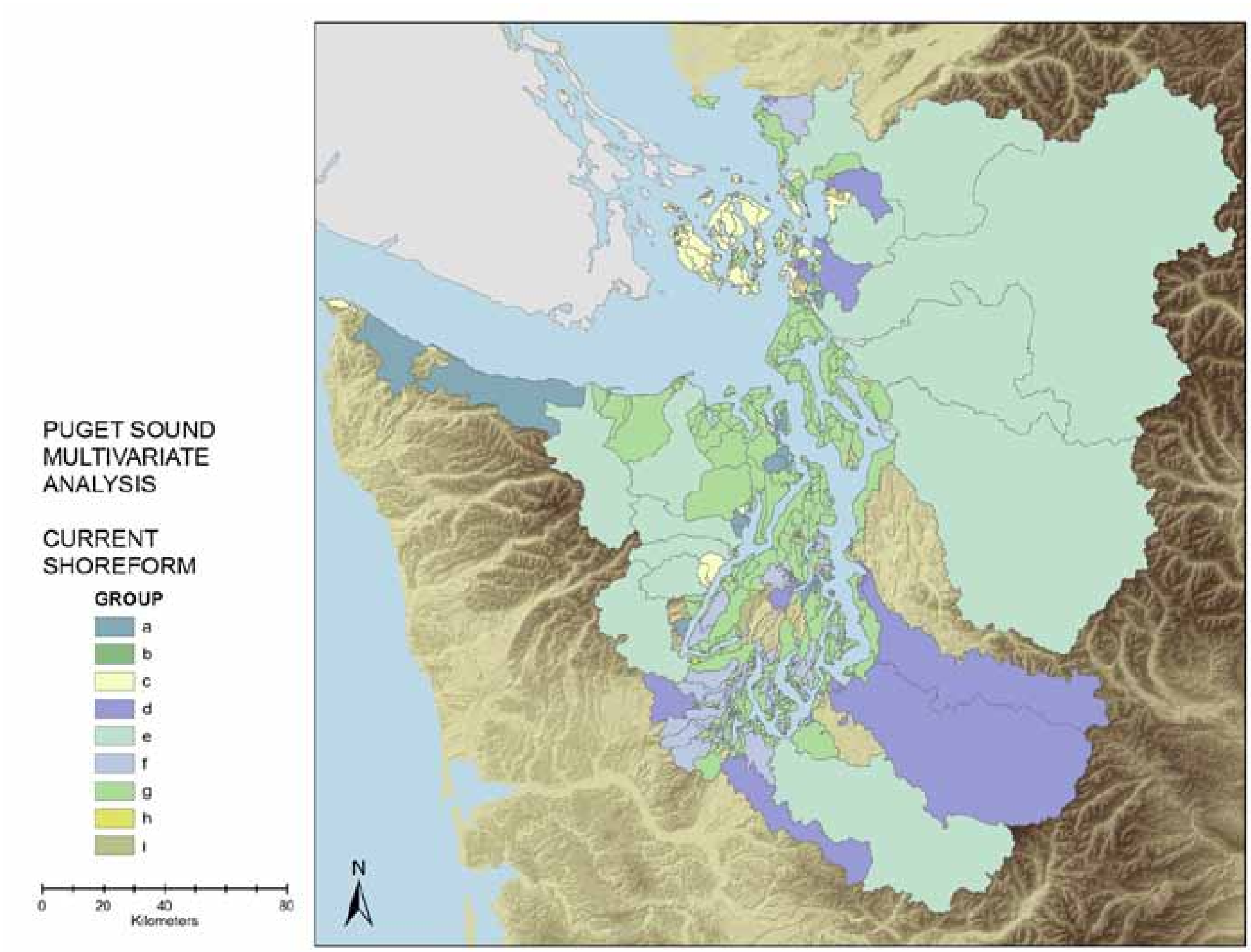
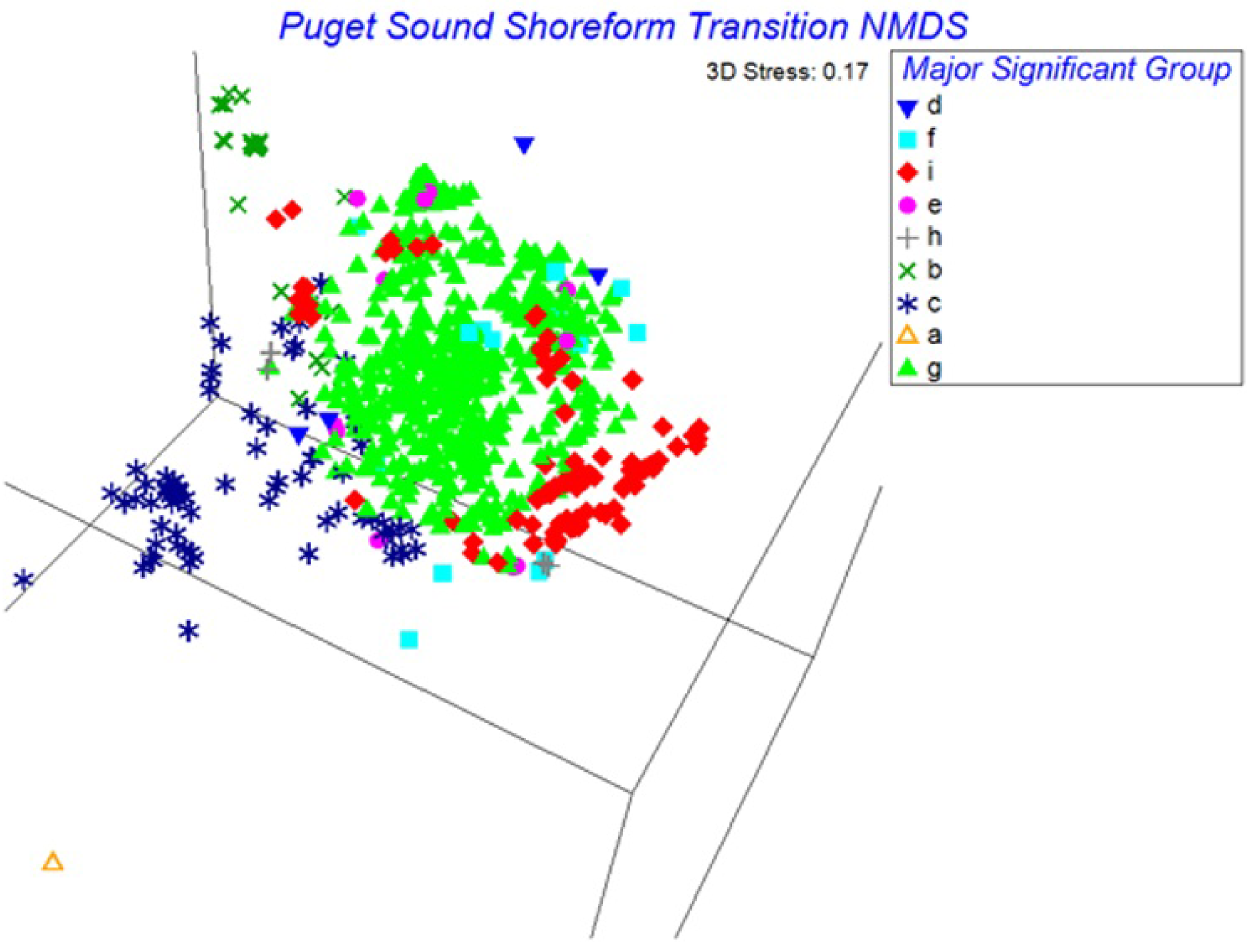


Figure 25. Map of Sound-wide distribution of process unit (PU) groups with significant similar current shoreform composition based on multivariate analysis (see Fig. 22). Areas left blank represent the overlap of two PU that do not belong to the same group.



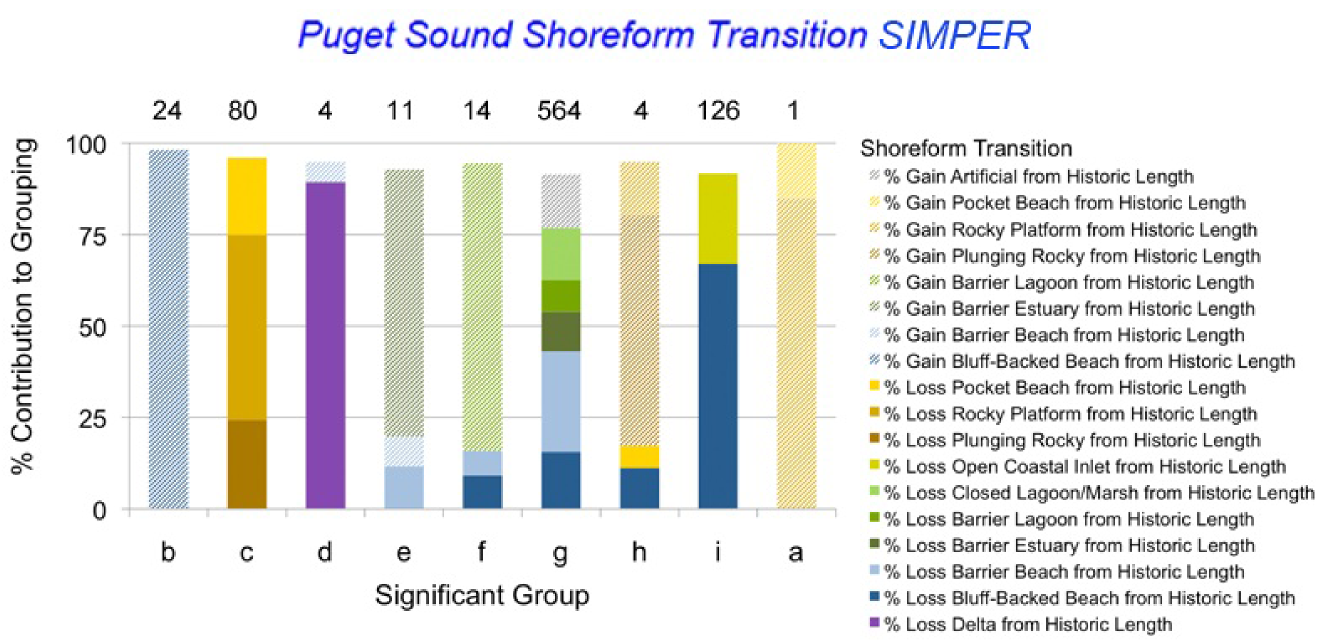


Figure 26. Non-Metric Multi-Dimensional Scaling (NMDS) plot and SIMPER multivariate analysis results for shoreform transitions in the process units (PU) of the Puget Sound Basin. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group. Values shown for groups composed of one PU are the descriptive composition of the PU.

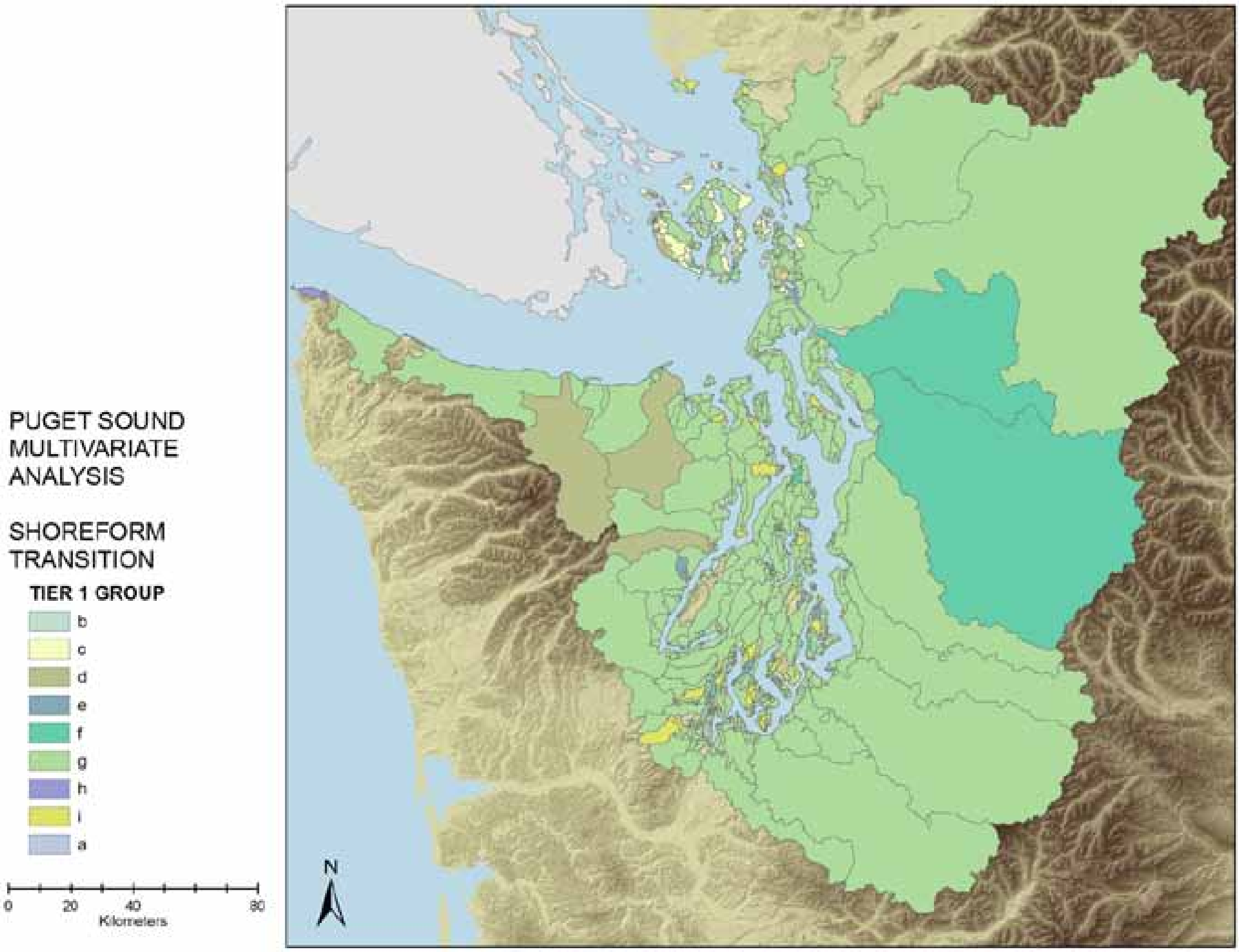
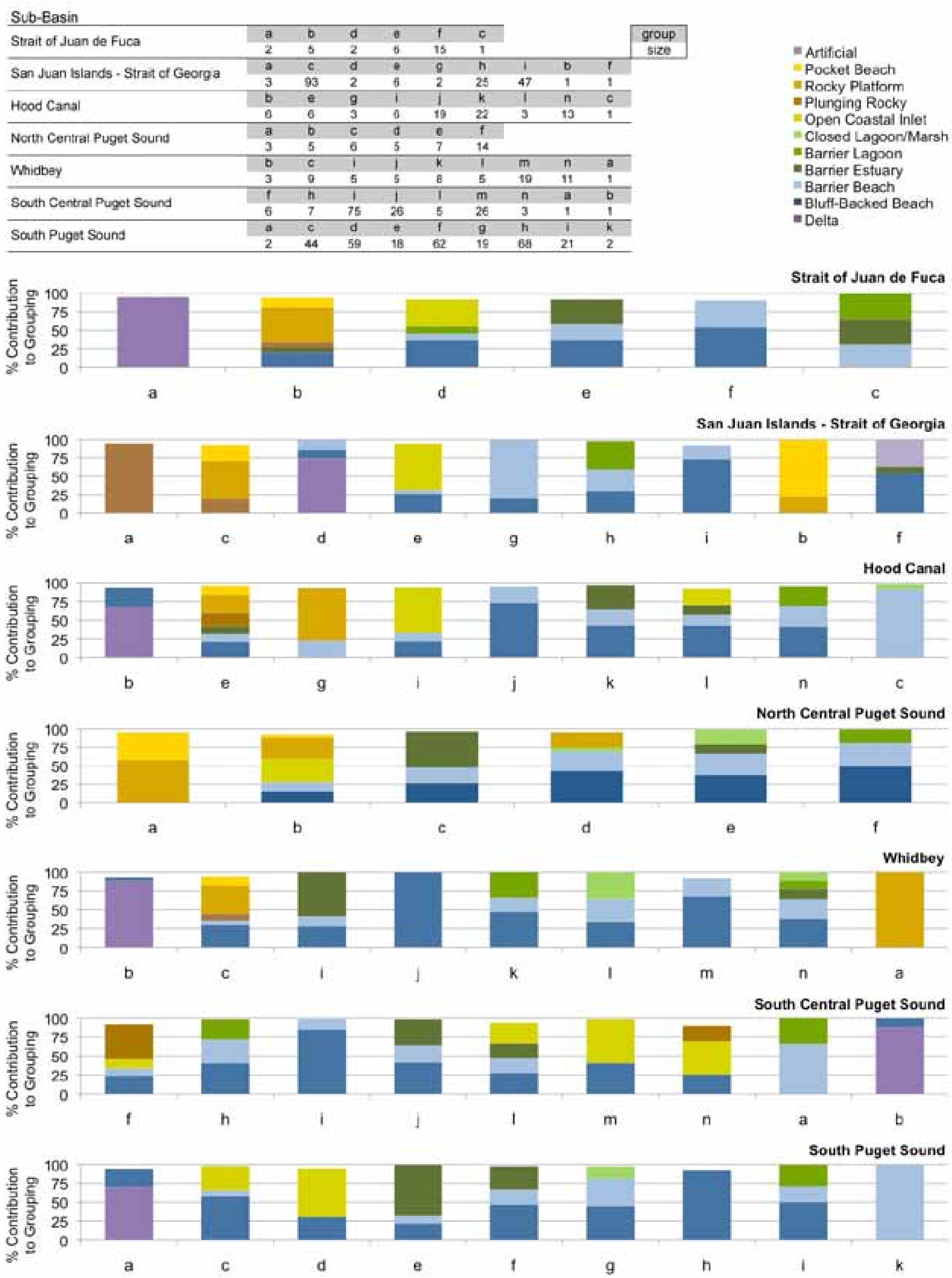


Figure 27. Map of Sound-wide distribution of process unit (PU) groups with significant similar shoreform transitions based on multivariate analysis (see Fig. 24). Areas left blank represent the overlap of two PU that do not belong to the same group.

While the Sound-wide perspective is informative for PSNERP planning at the comprehensive scale, it is also important to take into account the often considerable variation in both the natural composition of shoreforms in the PU of the seven sub-basins and the ways that shoreform transitions vary among them. Significant groups of PU shoreform compositions are presented for historical, current, and transitional conditions for each sub-basin in Figs. 28–30, and are described in the subsequent discussion under each sub-basin. In addition to variation in transitions due to sub-basin differences in the natural occurrence of shoreforms (e.g., more plunging rocky and rocky platform in the San Juan Islands–Strait of Georgia), most notable regional variations include: 1) the concentration among sub-regions of combined bluff-backed beach, barrier beach, barrier estuary, barrier lagoon and closed lagoon, and marsh transitions within PU; 2) the prevalence of bluff-backed beach, barrier beach, barrier lagoon and closed lagoon, and marsh transitions in South Central and South Puget Sound; and 3) indications that the South Puget Sound PU have experienced that most diffuse transitions of shoreforms (Fig. 30).



Sub-Basin										group size
Strait of Juan de Fuca	a	b	d	e	f	c				
	2	5	2	6	15	1				
San Juan Islands - Strait of Georgia	a	c	d	e	g	h	i	b	f	
	3	93	2	6	2	25	47	1	1	
Hood Canal	b	e	g	i	j	k	l	n	c	
	6	6	3	6	19	22	3	13	1	
North Central Puget Sound	a	b	c	d	e	f				
	3	5	6	5	7	14				
Whidbey	b	c	i	j	k	l	m	n	a	
	3	9	5	5	8	5	10	11	1	
South Central Puget Sound	f	h	i	j	l	m	n	a	b	
	6	7	75	26	5	26	3	1	1	
South Puget Sound	a	c	d	e	f	g	h	i	k	
	2	44	59	18	62	19	68	21	2	

Figure 28. Historical contribution of different shoreforms to significantly different groups of process units (PU) of the seven Puget Sound sub-basins; based on SIMPER multivariate analysis. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Table (top, left) shows the number of PU in each group.

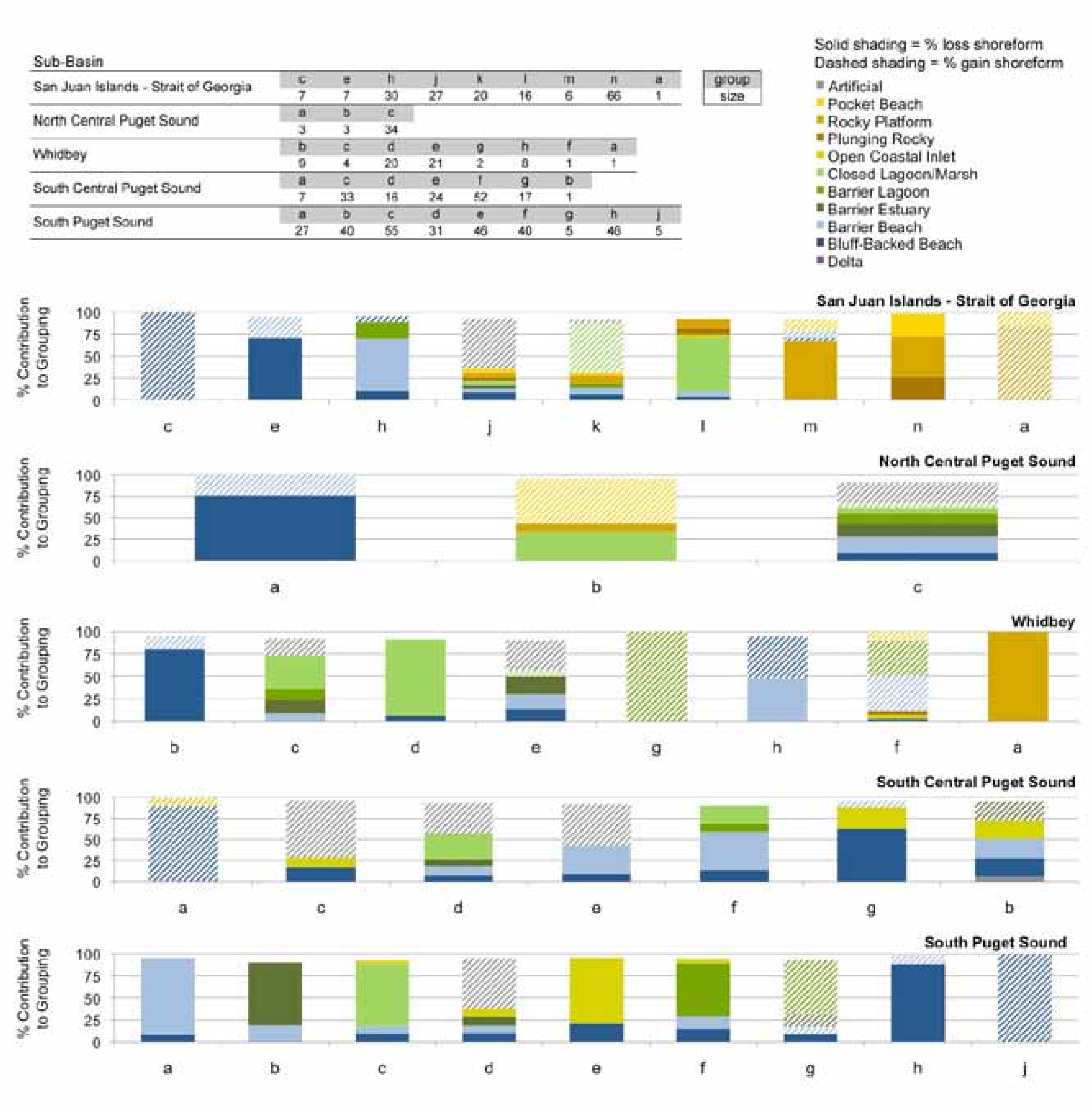


Figure 29. Current contribution of different shoreforms to significantly different groups of process units (PU) of the seven Puget Sound sub-basins; based on SIMPER multivariate analysis. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Table (top, left) shows the number of PU in each group.

Sub-Basin									
San Juan Islands - Strait of Georgia	c	e	h	j	k	l	m	n	a
	7	7	30	27	20	16	6	66	1
North Central Puget Sound	a	b	c						
	3	3	34						
Whidbey	b	c	d	e	g	h	f	a	
	9	4	20	21	2	8	1	1	
South Central Puget Sound	a	c	d	e	f	g	b		
	7	33	16	24	52	17	1		
South Puget Sound	a	b	c	d	e	f	g	h	j
	27	40	55	31	46	40	5	46	5

Figure 30. Contribution of different shoreform transitions to significantly different groups of process units (PU) of the five Puget Sound sub-basins that produced significant groupings (Strait of Juan de Fuca and Hood Canal sub-basins did not produce significant groups from the SIMPROF test). Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Table (top, left) shows the number of PU in each group.

Shoreline Alterations

The PSNERP change analysis quantifies shoreline alterations (Tier 2) as relative changes in historical attributes, such as wetlands, or anthropogenic modifications (considered stressors) along the shoreline. Within each PU, areal modifications (e.g. nearshore fill) are quantified as the percent of total aquatic area (wetted nearshore zone), while length features (e.g. tidal barriers) are quantified as the percent of total shoreline length. Nearshore roads and railroads were counted if they occurred within 25 m of the shoreline.

Descriptive

The total area of wetlands in Puget Sound has declined dramatically in most deltas, and particularly the more upper-estuary, fresher classes—tidal freshwater and oligohaline transition—where 97.8 km2 (–90.2 percent) and 54.5 km2 (–98.5 percent) have disappeared, respectively (Table 7). Loss of 39.7 and 40.6 km2 of estuarine mixing and euryhaline unvegetated wetlands is nontrivial, but proportionally less, –46.4 percent and –24.4 percent, respectively. The largest overall losses occurred in the South Central Puget Sound and Whidbey sub-basins. Among the individual deltas, the Skagit River delta has suffered the greatest absolute change, –22.5 and –25.7 km2 of tidal freshwater and oligohaline transition wetlands, respectively (Table 8). As might be expected, the heavily industrialized and urbanized Duwamish and Puyallup River deltas have suffered the greatest proportional losses (approximately 95–100 percent) in all wetland classes, but the absolute wetland loss is considerably less because the Skagit delta was so large. However, it should be recognized that an unestimated proportion of these deltas had already been changed by the time of the historical surveys. Other deltas with significant estuarine wetland losses include 47.9 km2 (–90.2 percent) and 11.7 km2 (–95.5 per-

Table 7. Historical and current area, and proportional change, of four classes of estuarine wetlands (Tier 2) in seven sub-basins and overall Puget Sound basin.

		Euryhaline Unvegetated			Estuarine Mixing			Oligohaline Transition			Tidal Freshwater		
		Historic Area (km^2)	Current Area (km^2)	Change (%)	Historic Area (km^2)	Current Area (km^2)	Change (%)	Historic Area (km^2)	Current Area (km^2)	Change (%)	Historic Area (km^2)	Current Area (km^2)	Change (%)
Strait of Juan de Fuca	Deltas	6.53	6.42	-1.68	1.25	0.84	-32.8	0	<0.01	?	0.13	0.4	207.69
	Non-deltas	*	*	*	2.44	2.36	-3.28	0.26	0.14	-46.15	0.6	0.2	-66.67
San Juan Islands- Strait of Georgia	Deltas	39.29	29.94	-23.8	13.41	5.23	-61.01	8.31	0.13	-98.41	12.49	0.66	-94.68
	Non-deltas	*	*	*	-0.01	6.45	**	32	0.08	-99.79	7.89	0.18	-97.71
Hood Canal	Deltas	10.3	4.91	-52.33	3.57	10.19	185.44	0.75	0.08	-89.33	0.86	0.76	-11.63
	Non-deltas	*	*	*	9.41	9.5	0.96	0.07	0.24	242.86	-0.01	0.02	**
North Central Puget Sound	Non-deltas	*	*	*	12.26	4.56	-62.81	0.34	0.05	-85.29	0.1	0.17	70
Whidbey	Deltas	83.82	76.58	-8.64	46.38	26.25	-43.4	46.05	0.59	-98.72	88.02	8.75	-90.06
	Non-deltas	*	*	*	-0.01	3.09	**	13.92	0.05	-99.64	0.04	0.17	325
South Central Puget Sound	Deltas	22.04	4.31	-80.44	14	0.1	-99.29	0.21	0	-100	4.61	0	-100
	Non-deltas	*	*	*	5.61	3.05	-45.63	0.17	0.06	-64.71	0	0	0
South Puget Sound	Deltas	10.57	7.46	-29.42	7.8	3.33	-57.31	0	0.01	?	2.38	0.11	-95.38
	Non-deltas	*	*	*	17.63	5.12	-70.96	6.44	0.1	-98.45	-0.01	0.27	**
Puget Sound Basin	Deltas	166.35	125.78	-24.39	85.61	45.9	-46.38	55.32	0.81	-98.53	108.49	10.68	-90.16
	Non-deltas	*	*	*	75	31.74	-57.68	8.73	0.7	-91.98	18.34	0.94	-94.87

* because outer margin of unvegetated mud- and sandflats were often not surveyed in smaller estuaries, changes in these data are not reliable

** change indeterminable because overlap occurs between Delta and Non-delta wetlands, total wetland area across Puget Sound Basin cannot be summed parentheses indicate suspected under-representation in historic surveys cent) decline of freshwater tidal wetlands in the Snohomish and Nooksack river deltas, respectively, and 13.1 km2 (–100 percent) loss of oligohaline transition wetlands in the Snohomish River delta. Several deltas actually gained some small portions of several wetland classes, most notably 1.3 km2 (14 percent), 0.8 km2 (124.9 percent) and 0.5 km2 (64.2 percent) gains in euryhaline unvegetated wetlands (mudflats) in the Snohomish, Dosewallips, and Duckabush river deltas, respectively.

Estuarine wetland loss in the smaller estuaries has involved considerably less area, but has been proportionally the same: 84.9 percent and –92.0 percent in tidal freshwater and oligohaline transition, respectively. Combined (not including the euryhaline unvegetated wetlands, that cannot be estimated from historical data), over 260 km2 of these vegetated estuarine wetlands no longer support ecosystem functions goods and services to the Sound and its populace.

Shoreline alterations (within the wetted nearshore zone, or within 25 m of the shoreline in the case of nearshore roads and railroads) over the entire Puget Sound Basin range in extent from as little as 0.4 percent (abandoned railroads) to as much as 27 percent (armoring) of the shoreline length (Table 9). Nearshore fill and breakwaters/jetties now completely cover almost 40 km2 and 37 km2, respectively, of the historical natural shoreline ecosystems. Overwater structures cover approximately 6.5 km2 of the intertidal. As would be expected, the largest PU have on average the greatest number of different shoreline alterations (approximately five types of alterations), while the lack of any alterations tend to occur in the smallest PU (Fig. 31). Only 6.5 percent (54) process units surrounding Puget Sound lack any alterations today (Table 10).

Table 8. Historical and current area, and proportional change, of four classes of estuarine wetlands (Tier 2) in sixteen major estuarine deltas in Puget Sound.

	Euryhaline Unvegetated			Estuarine Mixing			Oligohaline Transition			Tidal Freshwater		
	Historic Area (km^2)	Current Area (km^2)	Change (%)	Historic Area (km^2)	Current Area (km^2)	Change (%)	Historic Area (km^2)	Current Area (km^2)	Change (%)	Historic Area (km^2)	Current Area (km^2)	Change (%)
Deschutes	3.43	0.87	-74.5	0.05	1.08	1960	0	0	0	0	0	0
Dosewallips	0.62	1.4	124.9	0.25	0.47	88.1	0.12	0.03	-77.7	0.04	0.01	-83
Duckabush	0.72	1.18	64.2	0.25	0.31	24	0.02	0.01	-7.4	0.06	0.03	-46.4
Dungeness	6.39	6.01	-6	1.18	0.73	-37.6	0	0	100	0.03	0.1	301.9
Duwamish	8.92	0.15	-98.3	2.35	0.02	-99.1	0	0	100	3.85	0	-100
Elwha	0.14	0.42	191.8	0.08	0.11	39.8	0	0	100	0.11	0.29	170.5
Hamma Hamma	1.34	1.3	-2.7	0.18	0.23	28	0.05	0.01	-71	0.03	0.09	193
Nisqually	21.49	14.67	-31.7	4.05	4.85	19.6	2.7	0.09	-96.6	12.35	0.56	-95.5
Nooksack	7.13	6.59	-7.7	7.74	2.25	-70.9	0	0.01	100	2.38	0.11	-95.6
Puyallup	6.91	0.31	-95.5	10.85	0.04	-99.6	0.21	0	-100	0.76	0	-99.6
Quilcene	2.1	0.46	-78	0.59	2.46	315.3	0.09	0.01	-89.9	0.06	0.14	133
Samish	17.8	15.27	-14.2	9.36	0.38	-95.9	5.61	0.04	-99.3	0.14	0.11	-22.1
Skagit	43.25	42.62	-1.5	26.14	16.9	-35.3	26.2	0.5	-98.1	25.28	2.8	-88.9
Skokomish	5.52	0.56	-89.8	2.3	6.73	192.2	0.47	0.01	-97	0.67	0.49	-26.9
Snohomish	8.95	10.2	14	9.5	2.95	-68.9	13.13	0	-100	53.07	5.18	-90.2
Stillaguamish	35.57	26.8	-24.7	12.04	8.22	-31.7	7.63	0.1	-98.7	9.67	0.77	-92

Table 9. Total percent of shoreline length or nearshore aquatic area occupied by shoreline alterations (Tier 2) in Puget Sound and sub-basins.

	Percent (%) of Shoreline Length					Breakwater /Jetty (km)	Marina (km^2)	Nearshore Fill (km^2)	OWS (km^2)	Parcels (per 10 km)
	Tidal Barrier	Nearshore Road	Abandoned RR	Active RR	Armoring					
Strait of Juan de Fuca	3.7	6.8	4	0	16.1	4.7	0.23	1.58	0.2	64
San Juan Islands-Strait of Georgia	6	6.1	0.1	1.6	14	15.53	2.04	7.93	1.22	99.3
Hood Canal	7.7	12.8	0	0	21.2	0.87	0.13	0.72	0.35	157
North Central Puget Sound	3.3	3.2	0	0	9.8	1.49	0.2	1.34	0.2	171.1
Whidbey	31.3	6.7	0	1.4	22.5	8.97	1.02	9.86	0.79	170.9
South Central Puget Sound	11.7	11.2	0	2.7	62.8	8.83	3.08	20.38	3.7	210.9
South Puget Sound	3.4	6.5	0.1	2.6	34.5	0.73	0.33	3.98	0.52	166.3
Puget Sound Basin	10.5	7.9	0.4	1.4	27	37.23	6.33	39.3	6.45	146.1

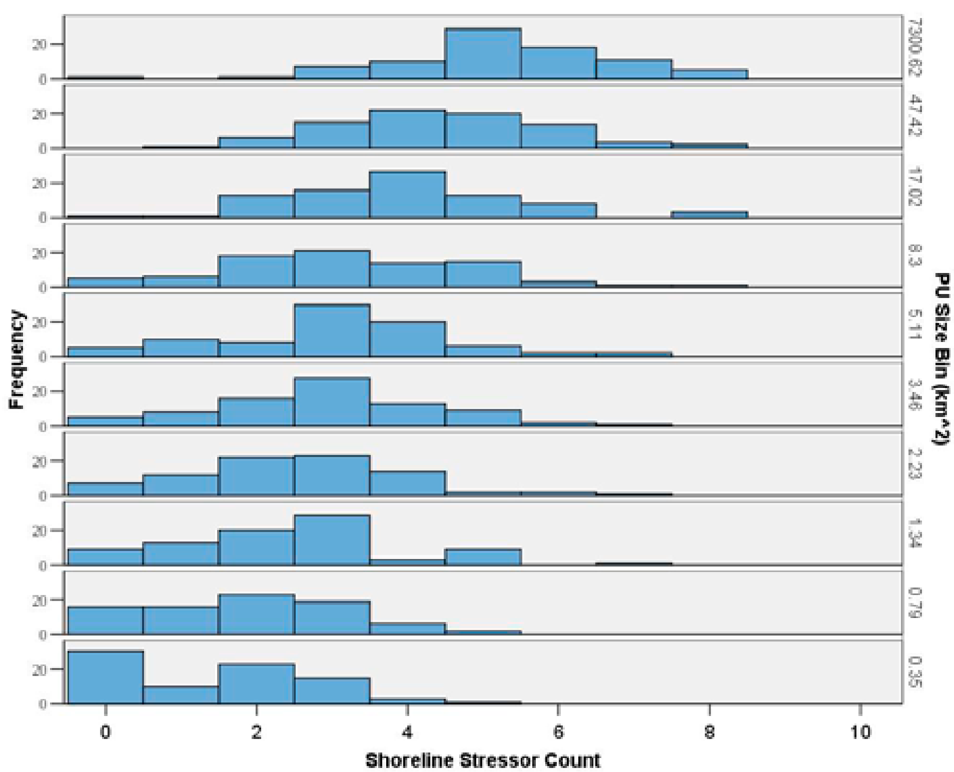


Figure 31. Frequency distributions of shoreline modifications of PU in the Puget Sound Basin; PU are divided into quantile size bins based on their total area and the number of PU are displayed according to their count of shoreline alteration types (1 through 8; excludes gain or loss of wetland classes).

Table 10. Number and percent of process units by sub-basin and Sound-wide without shoreline alterations (including wetland change and anthropogenic modifications).

	Count of PU	Percent (%) of PU
Strait of Juan de Fuca	2	6.25
San Juan Islands-Strait of Georgia	31	16.94
Hood Canal	2	2.47
North Central Puget Sound	4	9.76
Whidbey	5	7.25
South Central Puget Sound	2	1.31
South Puget Sound	34	11.53
Puget Sound Basin	54	6.52

Shoreline armoring is pervasive; almost 30 percent of the PU have no or undetected armoring, but the mean level of armoring is almost 30 percent (median 18 percent) and 25.6 percent of the PU have over half of their shoreline armored (Fig. 32). Only 20 percent of the PU have tidal barriers. These dikes, revetments, fill, and other barriers to tidal inundation cover considerably less shoreline length, except in the major river deltas, where 12 of the 16 have more than 40 percent of their shoreline length covered by such barriers (Fig. 33). Roads occur in slightly less than 50 percent of the PU and typically cover less than 50 percent of their shoreline lengths (Fig. 34); on average, only 8.2 percent of the shoreline length is covered (median 2.2 percent) but 21 PU (2.5 percent) have more than 50 percent of their shorelines covered by roads. Both active (<three percent) and abandoned (one percent) railroads rarely occur along a PU shoreline (Figs. 35 & 36), although five PU have half or more of their shoreline intersected by active railroads. Breakwaters and jetties occur in 74 PU (8.9 percent; six of which are deltas) but all occupy less than 20 percent of the PU shoreline length (Fig. 37).

Nearshore fill occurs in approximately ten percent of the PU, but can occupy up to 100 percent of the total nearshore aquatic area (in three PU); 50 percent or more of that area is covered in ~16 percent of the PU (Fig. 38). Overwater structures (OWS) are distributed in approximately the same frequency among the PU, where OWS cover 50 percent or more of the nearshore aquatic area in only six PU (Fig. 39); the nearshore aquatic area is completely covered in two PU. Marinas are located in more than 120 process units, many with more than one occurrence; although the vast majority cover very little of the PU nearshore aquatic area; 13 PU have marinas that comprise 50 percent or more (Fig. 40).

The type and magnitude of shoreline alterations vary considerably among the diverse nearshore environments of the seven Puget Sound sub-basins. While the majority of the PU in most of the sub-basins are armored less than 40–50 percent (e.g., North Central Sub-Basin has only PU>25 percent armored, mean 7.8 percent), most of the PU in the South Central Sub-Basin are armored >25 percent (mean 56.6 percent) and the mean level of armoring is >20 percent in three other sub-basins (South Puget Sound, 33.6 percent; Hood Canal, 25.1 percent; Whidbey, 20.4 percent) (Fig. 41). Tidal barriers account for >30 percent of shoreline length in DPU wherever they occur (Fig. 43), but also constitute up to 98.2 percent of SPU in the South Central Sub-Basin; the mean proportion of tidal barriers, including deltas, ranged from 1.6 percent (South Puget Sound) to 6.8 percent (Whidbey Sub-Basin). The occurrence of breakwaters and jetties varied between two PU (Hood Canal) and 21 PU (San Juan Island–Strait of Georgia) in the sub-basins, but never exceeded 20 percent of the PU shoreline length (Fig. 43); maximum shoreline length covered by breakwaters and jetties occurred in the San Juan Island–Strait of Georgia (52.7 percent and South Central (43.6 percent) sub-basins. Every sub-basin has some level of road development along the shoreline, but while the Juan de Fuca–Strait of Georgia and North Central sub-basins have no PU with roads >~25 percent of the shoreline length, the other sub-basins have PU with maximum road coverage of between 53.8 and 100 percent (Fig. 44); the Hood Canal Sub-Basin has the highest median road influence (9.8 percent). Active railroads intersect with PU shorelines quite variably, most notably in the San Juan–Strait of Georgia (mean 1.4 percent), South Central (mean 1.6 percent) and South Puget Sound (mean, 1.1 percent) sub-basins (Fig. 45). Abandoned railroads are concentrated primarily in the Strait of Juan de Fuca Sub-Basin (mean, 3.5 percent of PU shoreline length), but occur also in several PU in the San Juan–Strait of Georgia and South Puget Sound sub-basins (Fig. 46).

Nearshore fill typically occurs over <20 percent of the nearshore aquatic area, but is more extensive in the South Central (mean 7.4 percent) and South Puget Sound (mean 1.7 percent), where fills occupy up to 100 and 67.8 percent of the PU nearshore aquatic area, respectively (Fig. 47). Overwater structure coverage of the nearshore aquatic area reflects somewhat the same pattern as nearshore fill, with <1 percent mean coverage in the Juan de Fuca, North Central and Whidbey sub-basins, but extensive coverage (mean, 6.8 percent) in the South Central Sub-Basin and moderate coverage (mean 1.3–1.7 percent) in the Hood Canal, San Juan Island–Strait of Georgia and South Puget Sound sub-basins (Fig. 48). Although their density is relatively low (maximum of 10 in one PU), marinas cover the most (seven) PU with over 50 percent of the PU nearshore aquatic area in the South Central (mean, 6.7 percent) Sub-Basin, and to a lesser degree (one to two PU >50 percent coverage) in the San Juan Islands–Strait of Georgia (mean, 2.7 percent), Hood Canal (mean 2.5 percent), and South Puget Sound (mean, 1.0 percent) sub-basins (Fig. 49).

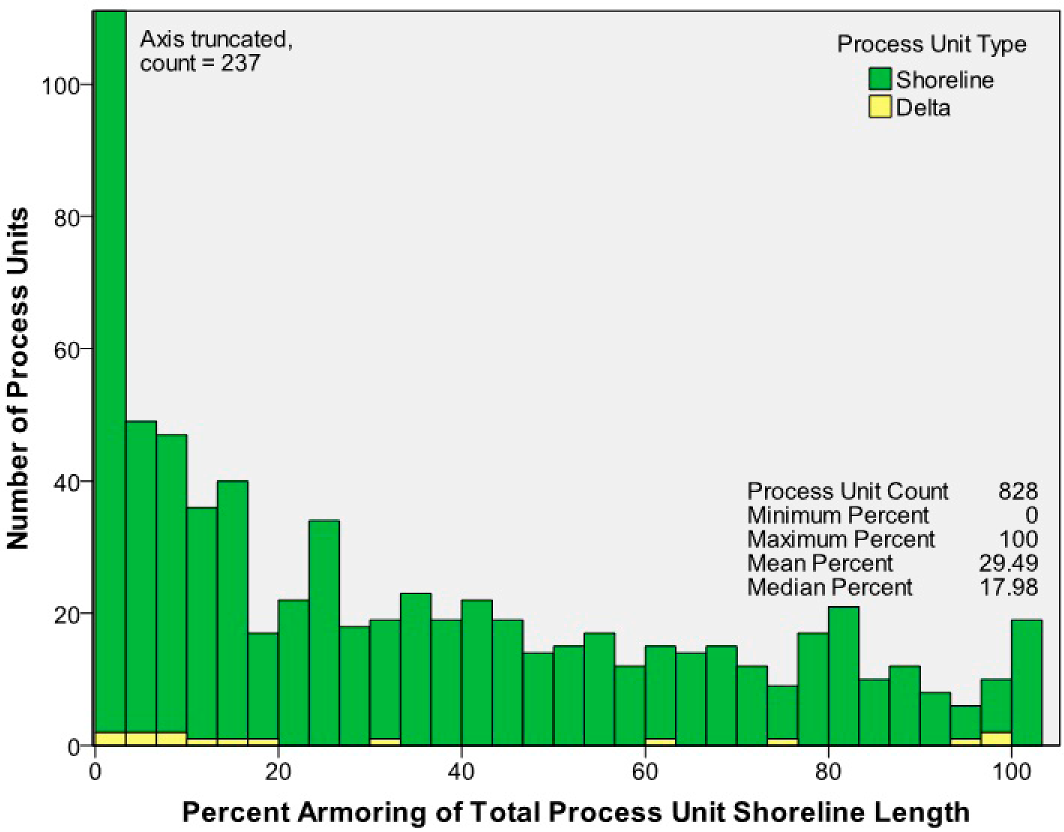


Figure 32. Frequency distribution of the percent of process unit shoreline length that is armored.

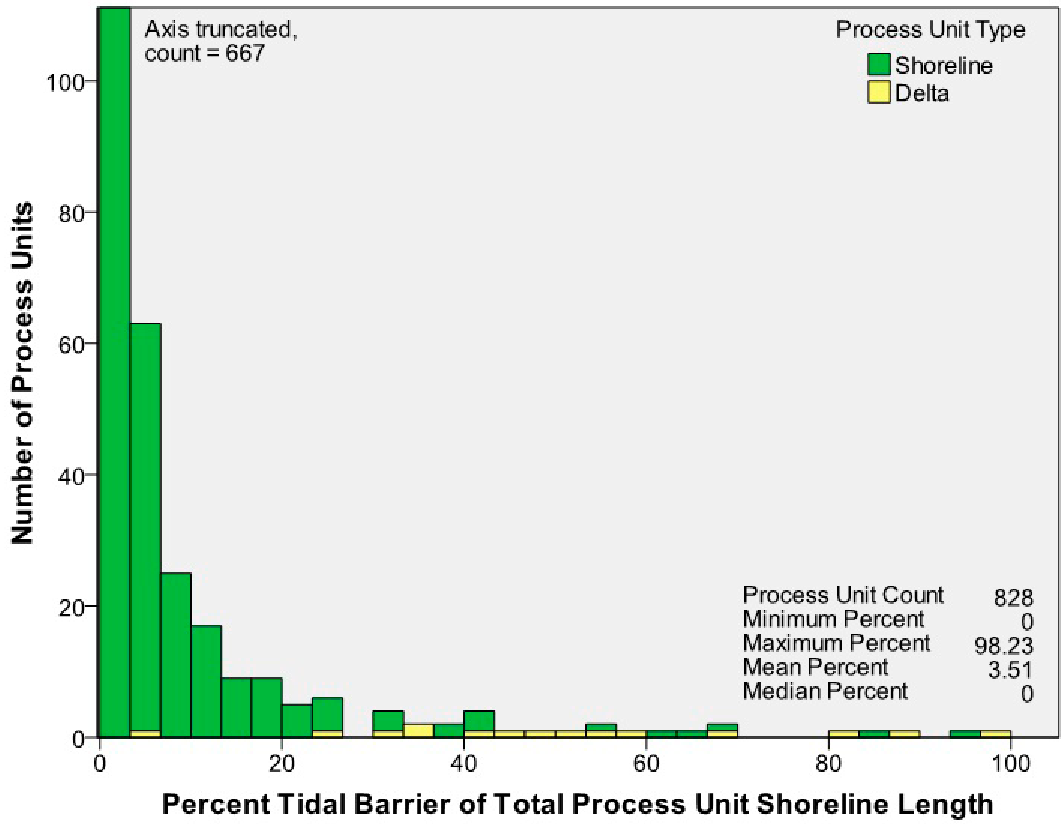


Figure 33. Frequency distribution of the percent of process unit shoreline length occupied by tidal barriers.

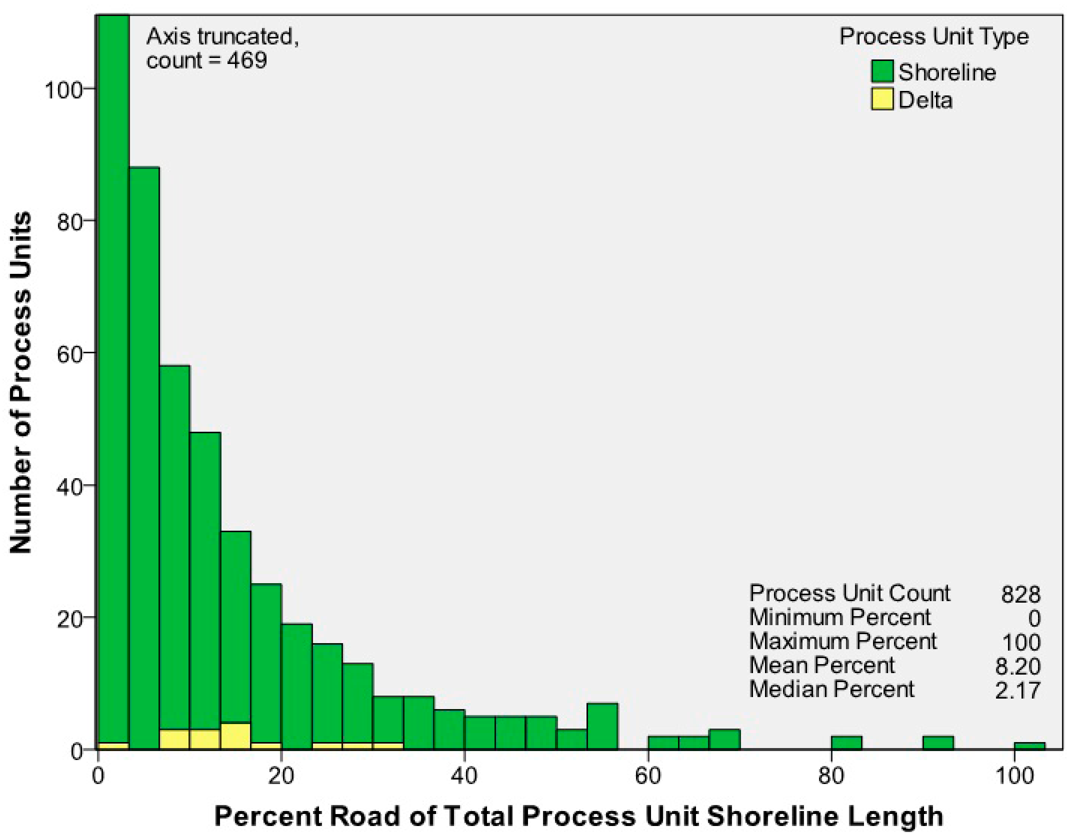


Figure 34. Frequency distribution of the percent of process unit shoreline length occupied by roads.

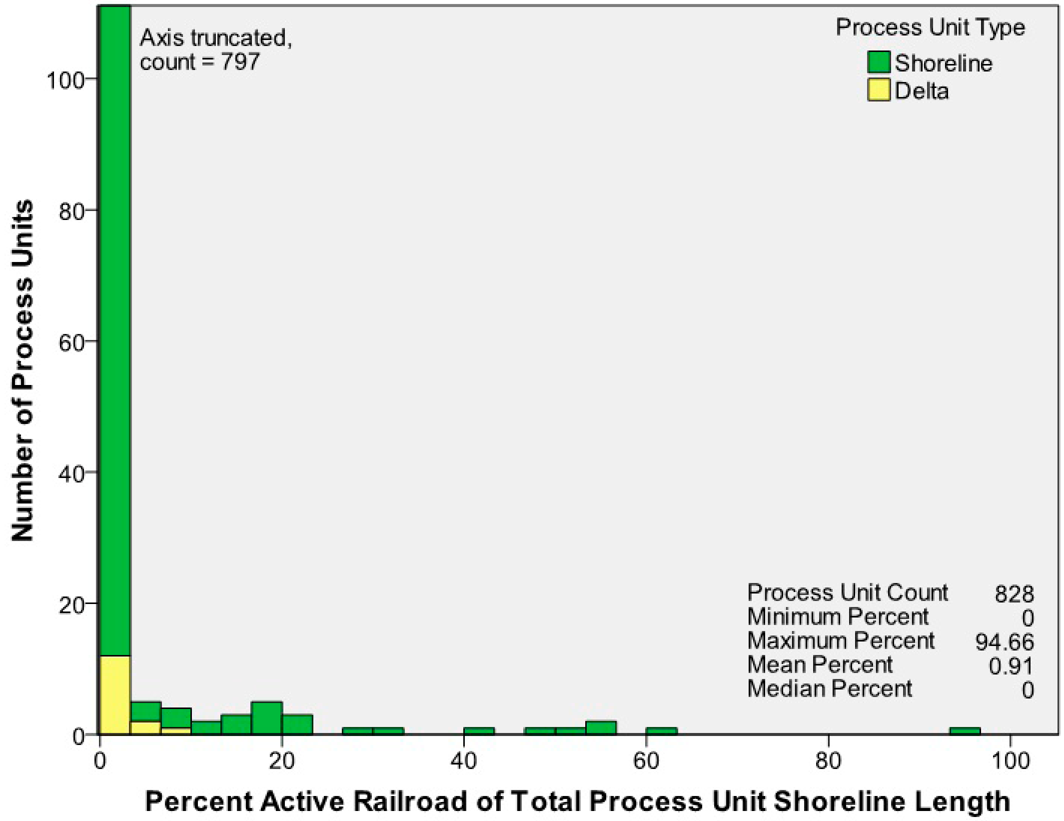


Figure 35. Frequency distribution of the percent of process unit shoreline length occupied by active railroads.

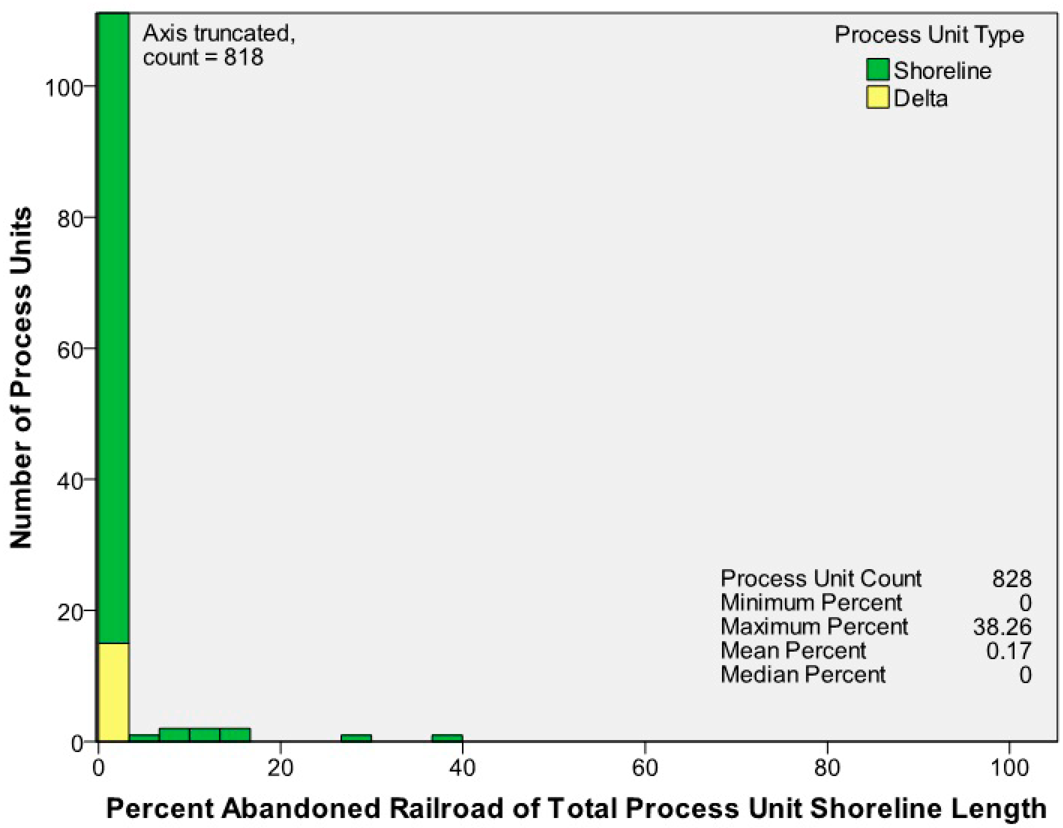


Figure 36. Frequency distribution of percent of process unit shoreline length occupied by abandoned railroads.

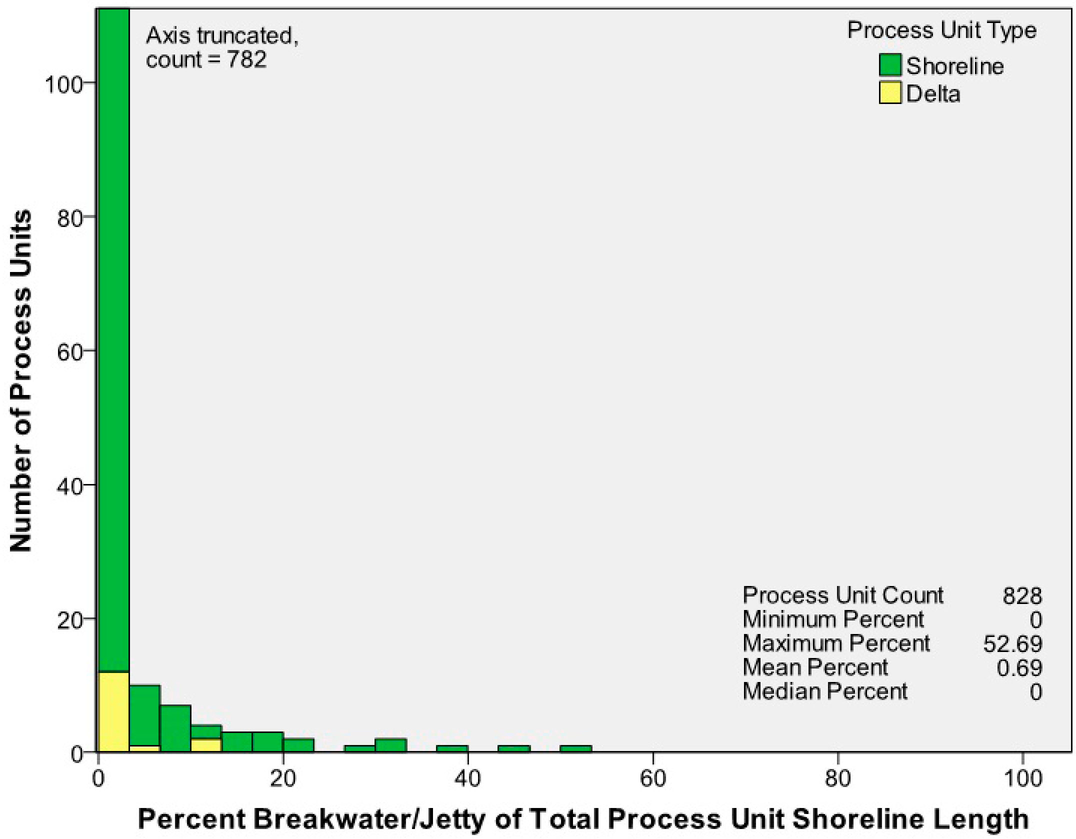


Figure 37. Frequency distribution of percent of process unit shoreline length occupied by breakwaters and jetties.

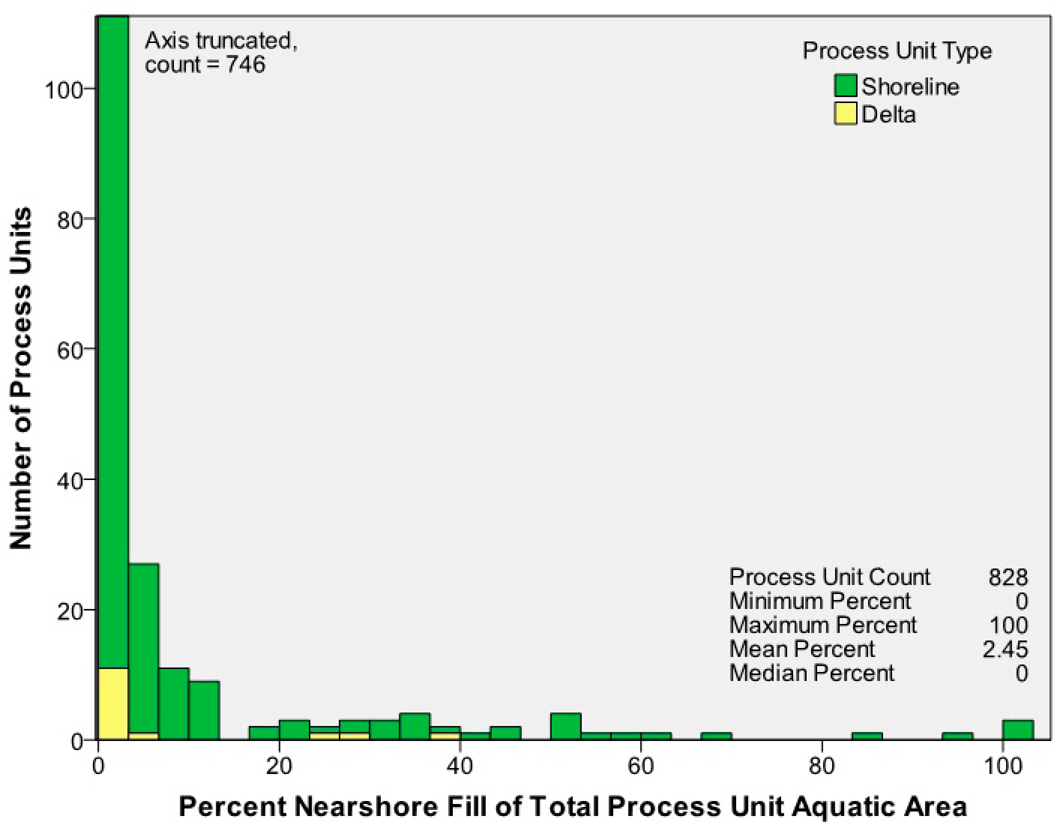


Figure 38. Frequency distribution of percent of nearshore aquatic area occupied by fill.

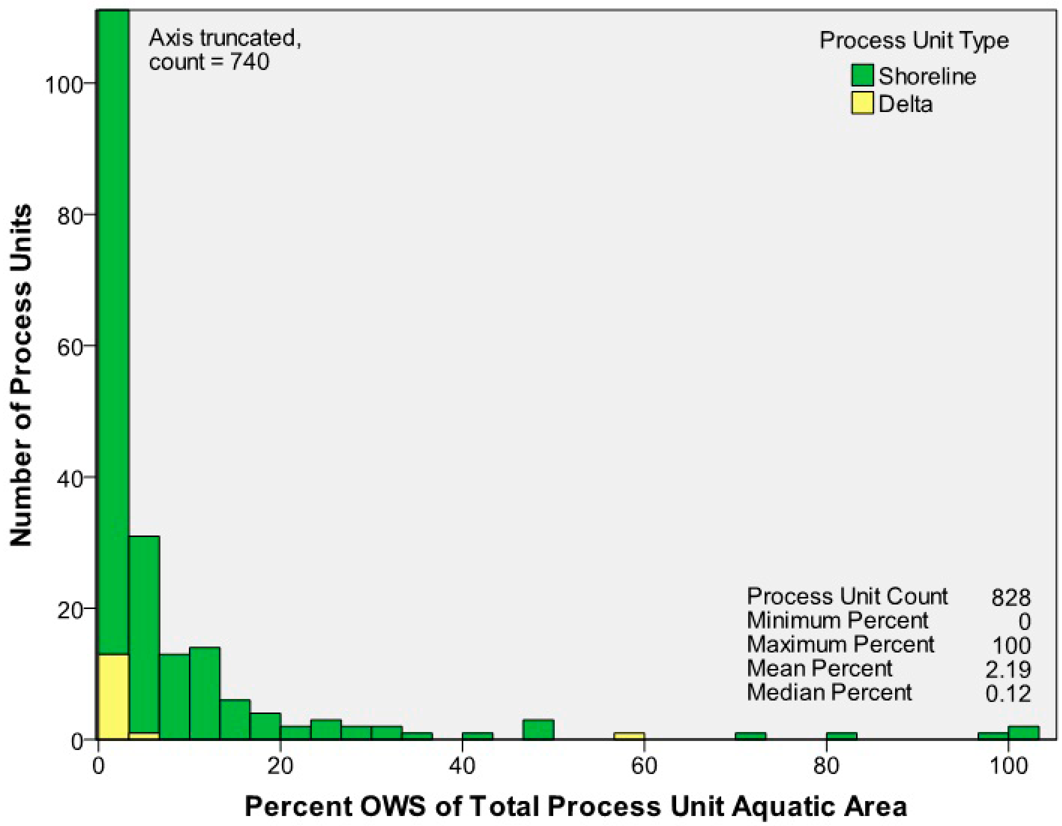


Figure 39. Frequency distribution of percent of process unit nearshore aquatic area occupied by overwater structures.

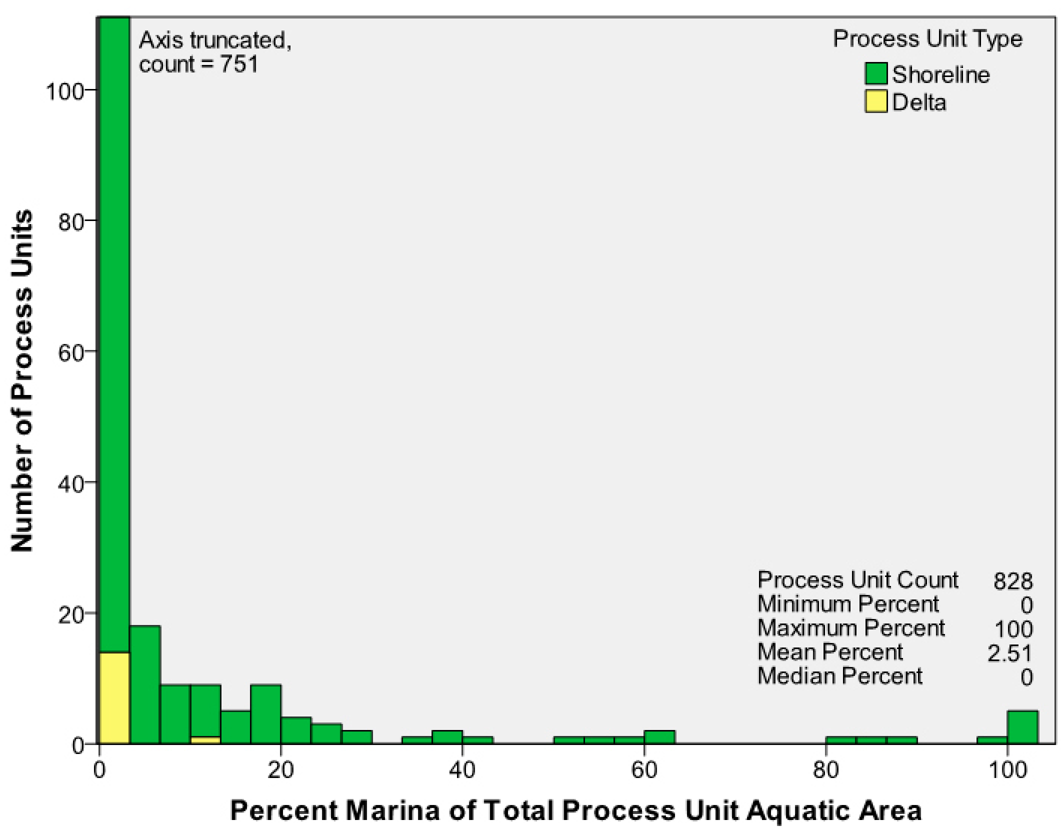


Figure 40. Frequency distribution of percent of process unit nearshore aquatic area occupied by marinas.

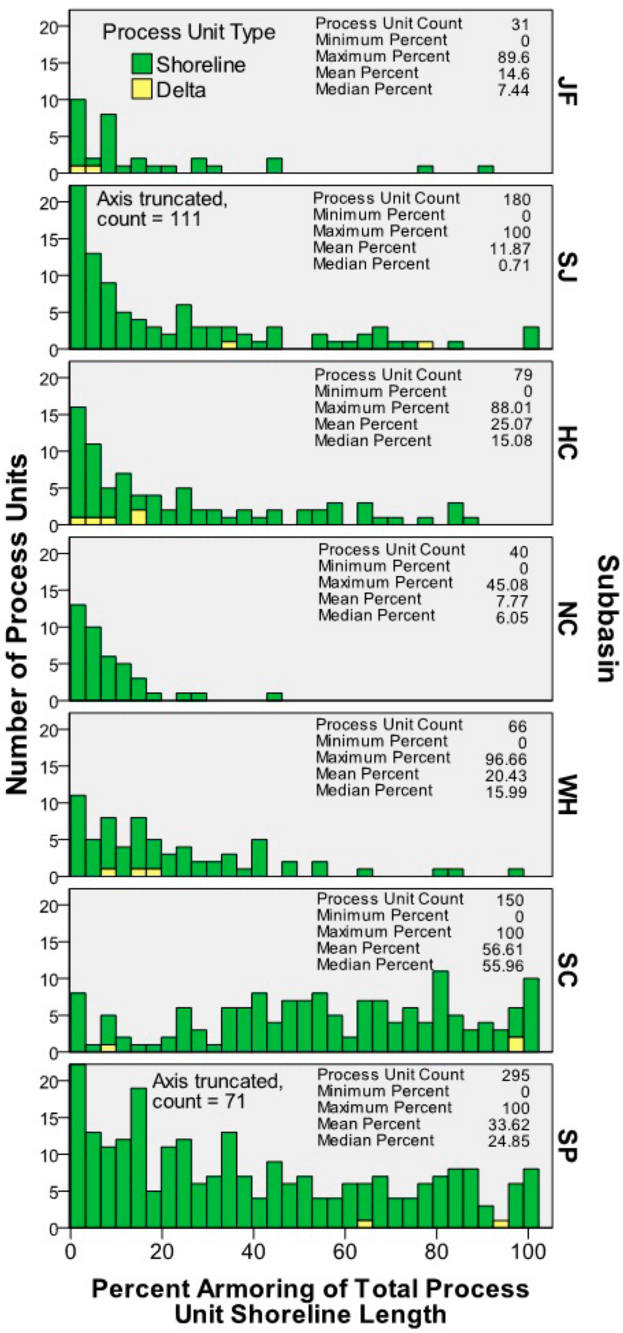


Figure 41. Frequency distribution of percent armoring of total process unit shoreline length among seven Puget Sound sub-basins.

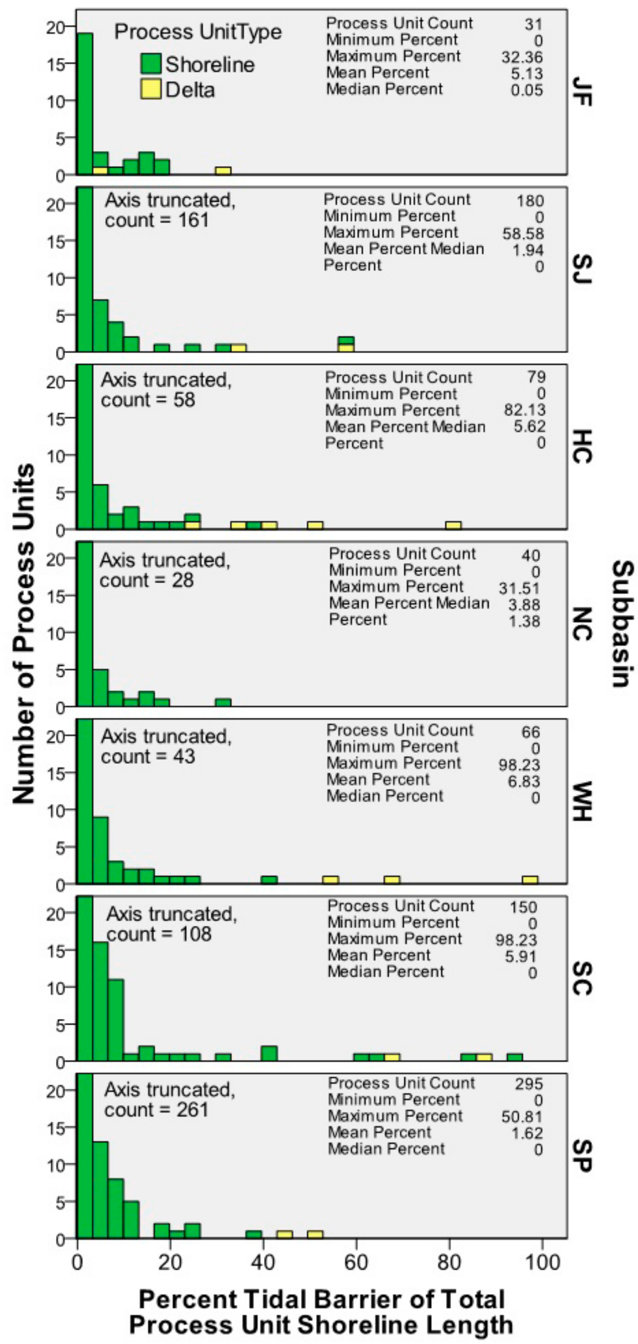


Figure 42. Frequency distribution of percent tidal barriers of total process unit shoreline length among seven Puget Sound sub-basins.

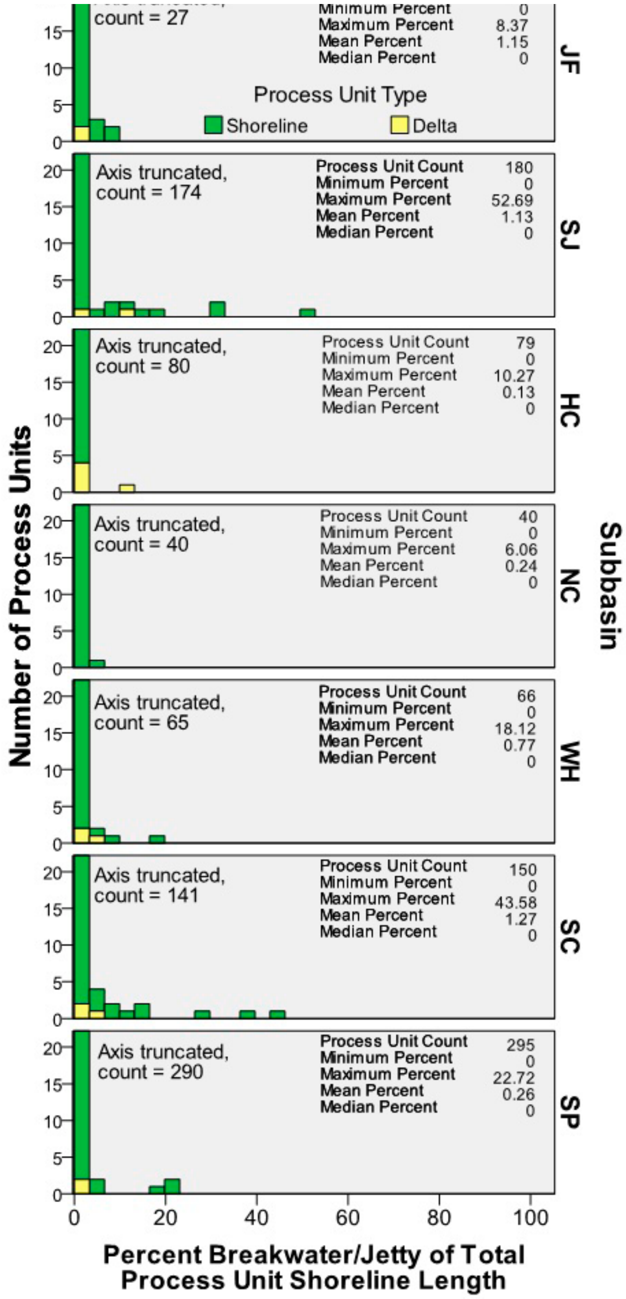


Figure 43. Frequency distribution of percent breakwaters/jetties of total process unit shoreline length among seven Puget Sound sub-basins.

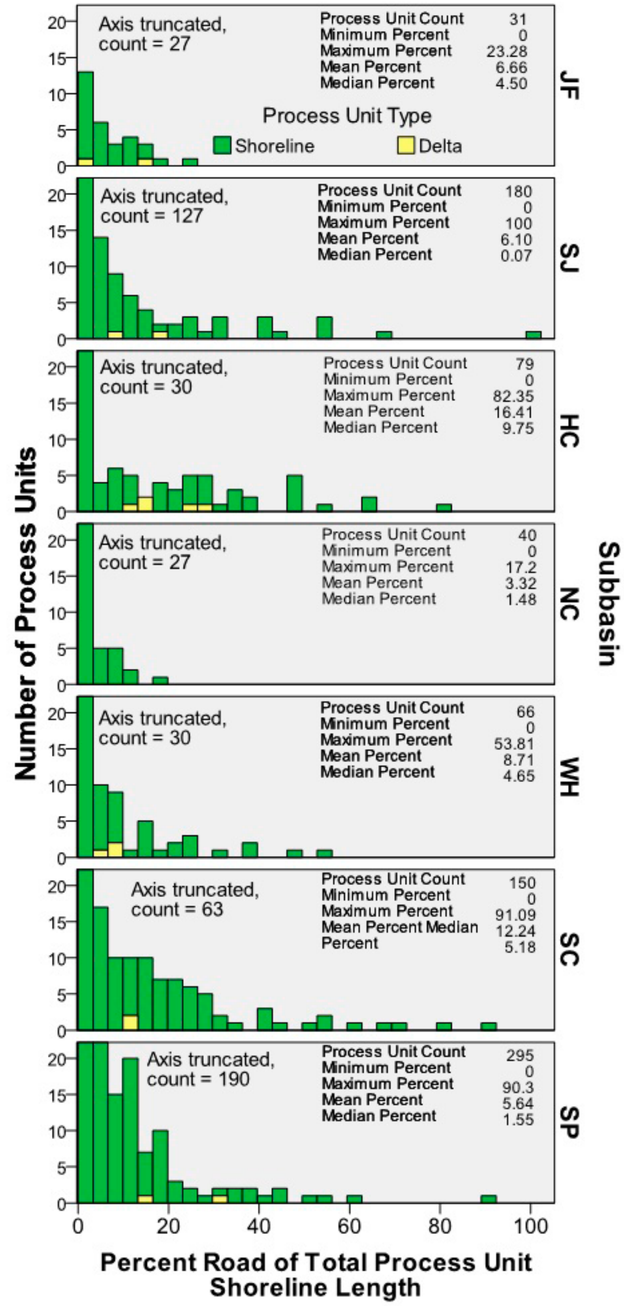


Figure 44. Frequency distribution of percent roads of total process unit shoreline length among seven Puget Sound sub-basins.

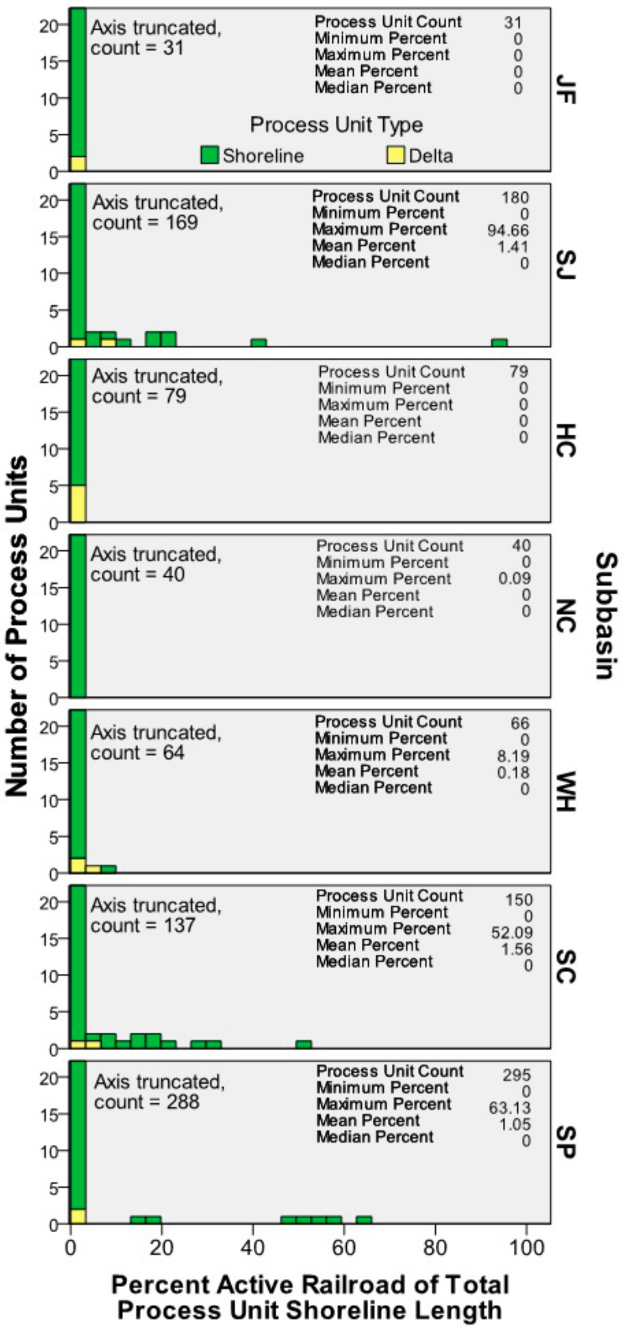


Figure 45. Frequency distribution of the percent active railroads of total process unit shoreline length among seven Puget Sound sub-basins.

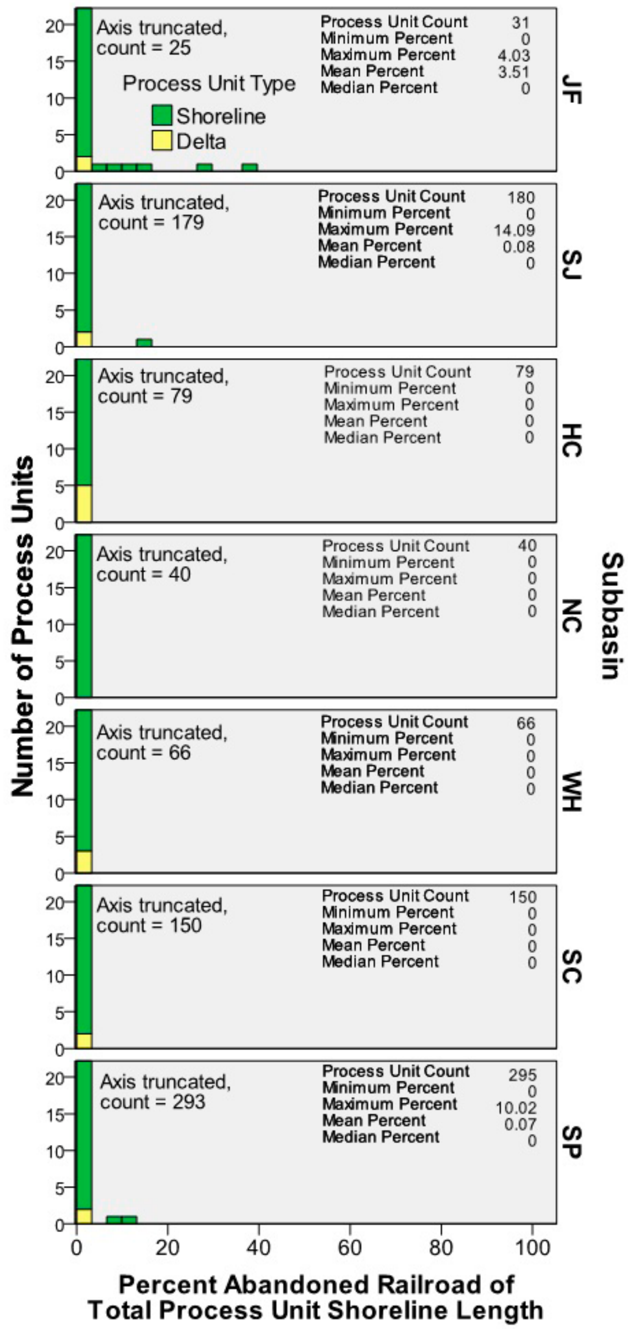


Figure 46. Frequency distribution of the percent abandoned railroads of total process unit shoreline length among seven Puget Sound sub-basins.

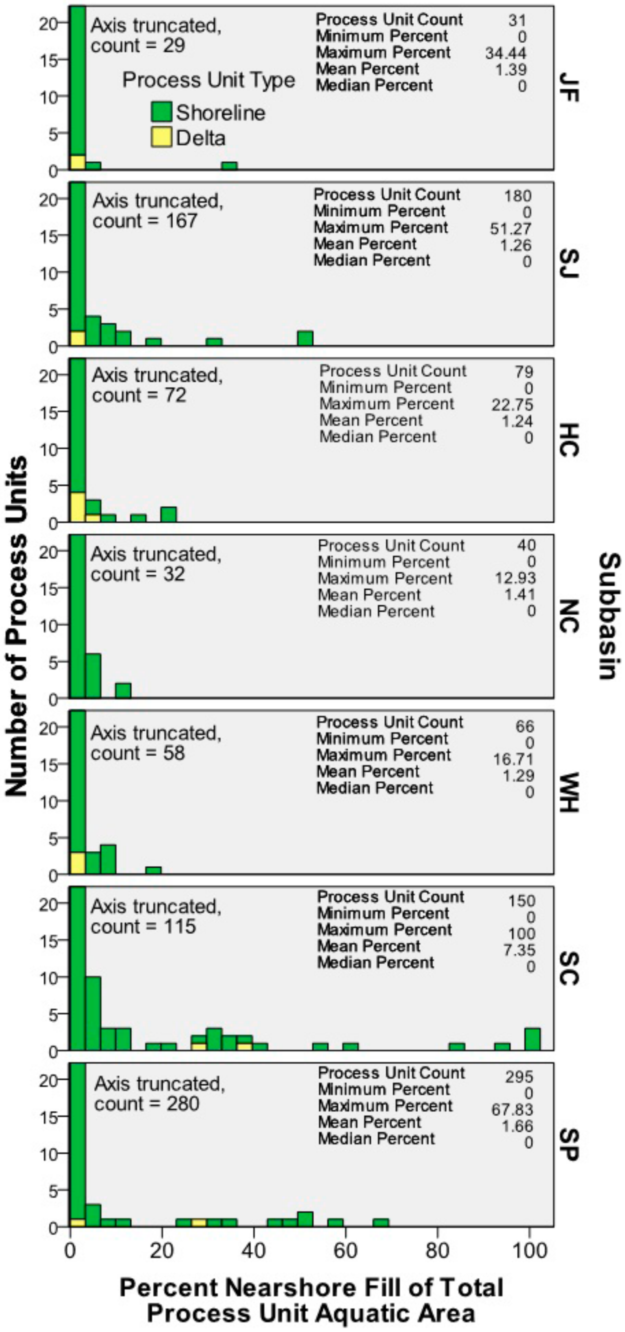


Figure 47. Frequency distribution of percent nearshore fill of total process unit aquatic area among seven Puget Sound sub-basins.

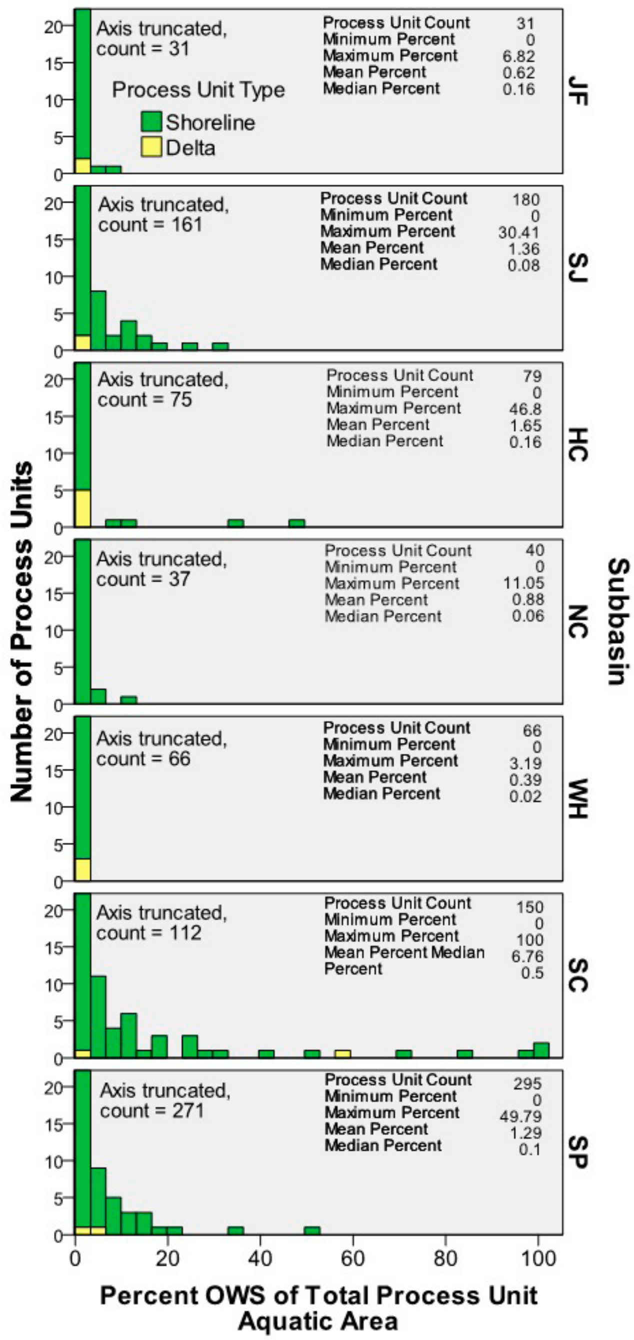


Figure 48. Frequency distribution of percent overwater structures (OWS) of total process unit aquatic area among seven Puget Sound sub-basins.

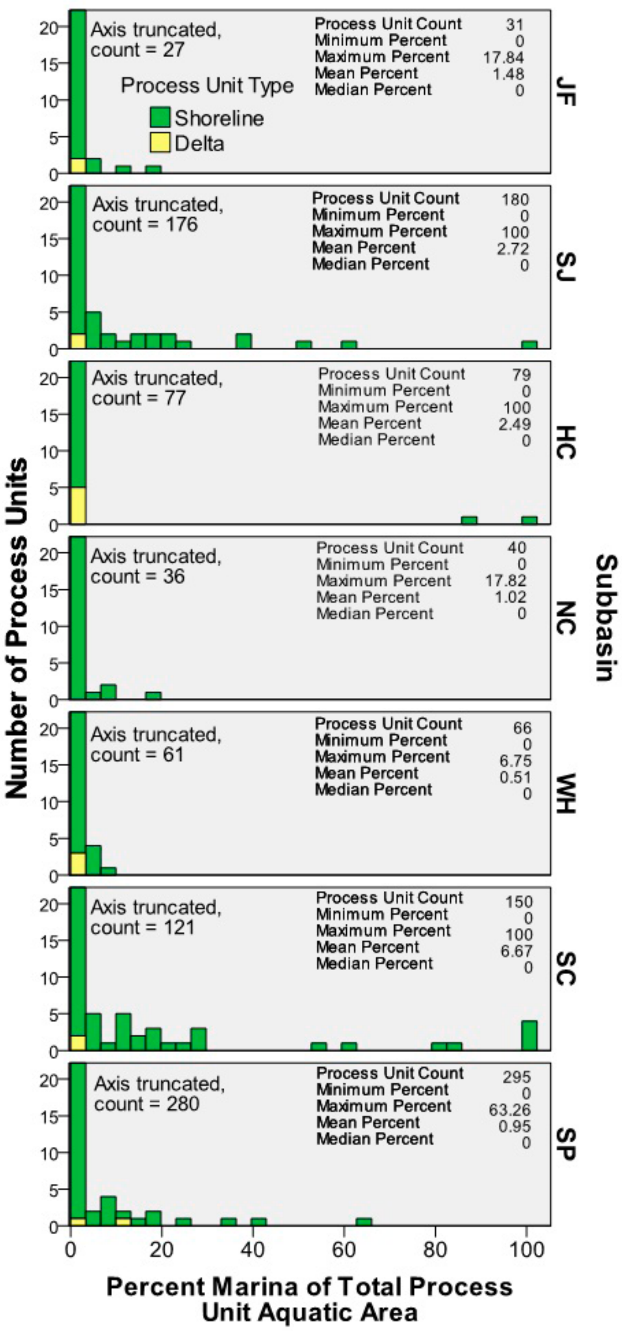


Figure 49. Frequency distribution of percent marinas of total process unit aquatic area among seven Puget Sound sub-basins.

Multivariate Analysis

When PU are grouped, using multivariate methods, by the types of modifications they contain, the most common grouping is characterized by the loss of estuarine mixing wetlands, armoring, and nearshore roads (group bk), which includes 517 PU around the Sound (Fig. 50). Other typical PU groups include gain of estuarine mixing, armoring, and nearshore roads (group bj; 170 PU); only overwater structures (group bc; 34); and predominantly armoring with a modest amount of overwater structures (group bm; 9 PU). Tidal barriers only occur in two groups (c, bi), where they are either associated with gain in estuarine mixing wetlands or a combination of a gain in estuarine mixing and tidal freshwater wetlands and nearshore roads, respectively. Distribution of these groups of consistent alterations appears to be somewhat homogeneous around the Sound (Fig. 51). Significant groups of PU shoreline alterations are presented for each sub-basin in Fig. 52, and are described in the subsequent discussion under each sub-basin.

Adjacent Upland and Watershed Area Changes

The PSNERP effort considers changes in the uplands and watersheds to have significant effects on the processes and health of nearshore ecosystems. As expected, the Change Analysis found that the scale of watershed changes has been very large in some areas.

Descriptive

Two major sources of change have been the building of dams on rivers draining into the Sound, and roads. The Puget Sound basin has 436 dams within its upland watershed area, over a third of which are found in the South Central Sub-Basin (Table 11). The density of roads, presented as a percent of total area, is fairly consistent between the adjacent upland (from shoreline to 200 m inland) and the watershed area (total drainage area); approximately 2.5 percent of Puget Sound land is covered by roads.

The majority of the upland and watershed area is classified as natural land, as opposed to developed land, which includes areas of industrial, residential, and agricultural development. The ratio of developed to natural land is always higher in the adjacent upland than in the watershed area, reflecting the concentration of human activities along the nearshore.

The upland and watershed area of the South Central Puget Sound Sub-Basin stand out as highly impacted, with all area measurements of human development (excluding the two low-impact categories: low intensity development and 0–10 percent impervious surface) exceeding that found in any other sub-basin (Table 11). On the other hand, the vast majority of the Hood Canal Sub-Basin remains as natural land with very little area categorized as impervious surface greater than 10 percent, despite a relatively high road density in the adjacent upland.

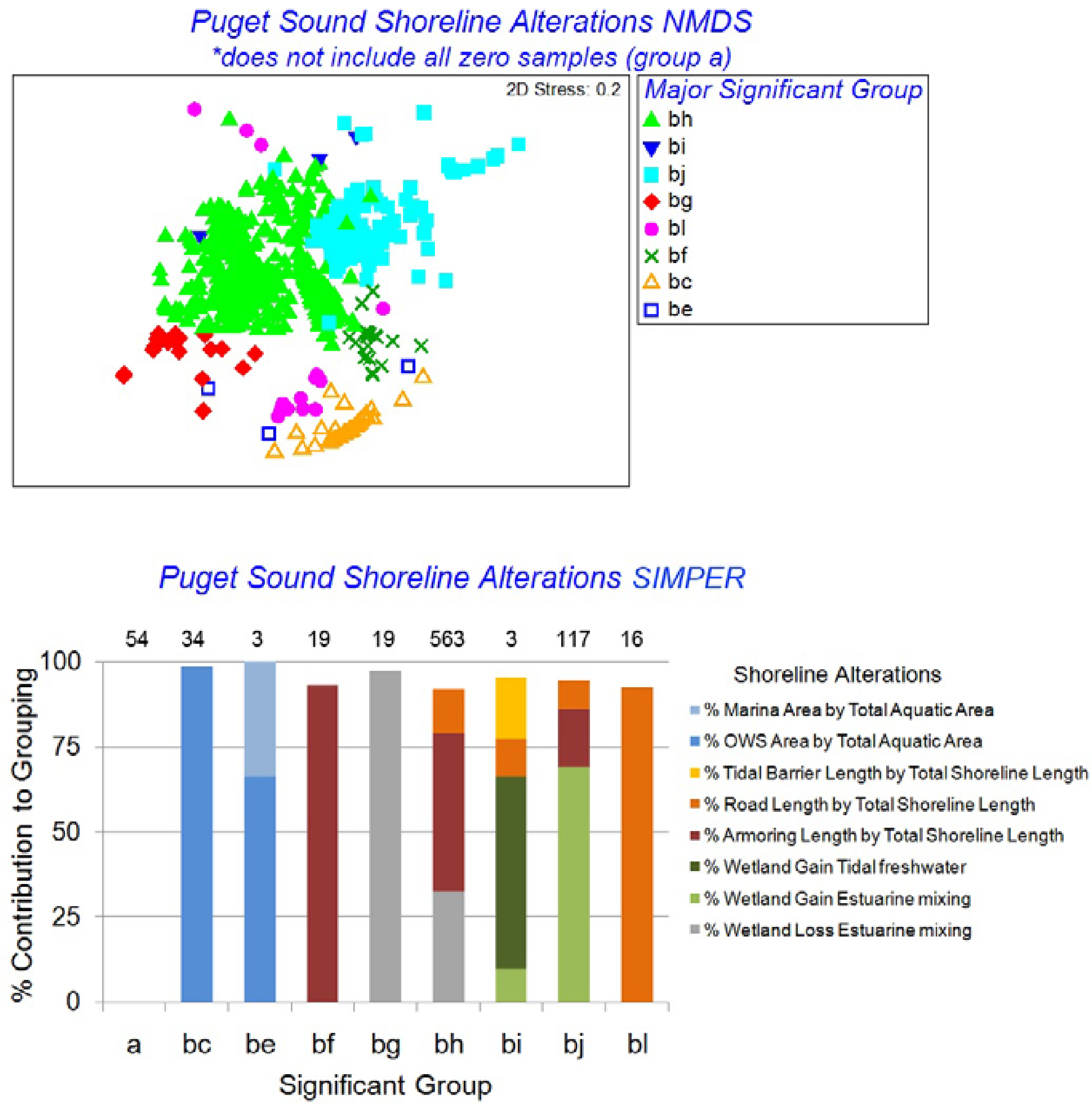


Figure 50. Non-Metric Multi-Dimensional Scaling (NMDS) plot and SIMPER multivariate analysis results for shoreline alterations in the process units (PU) of the Puget Sound Basin. PU within group 'a' do not contain any alterations. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group.

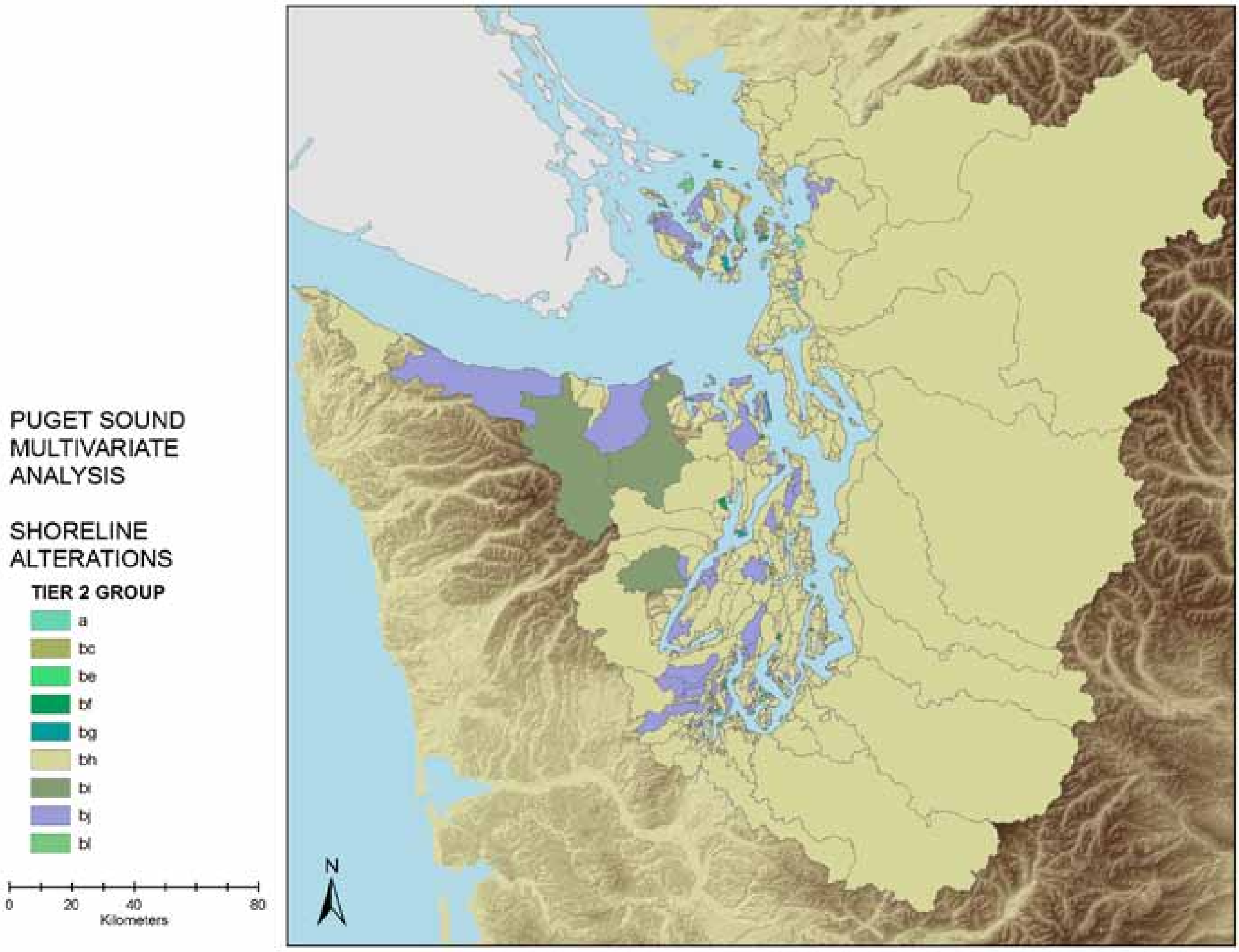


Figure 51. Map of Sound-wide distribution of process unit (PU) groups with significant similar shoreline alterations based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. See Fig. 29 for group

Multivariate Analysis

The most common grouping of adjacent upland changes within process units can be characterized as having moderate development, including low intensity and open space development, low to moderate impervious surface coverage, and roads (group h, 590 PU) (Fig. 53). Other PU are distinguished primarily by the presence of low impervious surface (group c, 190 PU). Two groups (d and e) comprise the more highly developed PU, with high intensity development and greater than 50 percent impervious surface. Hay/pasture is a discriminating variable for only one group, while cultivated crop area is not identified as a significant variable contributing to the similarity of any group. Distribution of these groups appears to be somewhat homogeneous around the Sound (Fig. 54). Significant groups of adjacent upland change are presented for each sub-basin in Fig. 55, and are described in the following sub-basin discussions.

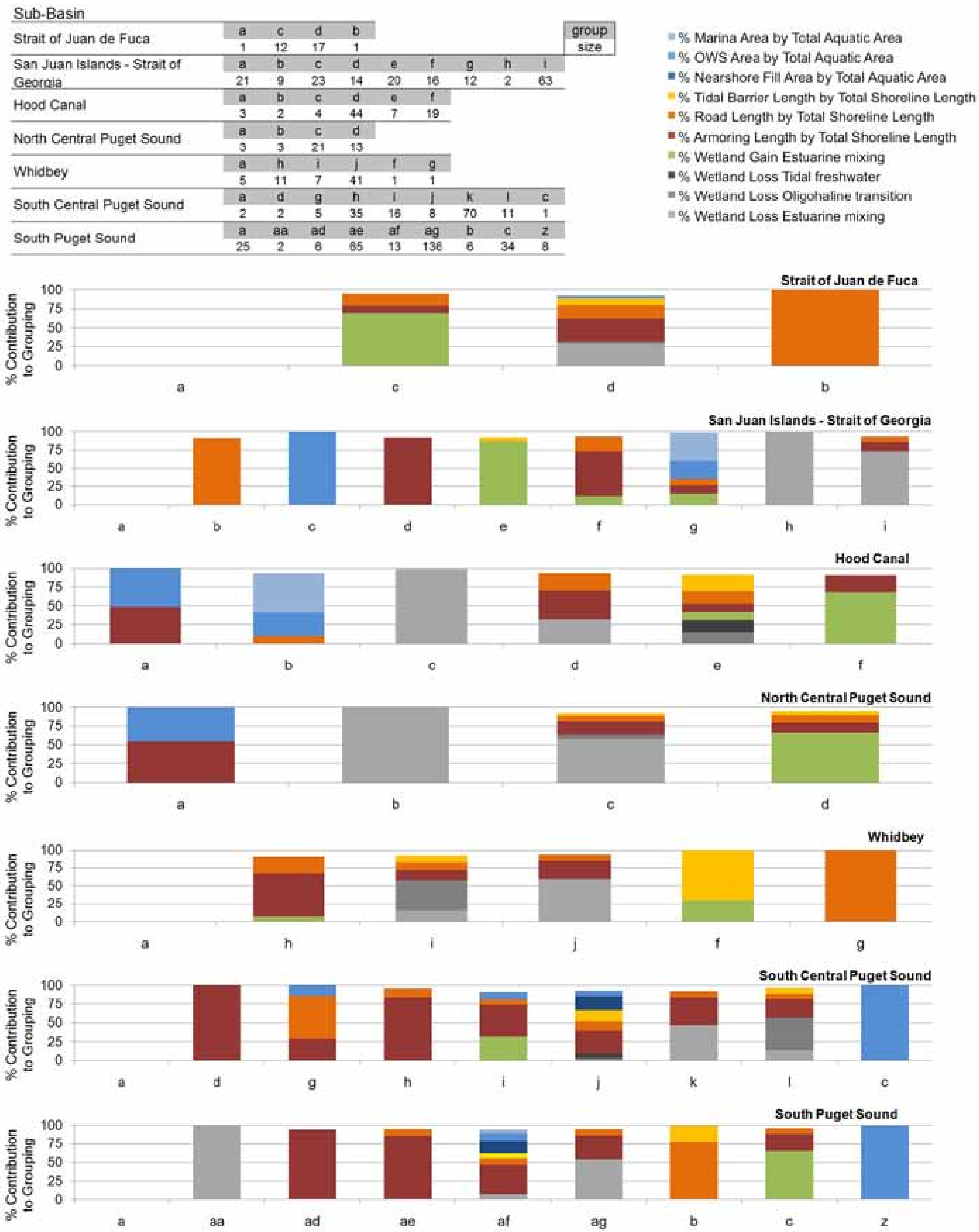
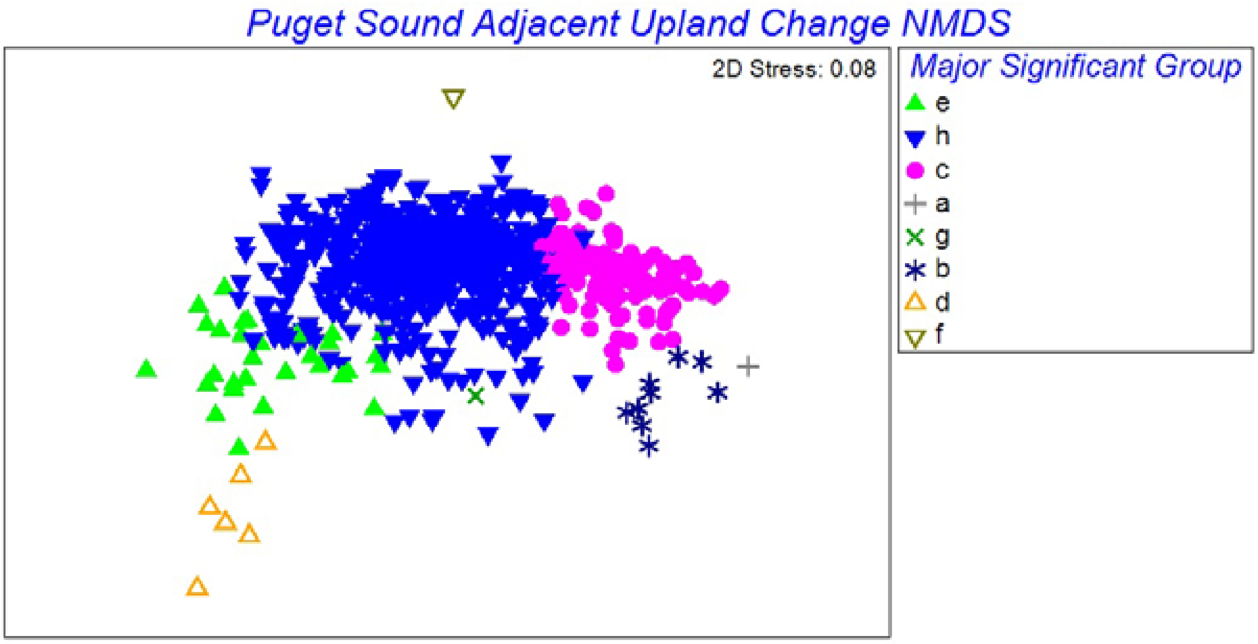


Figure 52. Contribution of different shoreline alterations to significantly different groups of process units (PU) of the seven Puget Sound sub-basins; based on SIMPER multivariate analysis. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Table (top, left) shows the number of PU in each group.

Table 11. Adjacent upland (Tier 3) and watershed area (Tier 4) changes in Puget Sound and Sub-basins.

			Strait of Juan de Fuca	San Juan Islands-Strait of Georgia	Hood Canal	North Central Puget Sound	Whidbey	South Central Puget Sound	South Puget Sound	Puget Sound Basin
Count in Area	Dams	T3	--	--	--	--	--	--	--	--
		T4	17	89	19	4	108	154	57	436
	Stream Crossings	T3	220	249	488	79	260	479	406	2140
		T4	4989	7193	4750	651	20061	13233	13682	64383
	Fish Passage Barrier	T3	35	70	113	6	144	34	135	531
		T4	272	1109	355	92	1929	1440	828	5975
Percent (%) of Area	Impounded Area	T3	--	--	--	--	--	--	--	--
		T4	26.4	7.2	15.3	0.4	44.2	53.7	39.7	37.2
	Roads	T3	1.8	1.5	3.8	1.8	1.7	4.2	3.2	2.4
		T4	2	2.6	2.1	3.1	1.6	4.2	3.8	2.5
	Abandoned RR	T3	0.5	0	0	0	0	0	0	0.1
		T4	0.1	0	0	0	0	0.1	0	0
	Active RR	T3	0	0.2	0	0	0.3	1	0.3	0.3
		T4	0	0.1	0	0	0	0.2	0.2	0.1
	Developed Land Cover	T3	22.4	28.6	10.1	30.3	50.2	50.6	25.6	33.6
		T4	7.4	26.6	5.2	24.2	9.2	33.6	21.4	16.4
	Natural Land Cover	T3	77.6	71.4	89.9	69.7	49.8	49.4	74.3	66.4
		T4	92.6	73.4	94.8	75.8	90.8	66.4	78.6	83.6
	Impervious Surface (0-10%)	T3	84.2	81.8	90.4	76.7	67.4	57	81.3	76.1
		T4	96.2	90.5	96.9	86.7	94.7	73.4	86.8	89.9
	Impervious Surface (10-30%)	T3	7.8	10.4	4.9	14.5	16.1	18.4	12.3	13
		T4	1.8	5.6	2.3	8.4	3.1	10.5	7.3	5.1
	Impervious Surface (30-50%)	T3	3.9	4	1.2	5.4	9.2	9.3	3.8	5.4
		T4	1	2	0.5	3.1	1.2	7.2	3.1	2.5
	Impervious Surface (50-100%)	T3	4.1	3.8	0.6	3.4	7.3	15.3	2.6	5.5
		T4	1	1.8	0.2	1.8	1	8.9	2.8	2.6

In a very similar pattern to the adjacent upland, the most common watershed area changes can be described as moderate development (including low intensity and open space development), low to moderate impervious surface coverage, and roads (group f, 643 PU) (Fig. 56). The second largest group (h), including 94 PU, shows very little impact to the watershed and is characterized solely by the lowest level of impervious surface. PU within groups b and c are mostly found in the urbanized Seattle, Tacoma, Olympia, and Bellingham regions and are distinguished from other groups by higher levels of impervious surface and by the presence of dams (signified by the impounded area category) in group b (Figs. 56 & 57). The most highly impacted group, a, is represented by only four process units, three of which are located adjacent to the Duwamish River delta in Seattle. All four of these PU are very small in size, leading to a proportionally high concentration of development. Significant groups of PU watershed area changes are presented for each sub-basin in Fig. 58, and are described in the subsequent discussion under each sub-basin.



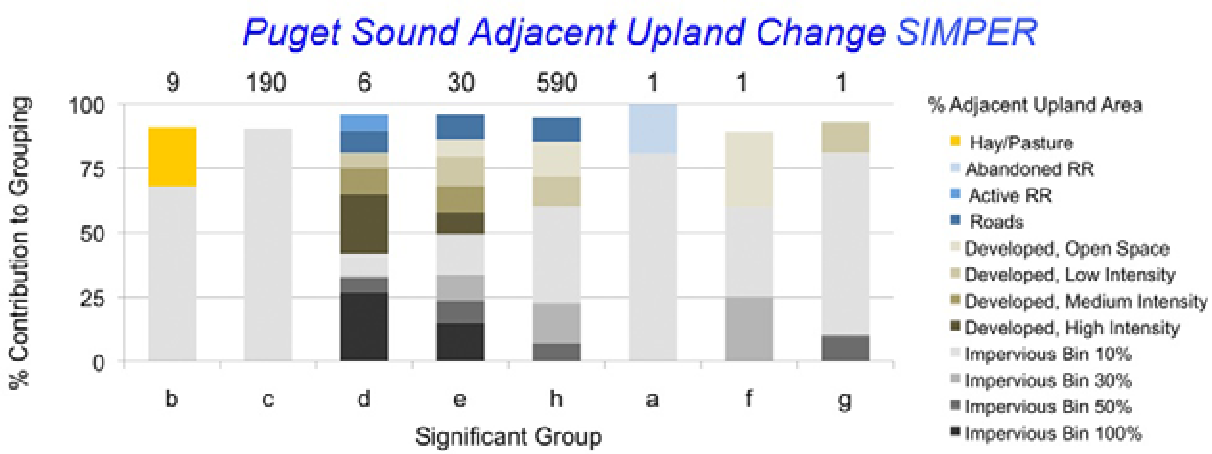


Figure 53. Non-Metric Multi-Dimensional Scaling (NMDS) plot and SIMPER multivariate analysis results for adjacent upland change in the process units (PU) of the Puget Sound Basin. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group. Values shown for groups composed of one PU are the descriptive composition of the PU.

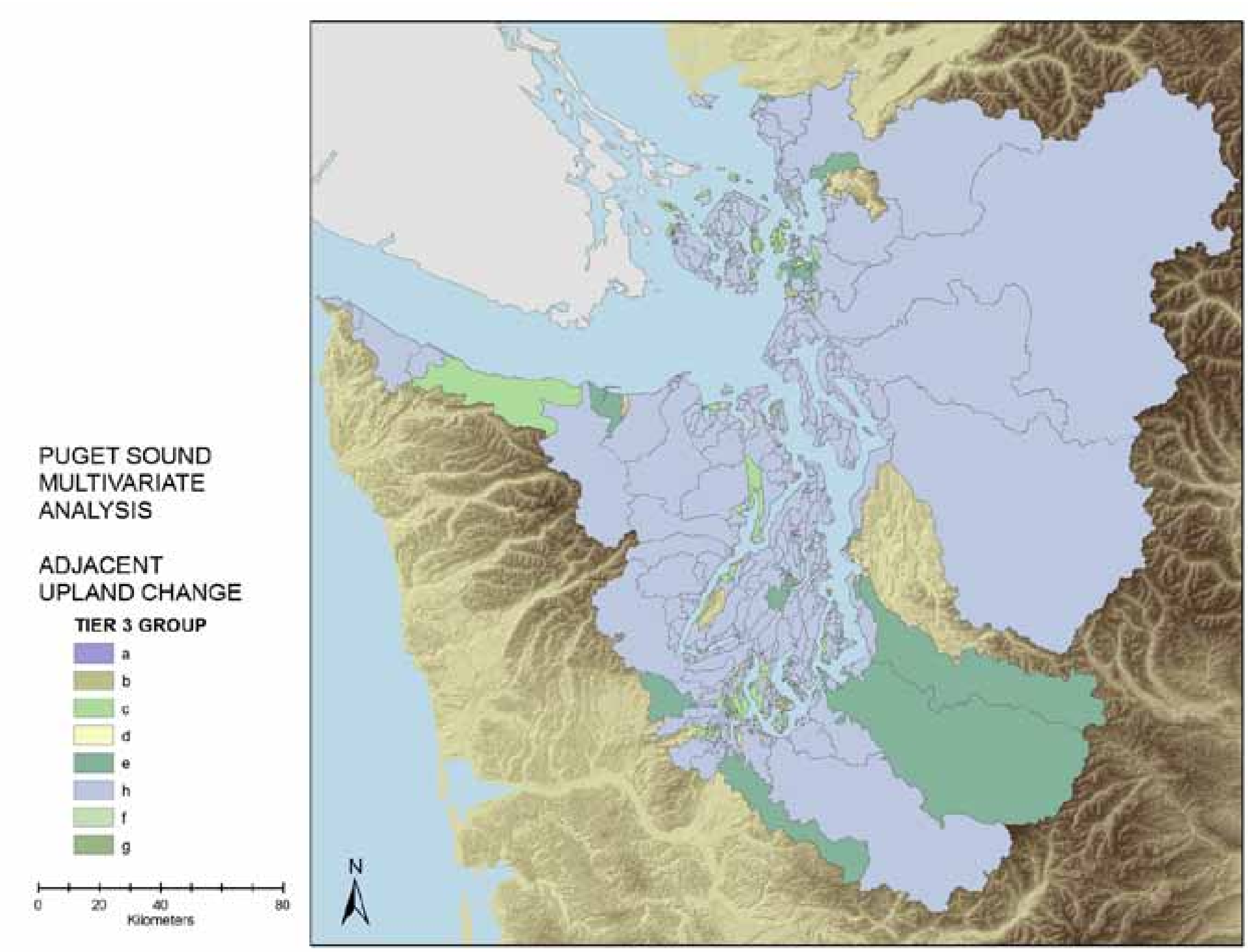
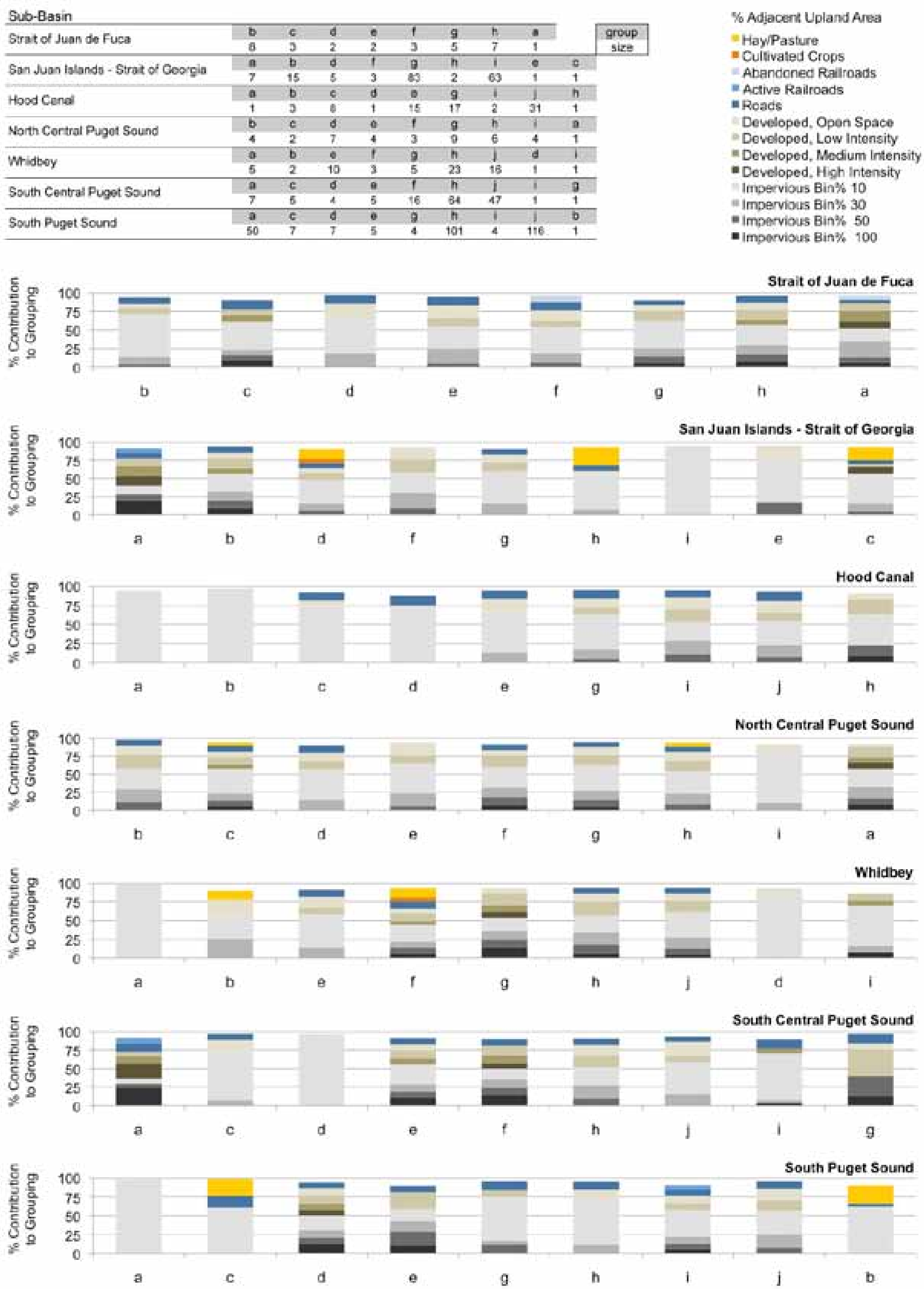


Figure 54. Map of Sound-wide distribution of process unit (PU) groups with significant similar adjacent upland changes based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. See Fig. 32 for group compositions.



Sub-Basin									
Strait of Juan de Fuca	b	c	d	e	f	g	h	a	
	8	3	2	2	3	5	7	1	
San Juan Islands - Strait of Georgia	a	b	d	f	g	h	i	e	c
	7	15	5	3	83	2	63	1	1
Hood Canal	a	b	c	d	e	g	i	j	h
	1	3	6	1	15	17	2	31	1
North Central Puget Sound	b	c	d	e	f	g	h	i	a
	4	2	7	4	3	9	6	4	1
Whidbey	a	b	e	f	g	h	j	d	i
	5	2	10	3	5	23	16	1	1
South Central Puget Sound	a	c	d	e	f	h	j	i	g
	7	6	4	5	16	64	47	1	1
South Puget Sound	a	c	d	e	g	h	i	j	b
	50	7	7	5	4	101	4	116	1

group size

Figure 55. Contribution of adjacent upland changes to significantly different groups of process units (PU) of the 7 Puget Sound Sub-basins; based on SIMPER multivariate analysis. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Table (top, left) shows the number of PU in each group.

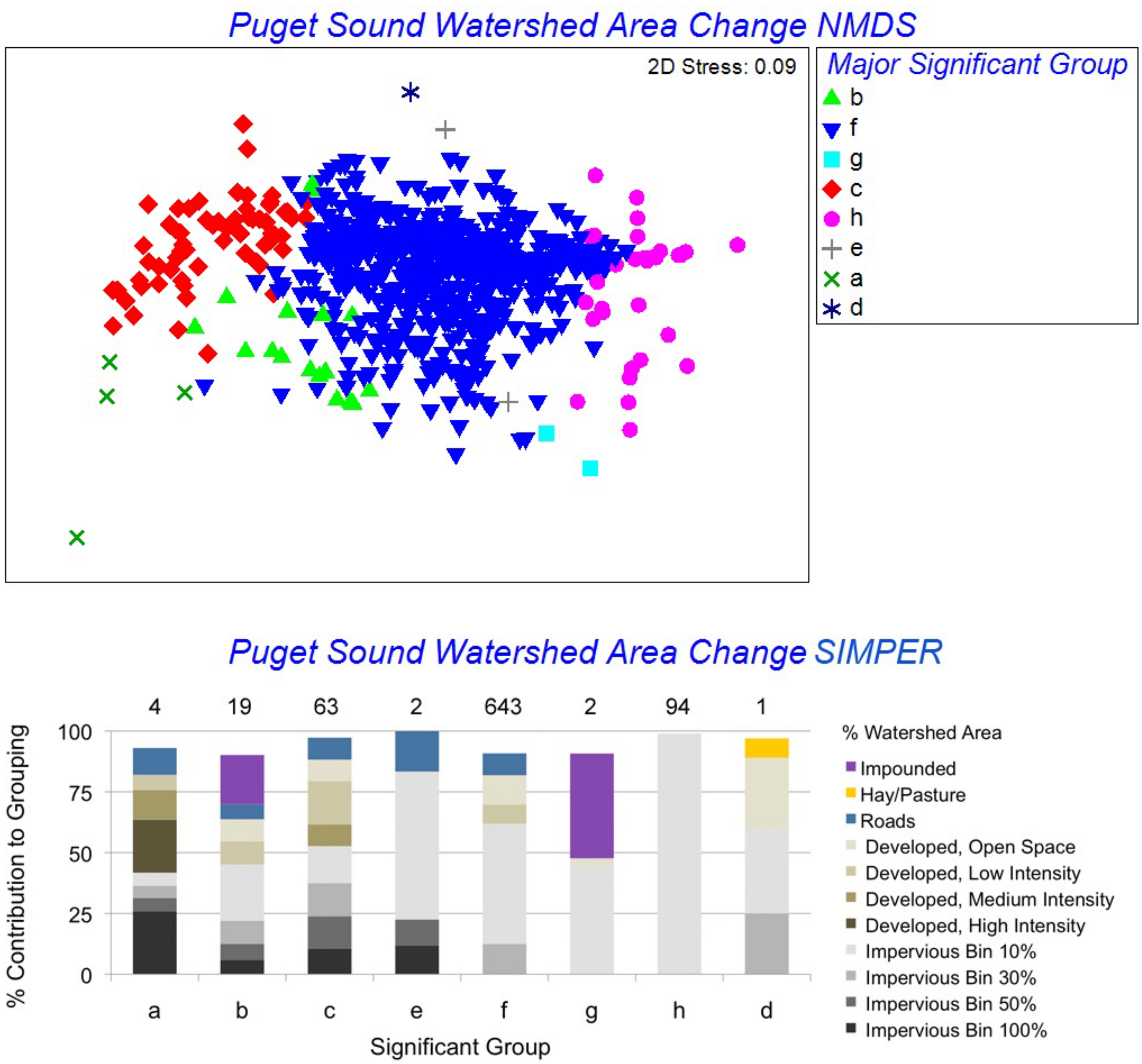


Figure 56. Non-Metric Multi-Dimensional Scaling (NMDS) plot and SIMPER multivariate analysis results for adjacent upland change in the process units (PU) of the Puget Sound Basin. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group. Values shown for groups composed of one PU are the descriptive composition of the PU.

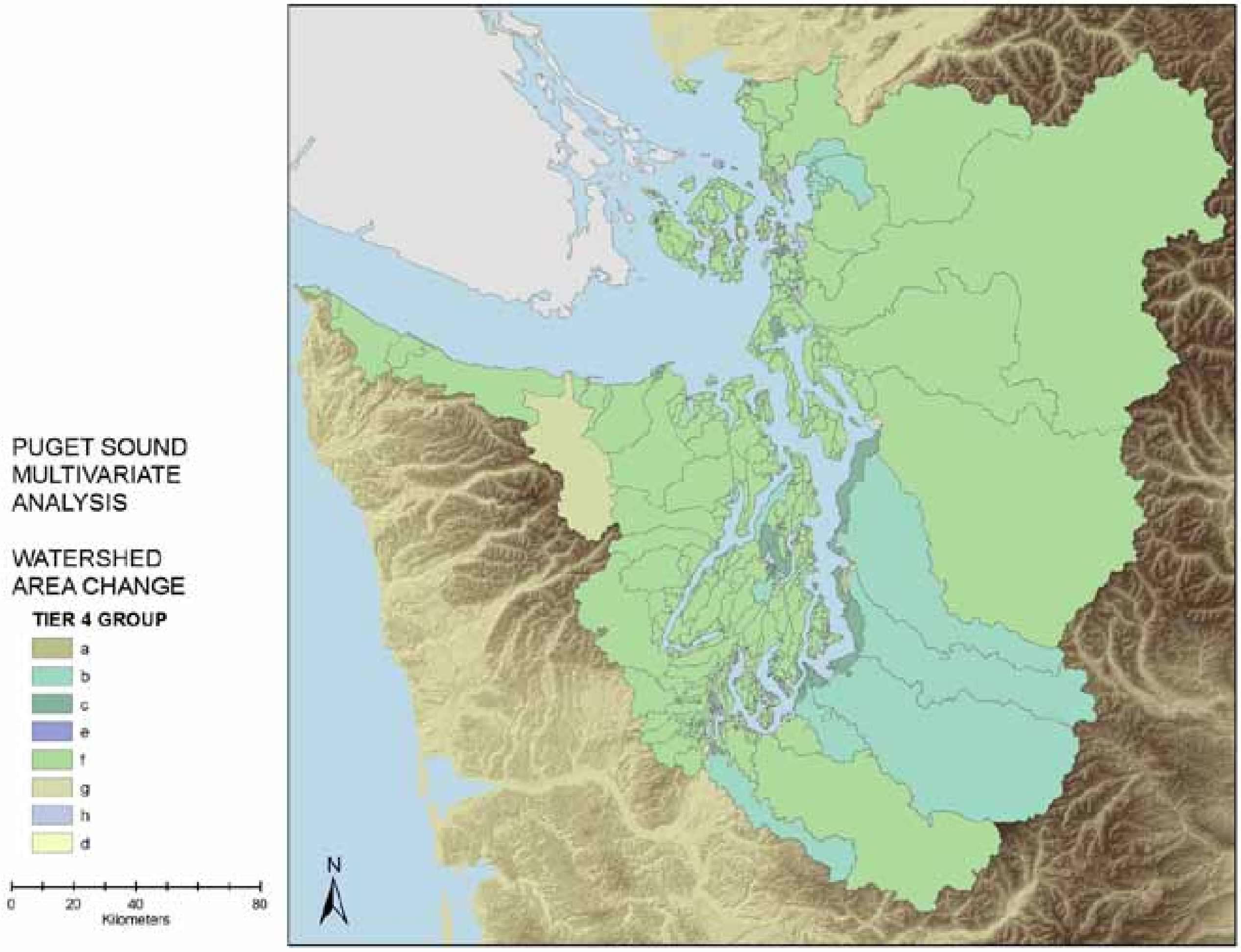
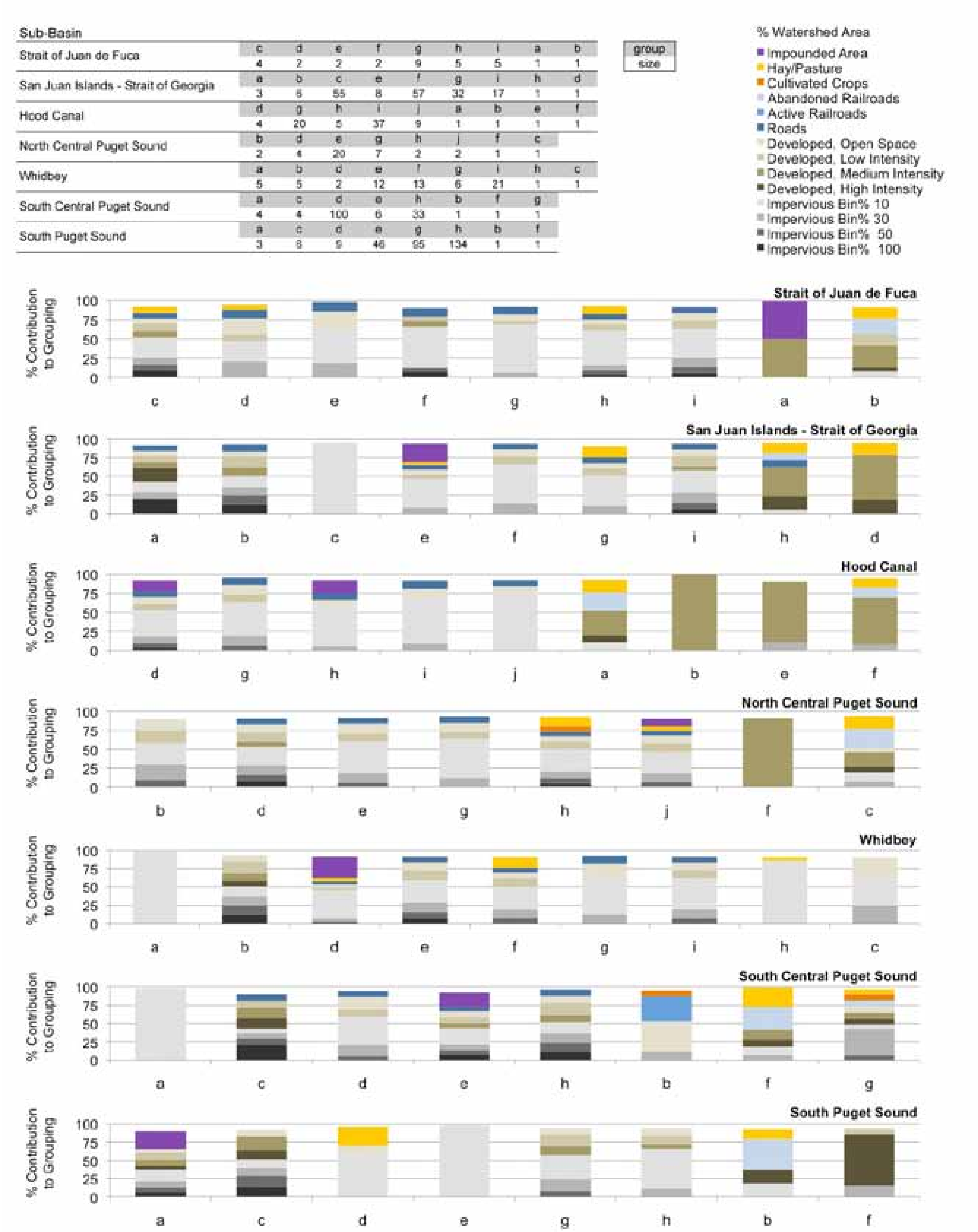


Figure 57. Sub-basin map of Sound-wide distribution of process unit (PU) groups with significant similar watershed area change based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. See Fig. 36 for group compositions.



Sub-Basin										
Strait of Juan de Fuca	c	d	e	f	g	h	i	a	b	group
	4	2	2	2	9	5	5	1	1	size
San Juan Islands - Strait of Georgia	a	b	c	e	f	g	i	h	d	
	3	5	55	8	57	32	17	1	1	
Hood Canal	d	g	h	i	j	a	b	e	f	
	4	20	5	37	9	1	1	1	1	
North Central Puget Sound	b	d	e	g	h	j	f	c		
	2	4	20	7	2	2	1	1		
Whidbey	a	b	d	e	f	g	i	h	c	
	5	5	2	12	13	6	21	1	1	
South Central Puget Sound	a	c	d	e	h	b	f	g		
	4	4	100	6	33	1	1	1		
South Puget Sound	a	c	d	e	g	h	b	f		
	3	8	9	46	95	134	1	1		

Figure 58. Contribution of total watershed changes to significantly different groups of process units (PU) of the 7 Puget Sound Sub-basins; based on SIMPER multivariate analysis. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Table (top, left) shows the number of PU in each group.

Strait of Juan De Fuca Sub-Basin

Shoreform Change and Transition

The Strait of Juan de Fuca Sub-Basin (Fig. 59) is formed of 31 process units, including two delta process units—the Elwha and Dungeness river deltas (refer to Appendix D, Fig. E.1, for PU distributions).

Descriptive

The shoreline geomorphology changes from dominance by beaches and bluffs on the eastern end to greater representation by rocky shoreforms at the western end of the Strait. Overall, barrier beach (23.2 percent), bluff-backed beach (19.6 percent), and rocky platform (24.1 percent) shoreforms dominated the number of historical shoreforms (Table 5). Change from historical to current shoreform composition reflects a proportional decline in barrier beach (to 19.8 percent) and bluff-backed beach (17.5 percent), and an increase in the proportion of rocky platform shoreforms (26.2 percent), in addition to the almost 6 percent representation by artificial shoreforms (Table 5). We attribute the increase in rocky shoreforms to omissions in historical surveys (no feature was mapped historically and therefore the analysis shows it as a transition from absent), not to an actual geomorphic transition. Change in shoreform composition by shoreline length, however, indicated that the greatest change has been the loss of complexity in open coastal inlets (44.6 percent), barrier lagoons (22.8 percent), and barrier estuaries (20.7 percent), while rocky platforms have increased proportionately in lineal extent by approximately 12 percent (Table 4; Fig. 60).

Changes in shoreform length are concentrated in several individual or contiguous PU along the Strait (Fig. 61). Both the Dungeness and Elwha rivers deltas indicate up to approximately 50 percent loss of shoreline complexity. In addition, barrier estuaries surrounding the Dungeness (SPU 1019–1024) are measurably reduced. Other concentrations of evident change include the southern end of Discovery Bay (SPU 1010–1011), Protection Island (SPU 1201), and surrounding Ediz Hook (SPU 1026, 1400).

Historical shoreform transitions are absent or rare for five of the ten shoreforms, but are significant for closed lagoon/marsh and barrier estuaries (Table 12). As with Sound-wide transitions, the vast majority of shoreform transitions were from natural shoreforms to artificial or shoreform-absent categories: between 83 percent and 100 percent of the historical shoreforms that transitioned were due to these anthropogenic changes. Only two of the 52 transitions (4 percent) involved potentially natural changes: one barrier beach to a barrier lagoon and one open coastal inlet to a barrier estuary.

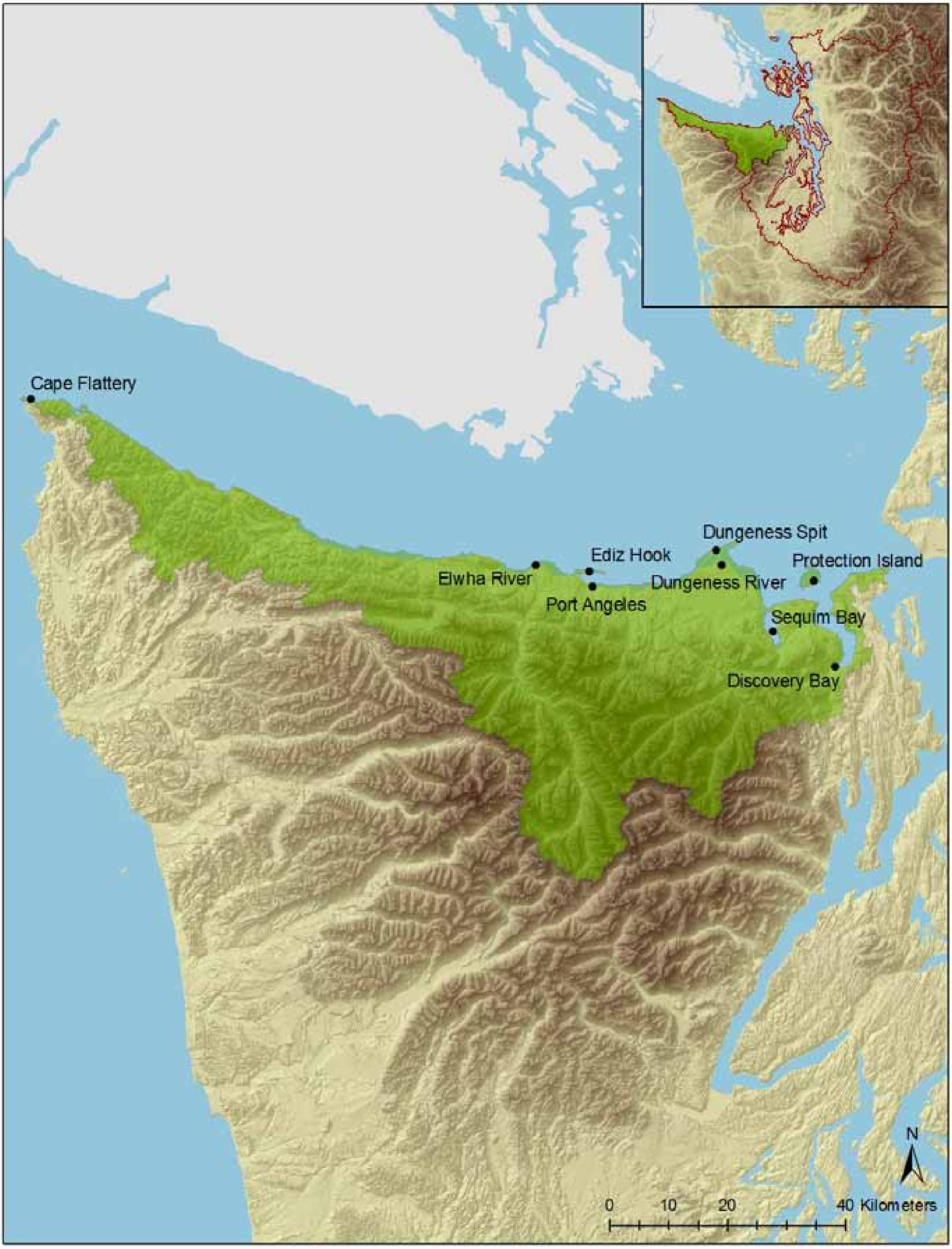


Figure 59. Strait of Juan de Fuca Sub-Basin.

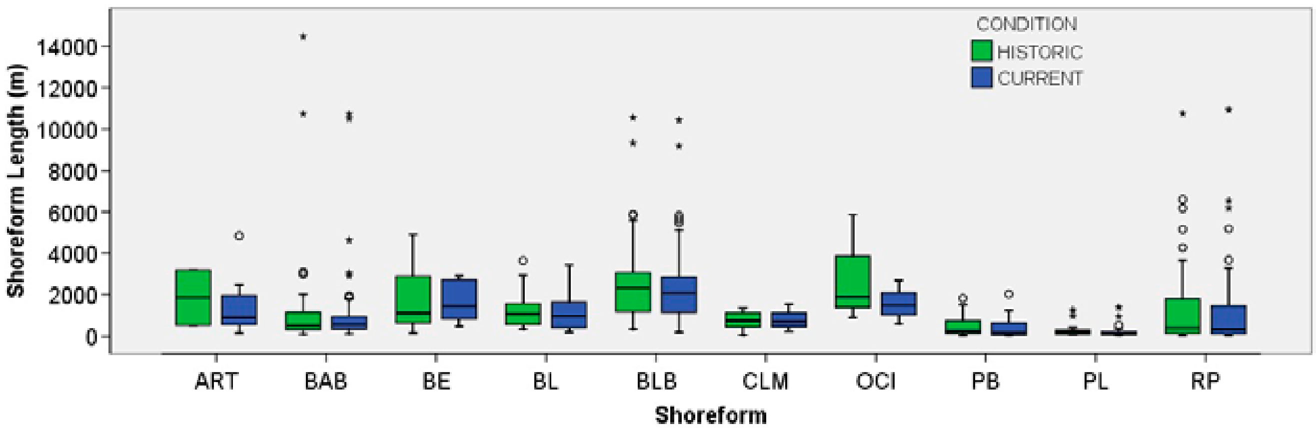


Figure 60. Historical and current contiguous shoreline length of Strait of Juan de Fuca shoreforms in PU (excludes delta shoreform); see Fig. 20 for shoreform codes. Each box represents the median and upper and lower quartile of the shoreform length data. The 'whiskers' (lines that extend out of the top and bottom of box) represent the highest and lowest values that are not outliers or extreme values. Outliers (values between 1.5 and 3 times the interquartile range) are marked with a circle and extreme cases (values more than 3 times the interquartile range) with an asterisk.

Multivariate Analysis

Historically, approximately half of the PU were characterized by bluff-backed beach and barrier beach shoreforms (group f, 15 PU); these types of PU are clustered around the eastern end of the sub-basin (Port Townsend Bay, Discovery Bay, Sequim Bay) and between the two deltas (Fig. 62). Other common PU compositions were bluff-backed beach, barrier beach, and barrier estuaries (group e; 6) concentrated at the southern end of Sequim Bay, and rocky shoreforms mixed with bluff-backed beach (group b; 5) that extend pervasively from the Elwha delta west to Cape Flattery, over half the length of the sub-basin.

In current configuration, the dominant PU group (group f) does not change (Fig. 63). However, the historical bluff-backed beach, barrier beach and barrier estuaries, occurring between Sequim Bay and the Dungeness River delta, now includes barrier lagoons as a distinguishing feature (group c). Barrier lagoons are also mixed in with the rocky shoreforms and bluff-backed beach group (group b) and still span the western half of the sub-basin. A complex group of three PU characterized by bluff-backed beaches, barrier beaches, barrier estuaries, barrier lagoons, closed lagoon/marshes, and artificial shoreforms (group e) are now found at the base of Discovery and Sequim bays. Another distinct group (group d), in which artificial shoreforms have become a distinguishing factor, is located in the two PU surrounding Ediz Hook/Port Angeles.

No transitions were distinct enough to form statistically significant NMDS groups.

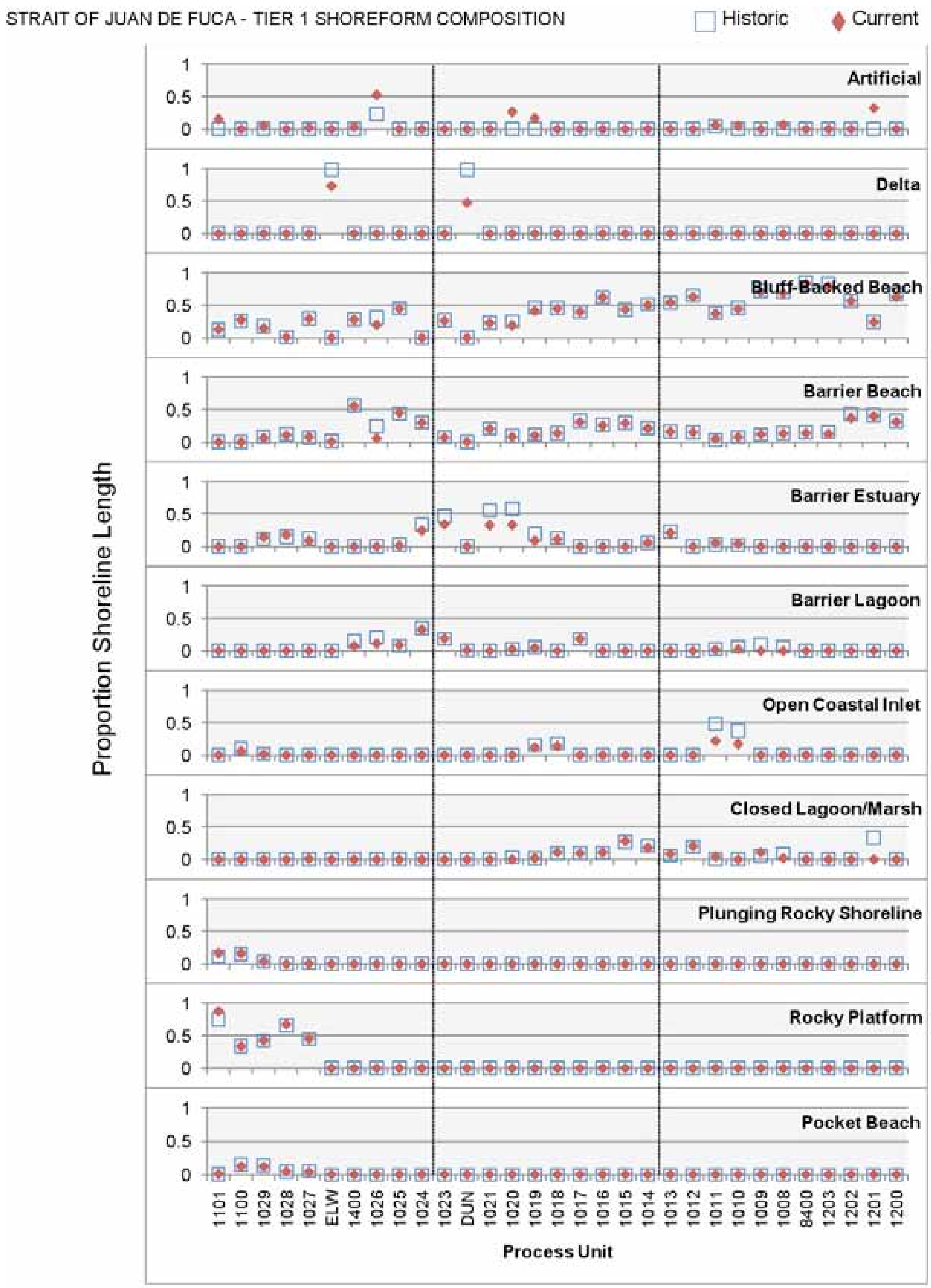


Figure 61. Proportional lengths of historical and current shoreforms along sequential process units (PU) of the Strait of Juan de Fuca Sub-Basin.

Table 12. Shoreform transitions (Tier 1) of Strait in Juan de Fuca Sub-Basin. Highlighted numbers (diagonal line) represent the number that did not transition and are derived as the difference between the historical shoreform count and the total number of transitions.

Shoreform Transition	*Current* ------------------------>												
Historic	Bluff-Backed Beach	Barrier Beach	Delta	Barrier Estuary	Barrier Lagoon	Closed Lagoon/ Marsh	Open Coastal Inlet	Plunging Rocky Shoreline	Rocky Platform	Pocket Beach	Artificial	Shoreform Absent	Total Transitions
Bluff-Backed Beach	36										7		7
Barrier Beach		45			1						5		6
Delta			2										0
Barrier Estuary				12								3	3
Barrier Lagoon					7	2							2
Closed Lagoon/Marsh						9					2	1	3
Open Coastal Inlet				1			1				1		2
Plunging Rocky Shoreline								13					0
Rocky Platform									50		3		3
Pocket Beach										17			0
Artificial		1									1		1
Shoreform Absent						2		10	11		2		25
Total Transitions	0	1	0	1	1	4	0	10	11	0	20	4	52

Shoreline Alterations

Descriptive

Coincident with shoreform changes along the Strait of Juan de Fuca Sub-Basin shoreline, much of the shoreline armoring and tidal barriers occur in (Elwha and Dungeness rivers) DPU or along adjacent SPU (Fig 64). Armoring covers over 75 percent of the shoreline in the two SPU immediately to the east of the Elwha River delta. Armoring, abandoned railroads, and tidal barriers also occur at the southern end of Discovery Bay.

Multivariate Analysis

The most common (17 PU) alterations occurring within PU are armoring, nearshore road, and tidal barrier within the nearshore zone, while loss of estuarine mixing wetlands and nearshore road typify the deltas and PU around Sequim Bay and Discovery Bay in the western end of the sub-basin (Fig 65).

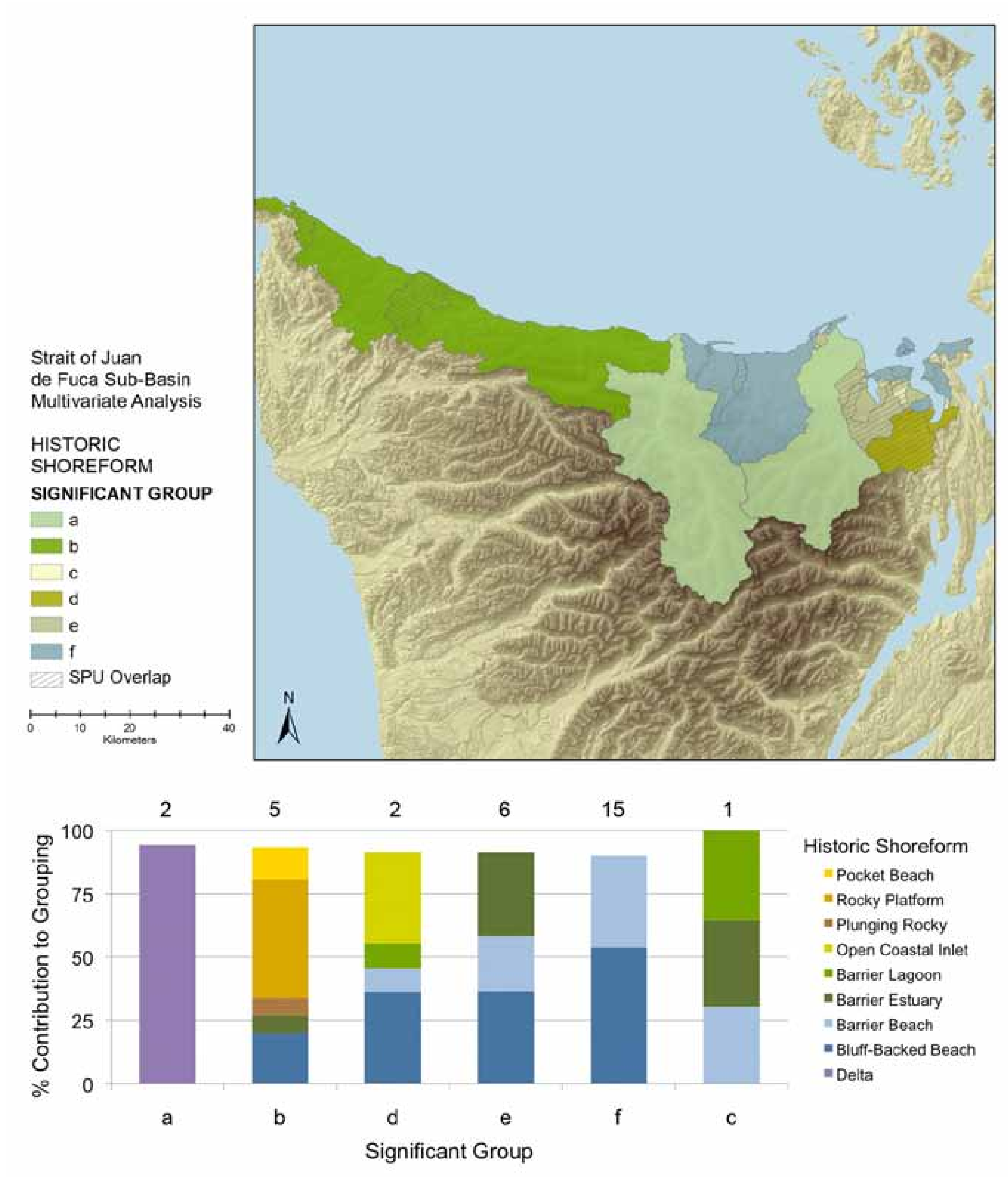


Figure 62. (Top) Distribution of process unit (PU) groups with significantly similar historical shoreform composition in Strait of Juan de Fuca Sub-Basin of Puget Sound based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for historical shoreform composition in the PU. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group. Groups composed of one PU show the descriptive composition of the PU.

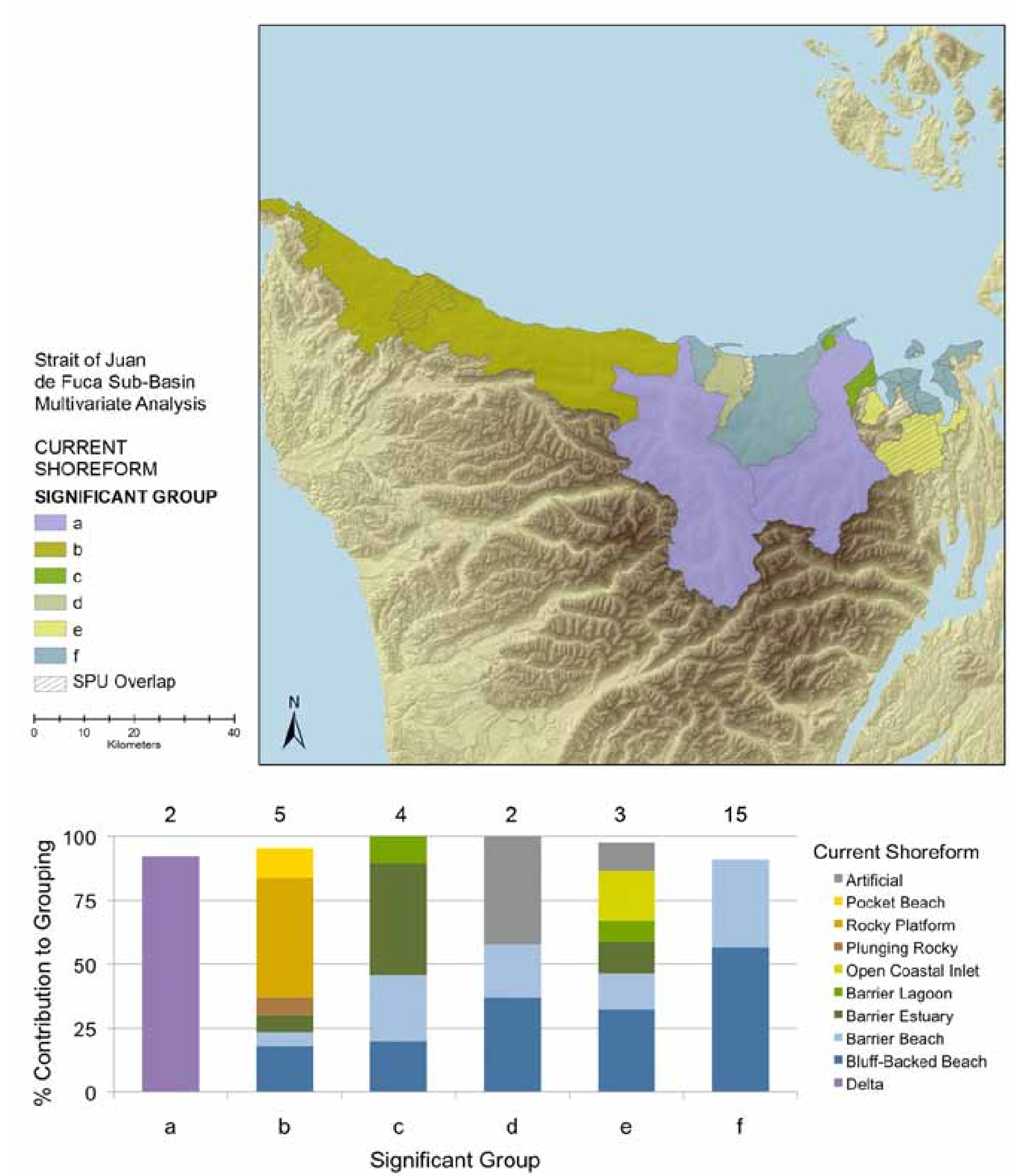


Figure 63. (Top) Distribution of process unit (PU) groups with significantly similar current shoreform composition in Strait of Juan de Fuca Sub-Basin of Puget Sound based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for current shoreform composition in the PU. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group.

STRAIT OF JUAN DE FUCA - TIER 2 SHORELINE ALTERATIONS

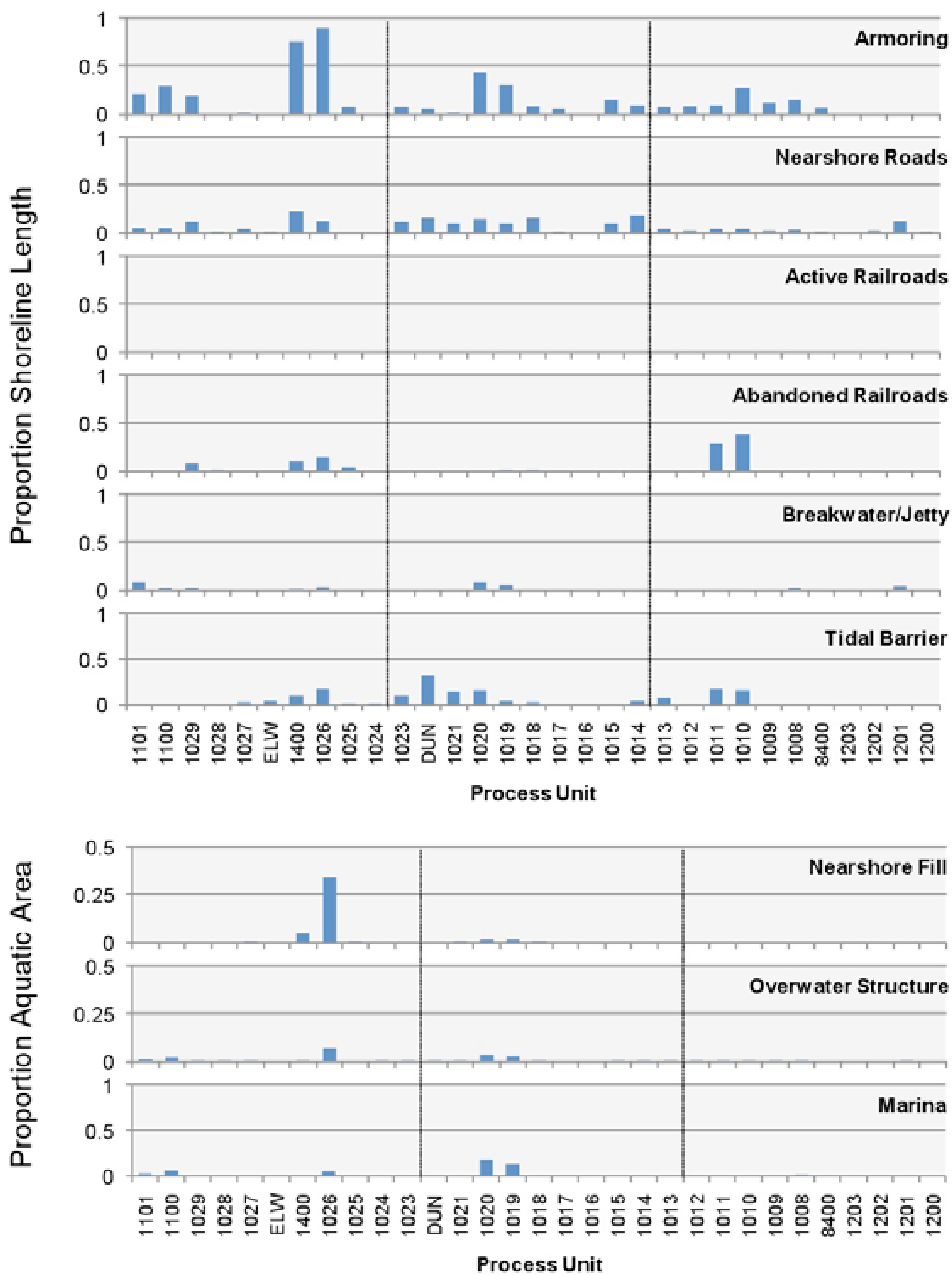


Figure 64. Shoreline alterations along sequential process units (PU) of the Strait of Juan de Fuca Sub-Basin.

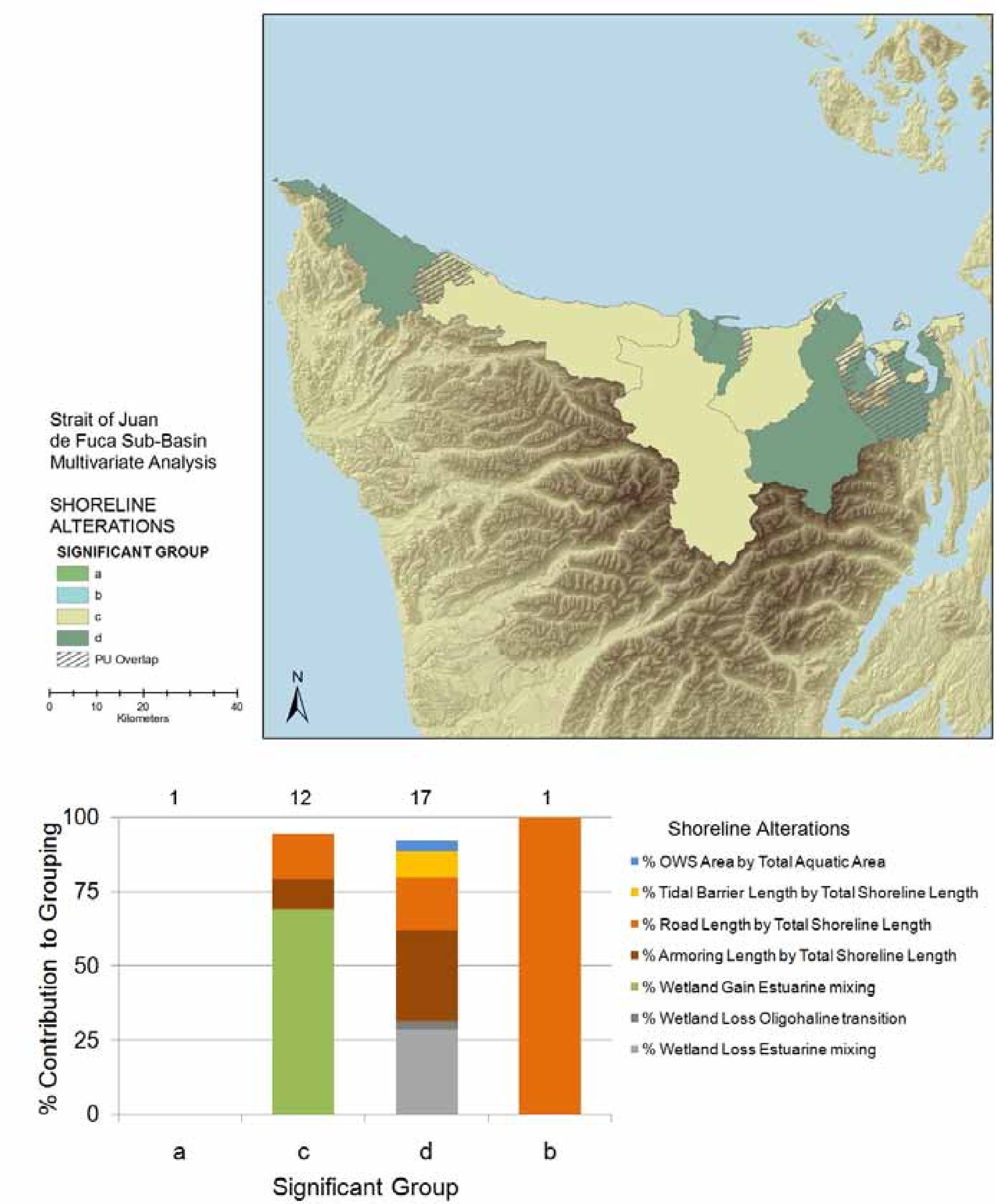


Figure 65. (Top) Process unit (PU) groups with significant similar shoreline alterations and stressors in Strait of Juan de Fuca Sub-Basin based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for shoreline alterations in the PU. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group. Groups composed of one PU show the descriptive composition of the PU. PU in group 'a' do not contain any shoreline alterations.

Adjacent Upland and Watershed Change

Descriptive

Overall, the adjacent upland area around the Strait of Juan de Fuca is approximately 75 percent natural land cover, while the watershed area is 90 percent natural, with much of that categorized as evergreen forest (Fig. 66). Process units around the Elwha and Dungeness deltas show more non-forested land cover, particularly that developed as hay and pasture land. SPU 1200–1203, which comprise Protection Island, located between the towns of Sequim and Port Townsend, also show a clear contrast to the predominantly forested surrounding areas, categorized as herbaceous vegetation and low impervious surface. The greatest development in the adjacent upland is found in the Port Angeles area (SPU 1026).

Multivariate Analysis

Groupings of upland change characteristics all share the contribution of less than 10 percent impervious surface to their similarity. Groups are distinguished by varying degrees of higher impervious surface coverage and development (Fig. 67).

In terms of watershed change, group g has the greatest numeric presence in the sub-basin with nine PU, and is characterized by low impervious surface and development (Fig. 68). Other groups are distinguished by the extent of hay/pasture with varying degrees of impervious surface and development.

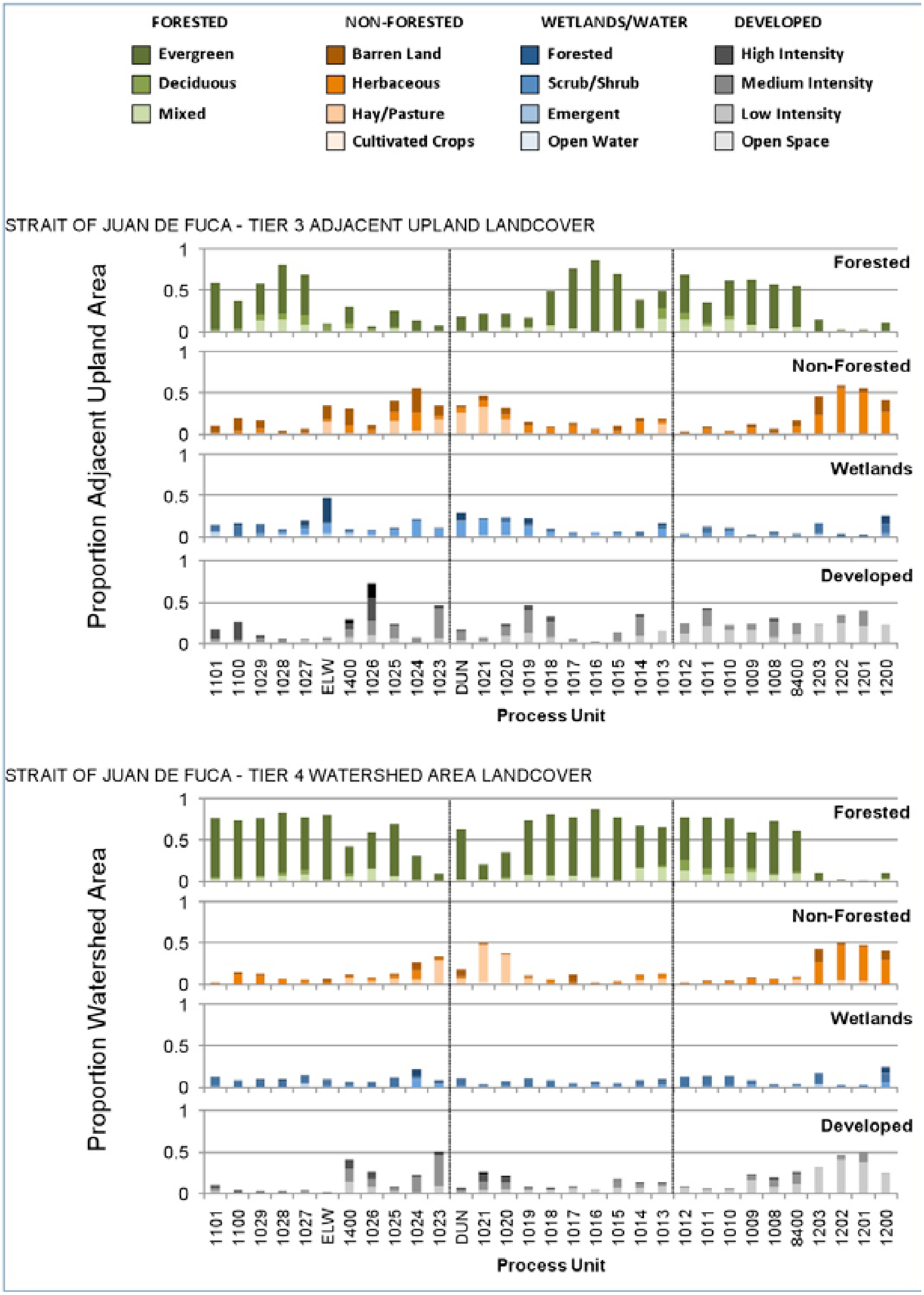


Figure 66. Land cover/land and stressors in adjacent upland (Tier 3, top) and watershed areas (Tier 4, bottom) in Strait of Juan de Fuca Sub-Basin.

San Juan Islands–Strait of Georgia Sub-Basin

Shoreform Change and Transition

Descriptive

Although the shorelines of the San Juan Islands–Strait of Georgia Sub-Basin (Fig. 69) are not altered to the degree of many of the other Puget Sound Sub-Basins, the shoreline of the two deltas (Nooksack and Samish) have been reduced by greater than 50 percent and the shoreline length of barrier estuaries, barrier lagoons, and open coastal inlets have been reduced by 50–64 percent (Table 4; Fig. 70). Most of the other shoreforms have been reduced by 15 percent or less.

The complexity of this sub-basin is illustrated by the number of individual shoreform counts. Historically, nearshore PU were composed of 1204 rocky platform and 944 pocket beach segments, and between 100 and more than 300 bluff-backed beach, barrier beach, and plunging rocky segments; overall 2855 individual shoreform segments, including five artificial shoreforms, were represented (Table 5). Proportional composition of the current shoreforms is comparable, with only the increase in artificial shoreforms (composing 2.1 percent of current shoreforms).

Shoreform transitions were dominated by changes of natural shoreforms to artificial and absent shoreforms (Table 13). Only nine occurrences (5.6 percent of total current shoreforms) between natural shoreforms might represent nearshore process changes, either from natural variability (e.g., barrier lagoon to closed lagoon/marsh), potential anthropogenic influence (e.g., open coastal inlet to barrier estuary), or likely mapping error (e.g., rocky platform to barrier lagoon). In addition, 35 shoreline segments that had no shoreform delineated in the historical data demonstrated transitions to natural shoreforms, which may not represent actual transitions. Again, we attribute these increases (particularly to rocky shoreforms) to omissions in historical surveys (no feature was mapped historically and therefore the analysis shows it as a transition from absent), not an actual geomorphic transition. Thus, considering 35 of these shoreform absent categories as potentially natural, a conservative estimate of anthropogenic transitions is 3.9 percent.

We have partitioned the sub-basin into five components (see Appendix D, Figs. E.2–E.6 for PU distributions) in order to examine the contiguous shoreline for concentrations of shoreline length change (Figs. 71-75). These indicate the following primary types of concentrated shoreline changes: 1) significant simplifications of the two deltas—Nooksack and Samish rivers—on the scales of 30–60 percent (Fig. 71); 2) the urban and surburban modified shorelines of Bellingham Bay and Drayton Harbor/Birch Bay, respectively, in the northeastern corner of the Sound (SPU 7140–7146) (Fig. 71); and 3) reductions embayment shoreforms around Lummi (Fig. 72) and Lopez (Fig. 74) islands.

Multivariate Analysis

The historical shoreform composition included three prominent PU groups among the nine identifiable ordination groups (including two with only one PU in group) (Fig. 76): 1) a dominant (93 of 180 PU) group composed of all three rocky shoreforms—plunging rocky, rocky platform, and pocket beach (group c); 2) 47 PU in a group characterized by bluff-backed beach and barrier beach (group i); and 3) 25 PU with bluff-backed beach, barrier beach mixed with closed lagoon/marsh (group h). The rocky group c dominated the shorelines of the San Juan Islands and some segments of the exposed shore of the eastern margin, while the bluff-backed and barrier beach group (i) is a more common nearshore feature along the east margin. The bluff-backed beach, barrier beach mixed with closed lagoon/marsh group is scattered throughout the sub-basin (Fig. 76). Even at the time of historical surveys, artificial shoreform dominated a "group" (f) of one PU (SPU 7158 in Bellingham Bay).

Current shoreform compositions of the PU generally group similarly to the historical nearshore structure (Fig. 77), except that statistically distinct groups of PU now occur where an artifical shoreform dominates (group e) and where artificial combines with bluff-backed beach, barrier estuary, plunging rocky, and rocky platform shoreforms (group d). These PU with significant contributions of artificial shoreforms tend to occur in the more developed regions around Bellingham Bay along the eastern margin of the sub-basin (Fig. 77).

The resulting shoreform transition groups (Fig. 787) are still populated by the dominant PU and have not changed significantly, showing only slight loss of rocky shoreforms (group n). These PU are predominantly located around San Juan, Orcas, and Cypress islands. Loss in barrier beach contributes significantly to group h, while group j is discriminated by gains in the artifical shoreform (largely located around Bellingham Bay).

Figure 69. San Juan Islands–Strait of Georgia Sub-Basin.

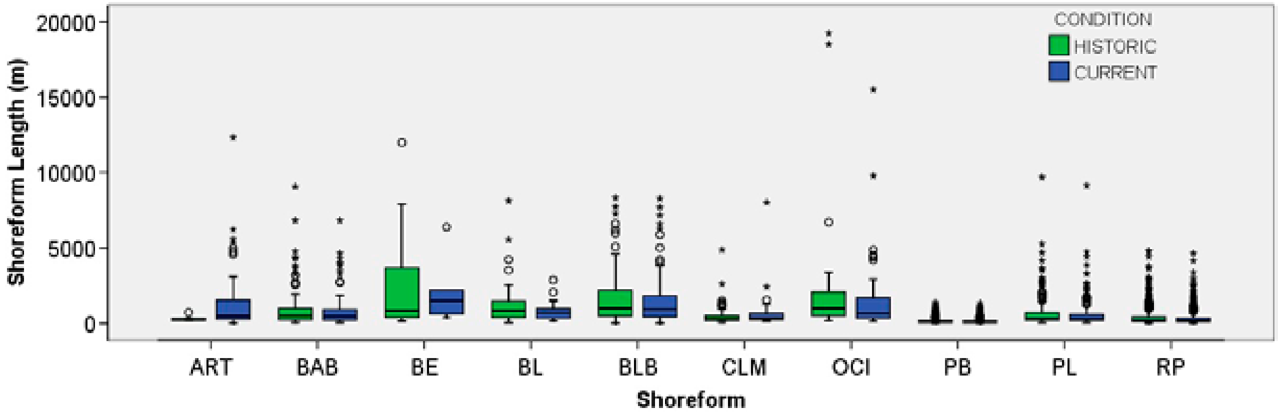


Figure 70. Historical and current contiguous shoreline length of San Juan Islands–Strait of Georgia shoreforms in PU (excludes delta shoreform); see Fig. 20 for shoreform codes. Each box represents the median and upper and lower quartile of the shoreform length data. The 'whiskers' (lines that extend out of the top and bottom of box) represent the highest and lowest values that are not outliers or extreme values. Outliers (values between 1.5 and 3 times the interquartile range) are marked with a circle and extreme cases (values more than 3 times the interquartile range) with an asterisk.

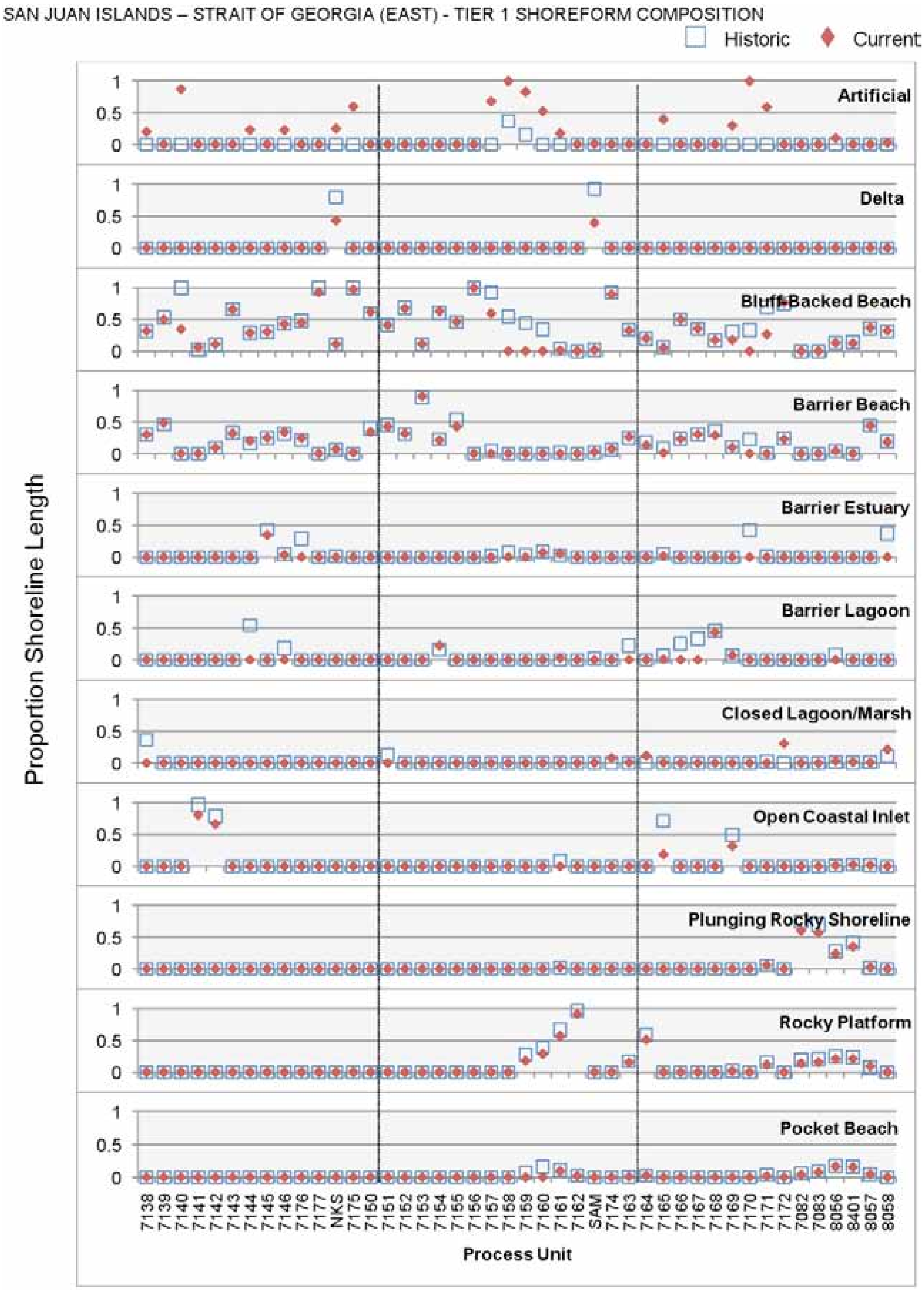


Figure 71. Proportional lengths of historical and current shoreforms along sequential process units (PU) in the eastern component of the San Juan Islands–Strait of Georgia Sub-Basin.

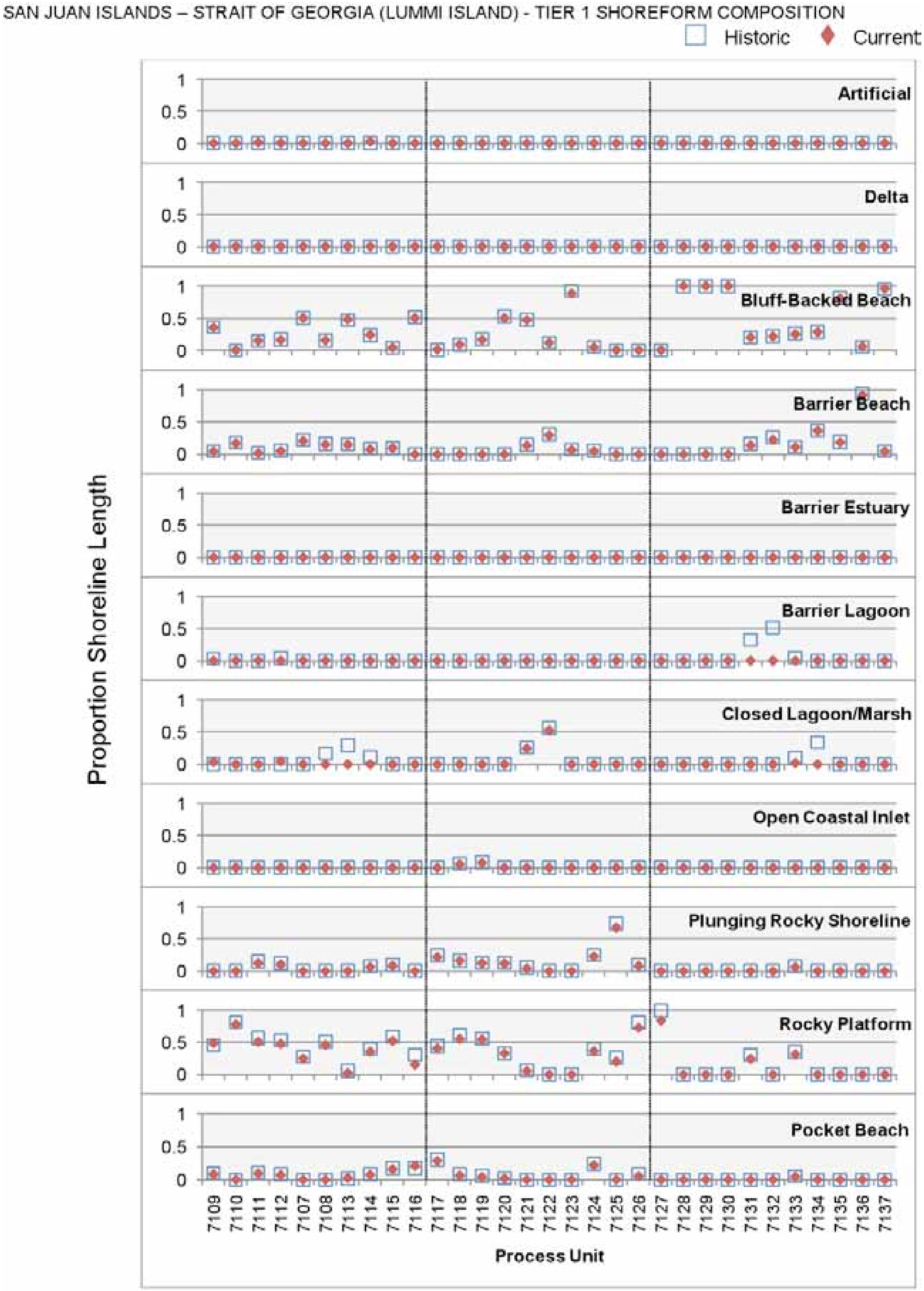


Figure 72. Proportional lengths of historical and current shoreforms along sequential process units (PU) in the central (Lummi Island) component of the San Juan Islands–Strait of Georgia Sub-Basin.

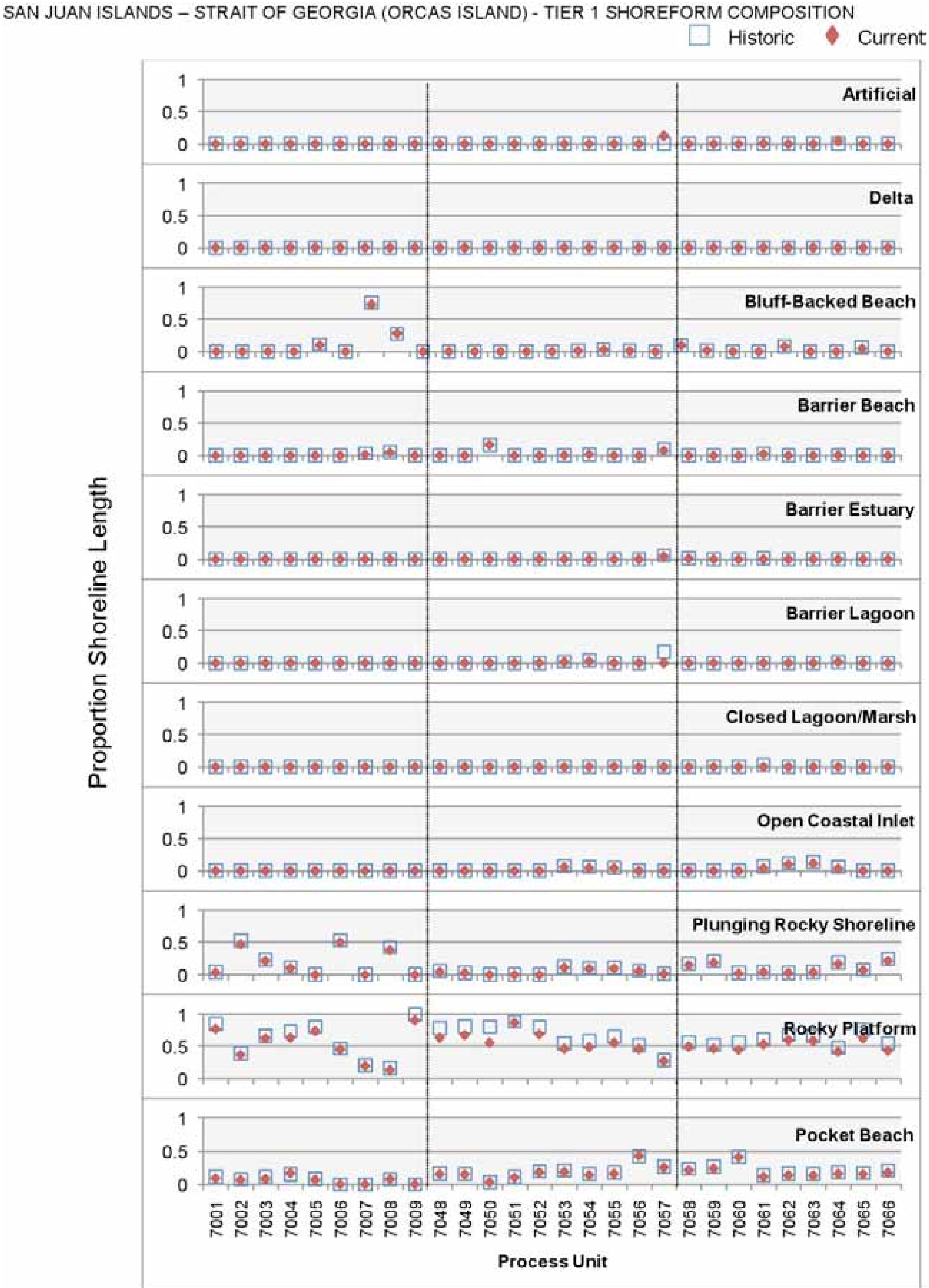


Figure 73. Proportional lengths of historical and current shoreforms along sequential process units (PU) in the Orcas Island component of the San Juan Islands–Strait of Georgia Sub-Basin

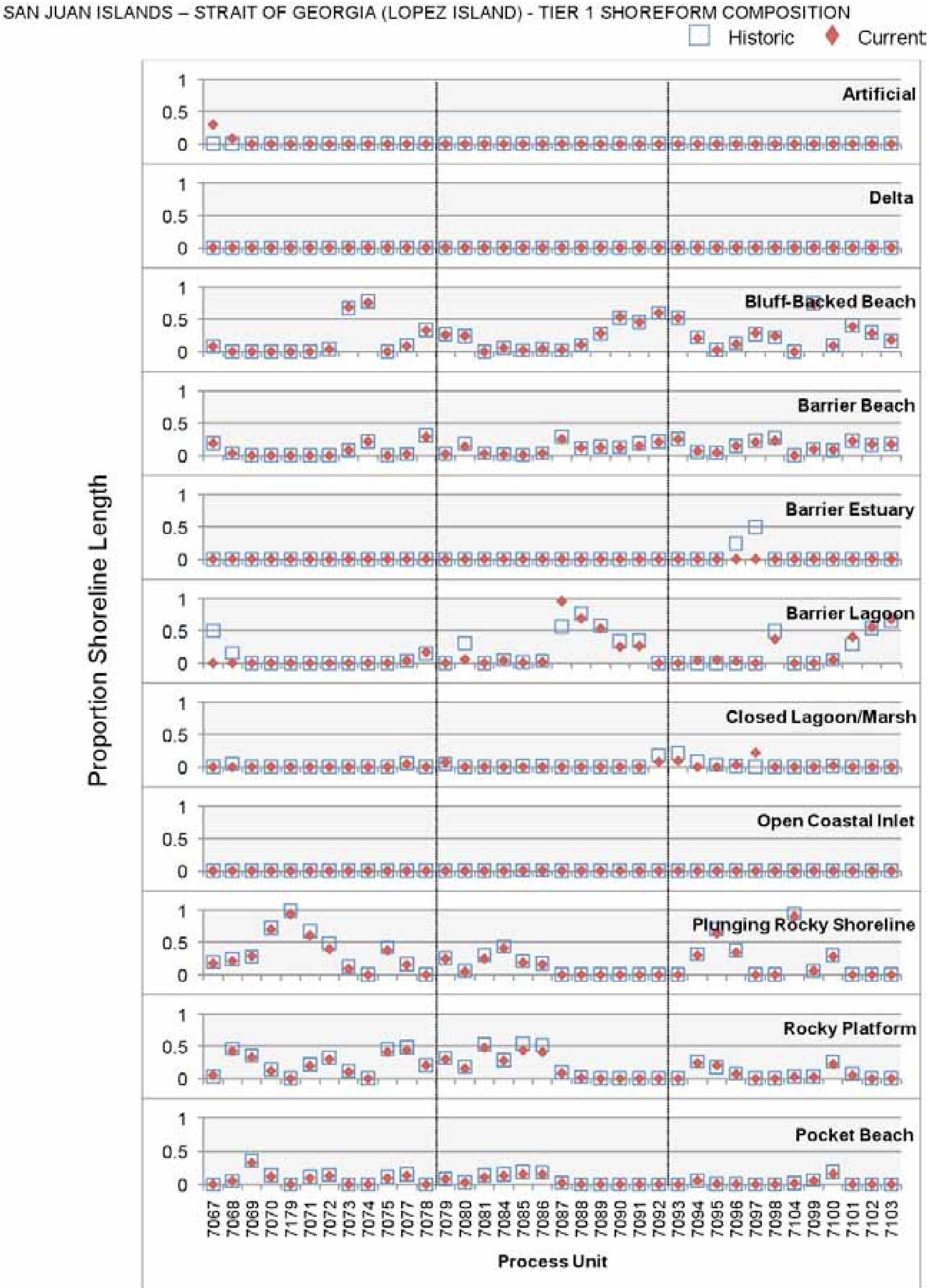


Figure 74. Proportional lengths of historical and current shoreforms along sequential process units (PU) in the Lopez Island component of the San Juan Islands–Strait of Georgia Sub-Basin.

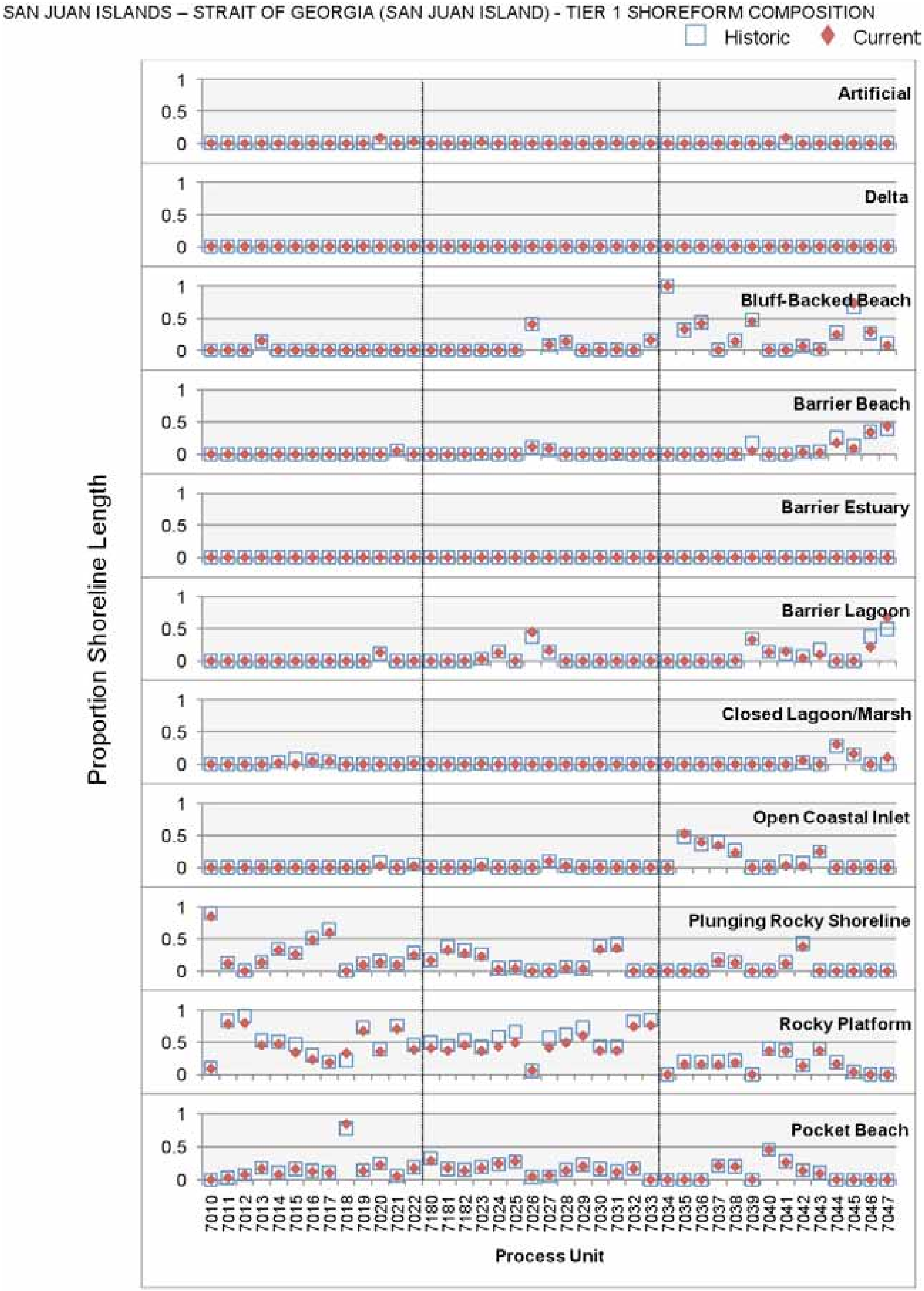


Figure 75. Proportional lengths of historical and current shoreforms along sequential process units (PU) of the San Juan Island component of the San Juans–Strait of Juan de Fuca Sub-Basin

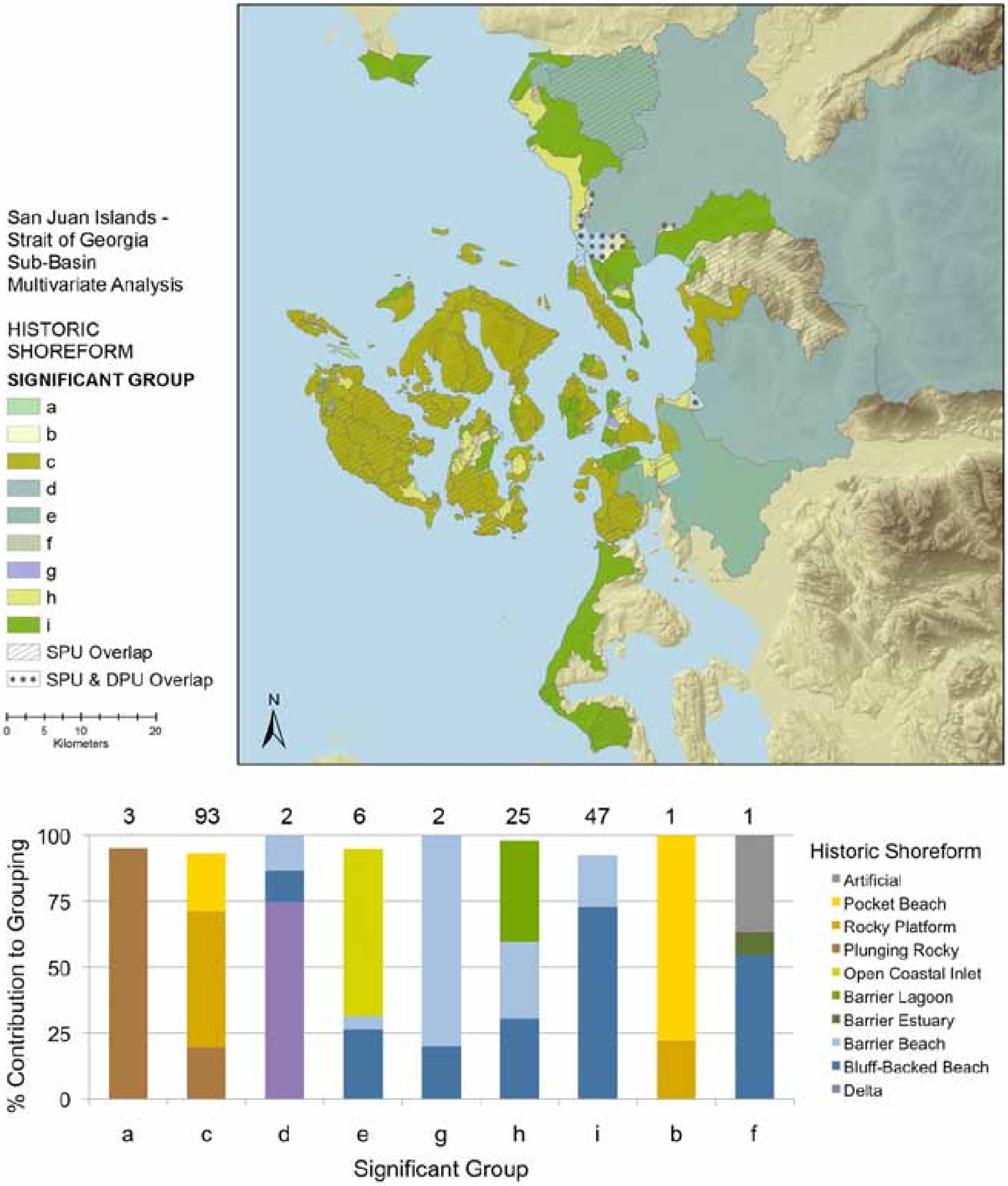


Figure 76.(Top) Distribution of process unit (PU) groups with significantly similar historical shoreform composition in San Juan Islands–Strait of Georgia Sub-Basin of Puget Sound based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for historical shoreform composition in the PU. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group. Groups composed of one PU show the descriptive composition of the PU.

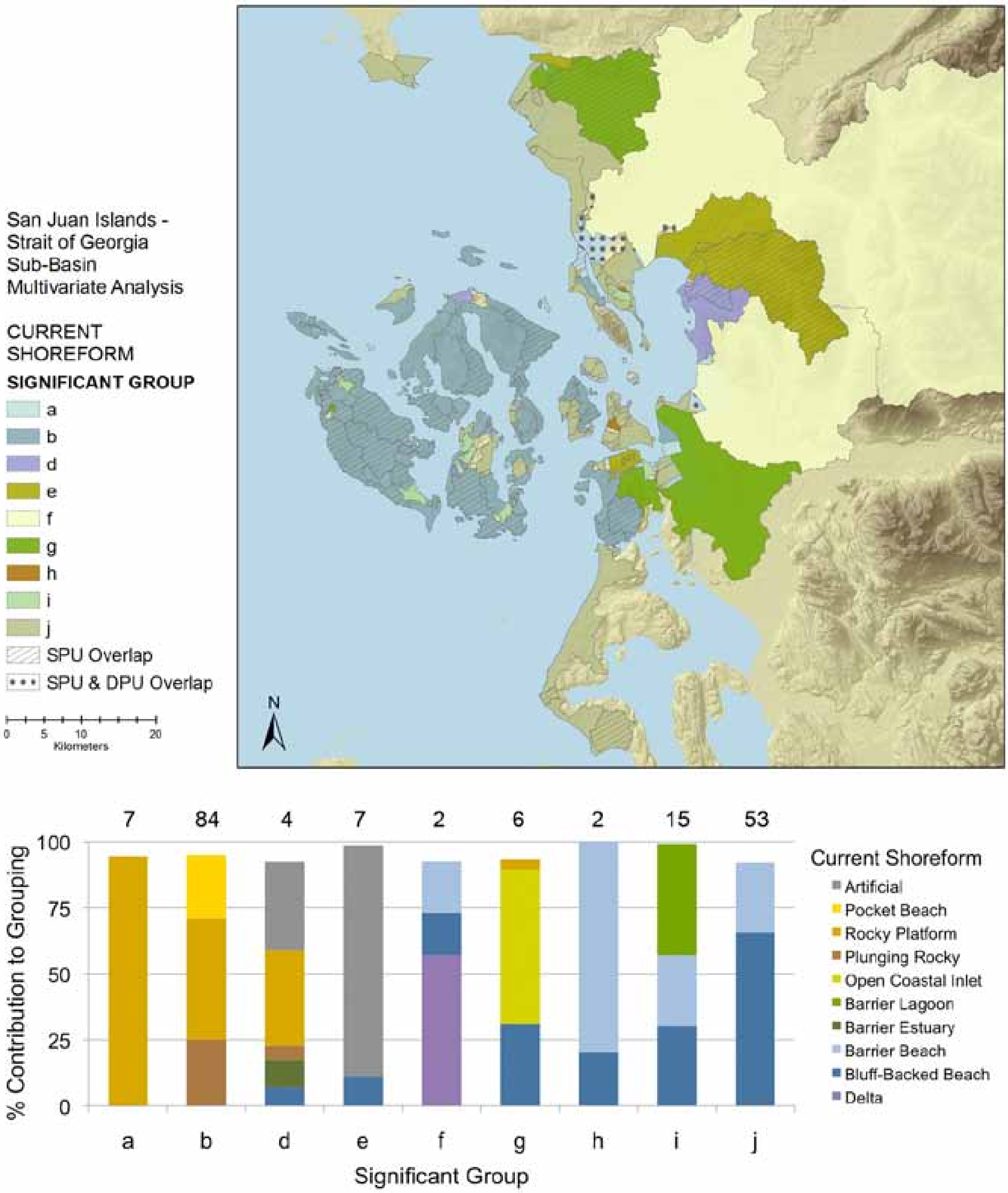


Figure 77.(Top) Distribution of process unit (PU) groups with significantly similar current shoreform composition in San Juan Islands–Strait of Georgia Sub-Basin of Puget Sound based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for current shoreform composition in the PU. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group. Groups composed of one PU show the descriptive composition of the PU

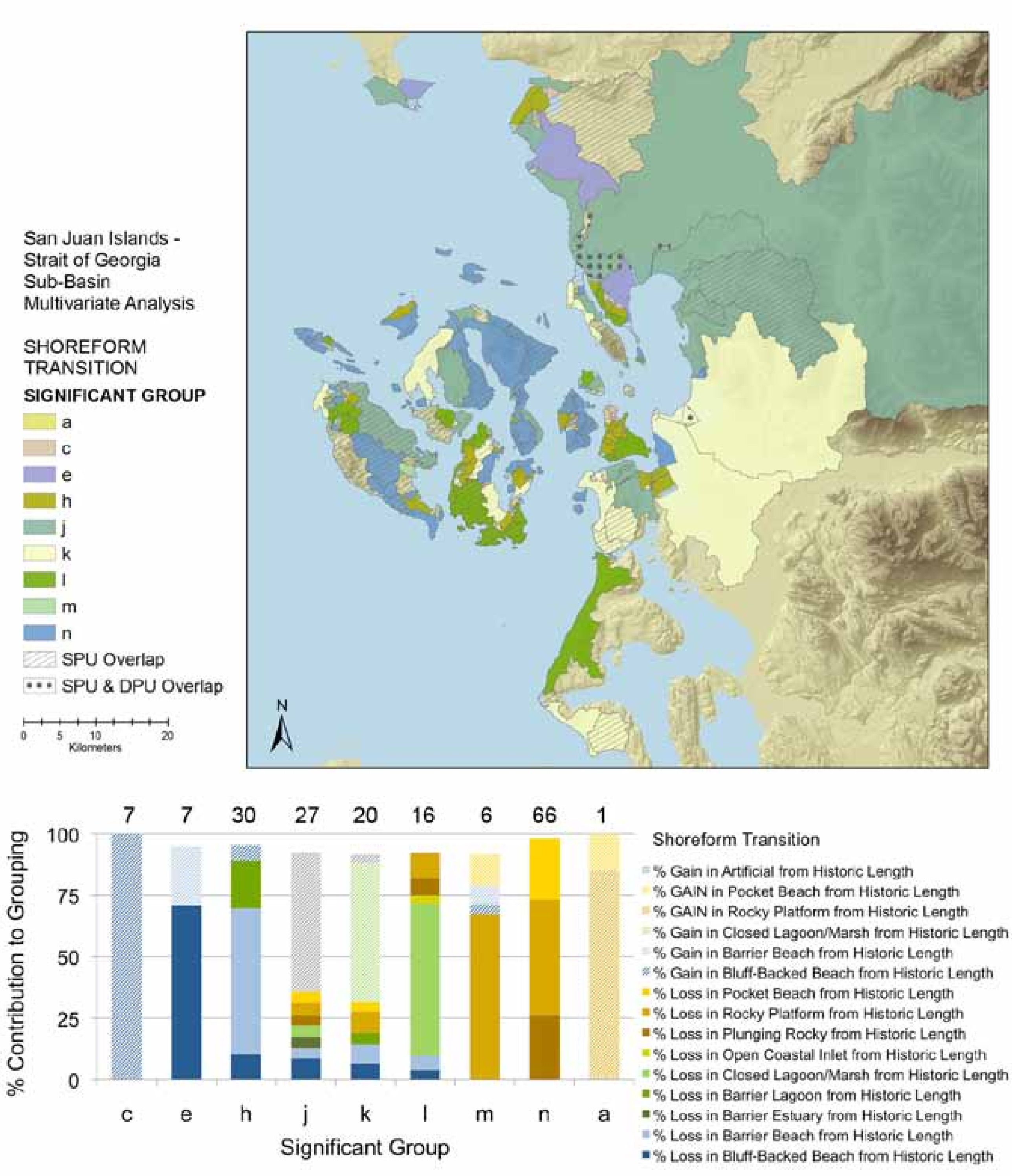


Figure 78. (Top) Distribution of process unit (PU) groups with significantly similar shoreform transitions in San Juan Islands–Strait of Georgia Sub-Basin of Puget Sound based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for shoreform transition in the PU. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group. Groups composed of one PU show the descriptive composition of the PU.

Table 13. Shoreform transitions (Tier 1) of San Juan Islands–Strait of Georgia Sub-Basin. Highlighted numbers (diagonal line) represent the number that did not transition and are derived as the difference between the historical shoreform count and the total number of transitions.

Shoreform Transition	*Current* ----------------------->												
Historic	Bluff-Backed Beach	Barrier Beach	Delta	Barrier Estuary	Barrier Lagoon	Closed Lagoon/ Marsh	Open Coastal Inlet	Plunging Rocky Shoreline	Rocky Platform	Pocket Beach	Artificial	Shoreform Absent	Total Transitions
Bluff-Backed Beach	113	1			1						19		21
Barrier Beach		108									9		9
Delta			1								1		1
Barrier Estuary				5		1					3	5	9
Barrier Lagoon					36	1					5	7	13
Closed Lagoon/Marsh					1	21					1	19	21
Open Coastal Inlet				1			21				7		8
Plunging Rocky Shoreline								313			2		2
Rocky Platform					1				1188		15		16
Pocket Beach										939	5		5
Artificial											5		0
Shoreform Absent					1	5			29		11		46
Total Transitions	0	2	0	1	4	8	0	0	29	0	78	31	153

Shoreline Alterations

Descriptive

In the eastern component of the San Juan Islands–Strait of Georgia Sub-Basin, armoring is relatively pervasive along most of the shoreline, but becomes particularly common (>50 percent) from Lummi Bay to south of Anacortes (SPU 7155–7172; Fig. 79). Nearshore roads compound the alterations, particularly in the Anacortes region (SPU 7166–7171). Nearshore fill, overwater structures, and marinas are similarly concentrated around Anacortes and Birch Bay; they cover up to 50 percent of the aquatic zone area in Birch Bay (7158–7160). The Lummi Island component of the sub-basin does not contain much shoreline alteration except for moderate armoring around the north and western shoreline of Guemes Island (7130–7137; Fig. 80). The Orcas Island component also is not heavily altered, except for the large marina coverage on the east side of East Sound (7064; Fig. 81). Armoring and some coincident nearshore roads are more common in the Lopez Island component, especially the northwest corner of Lopez Island where marina coverage also approaches 20 percent of the nearshore aquatic area (7087–7094; Fig 82). The San Juan Island component of this sub-basin is also relatively free of shoreline alterations, with overwater structures and marinas indicating only scattered coverage in the region of Roche Harbor, in the northwestern corner of the Island (Fig. 83).

Multivariate Analysis

The most common groups of alterations to PUs, including 1) a combination of the loss of estuarine mixing wetlands with armoring and nearshore roads (group ab), 2) the gain of estuarine mixing wetlands with armoring and nearshore roads (group z), and 3) overwater structures (group x), are distributed in a general mosaic pattern through the sub-basin (Fig. 84).

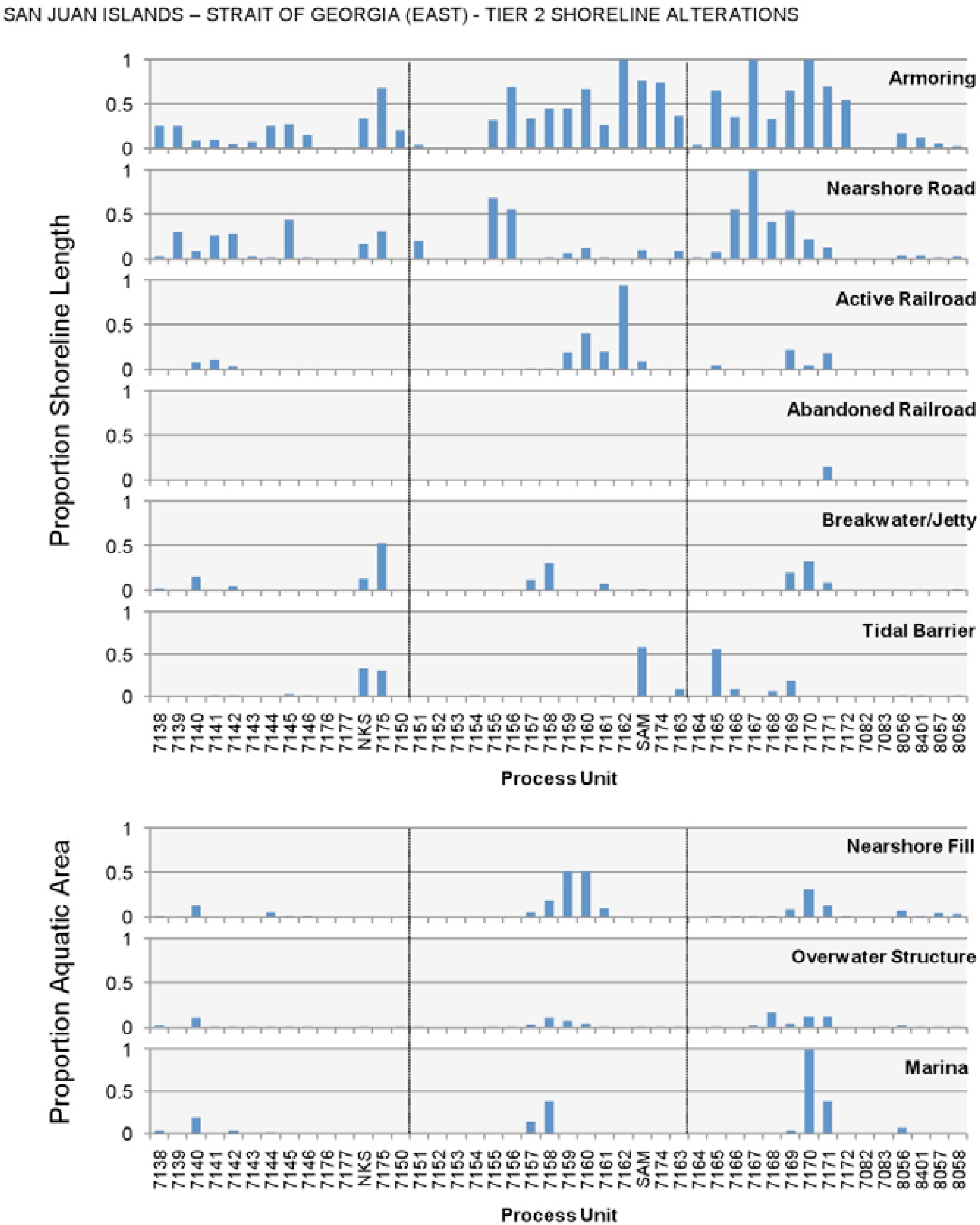


Figure 79. Shoreline alterations along sequential process units (PU) in the eastern component of the San Juan Islands–Strait of Georgia Sub-Basin.

SAN JUANS (LUMMI ISLAND) - TIER 2 SHORELINE ALTERATIONS

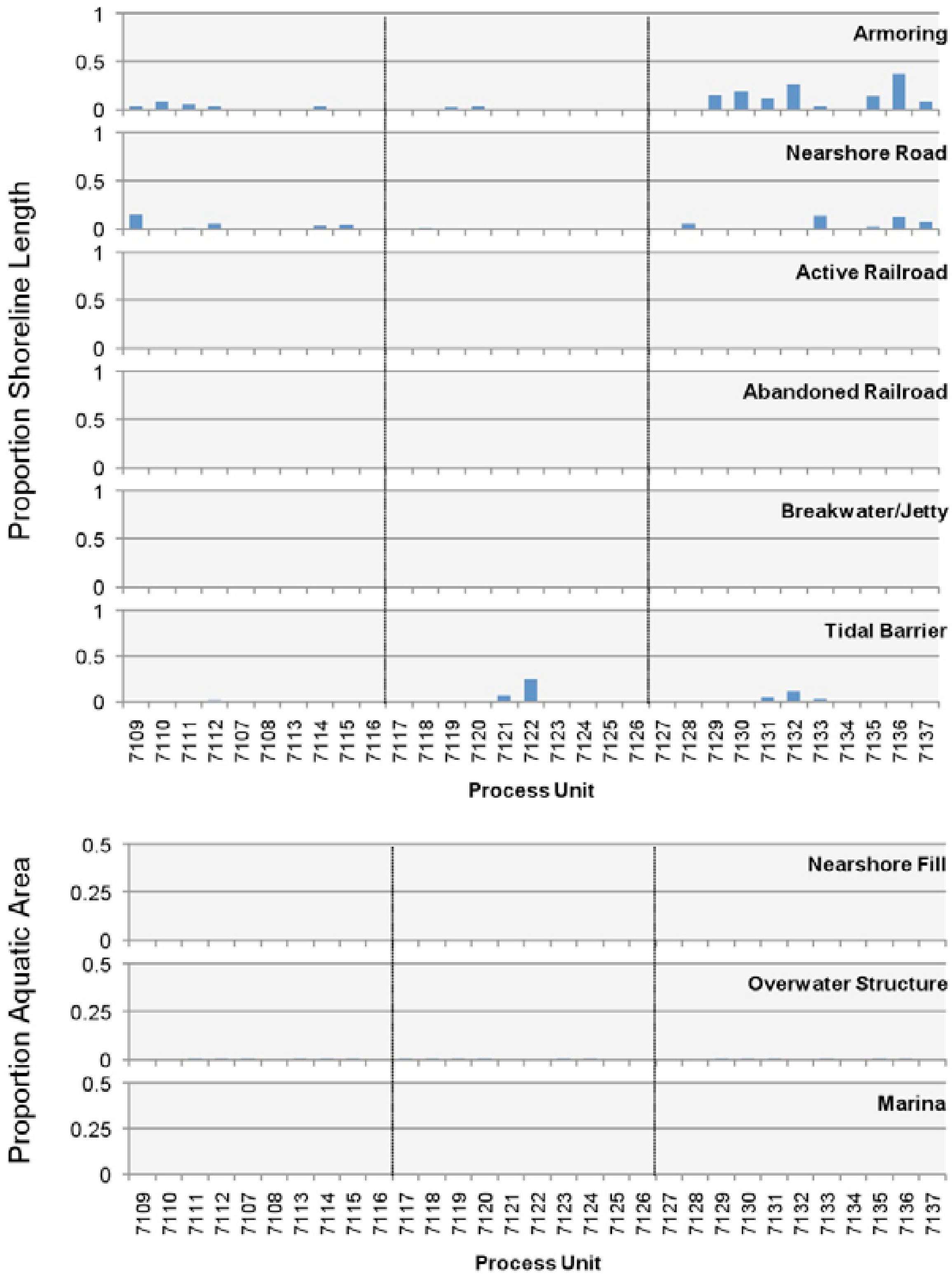
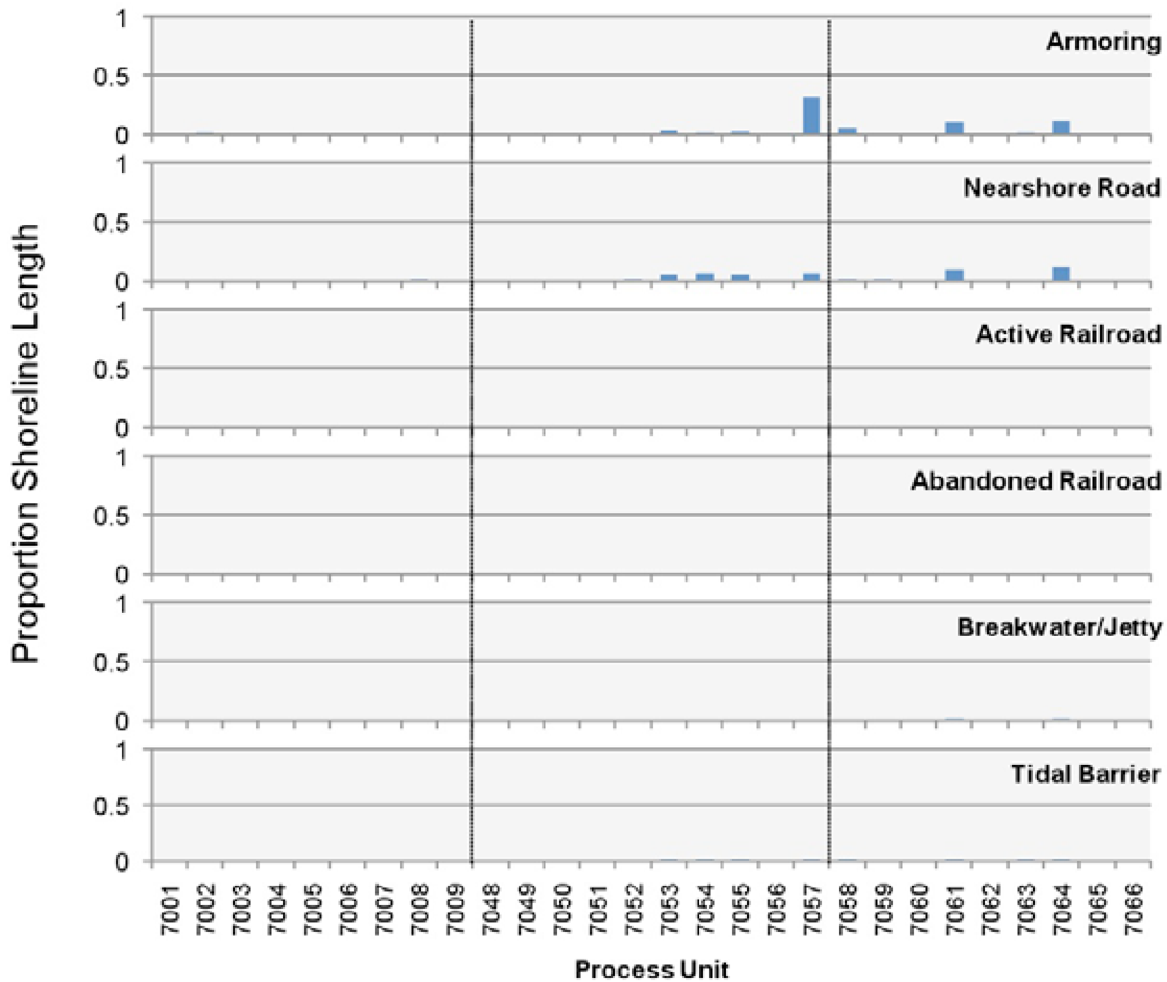


Figure 80. Shoreline alterations along sequential process units (PU) in the central (Lummi Island) component of the San Juan Islands–Strait of Georgia Sub-Basin.

SAN JUAN ISLANDS – STRAIT OF GEORGIA (ORCAS ISLAND) - TIER 2 SHORELINE ALTERATIONS



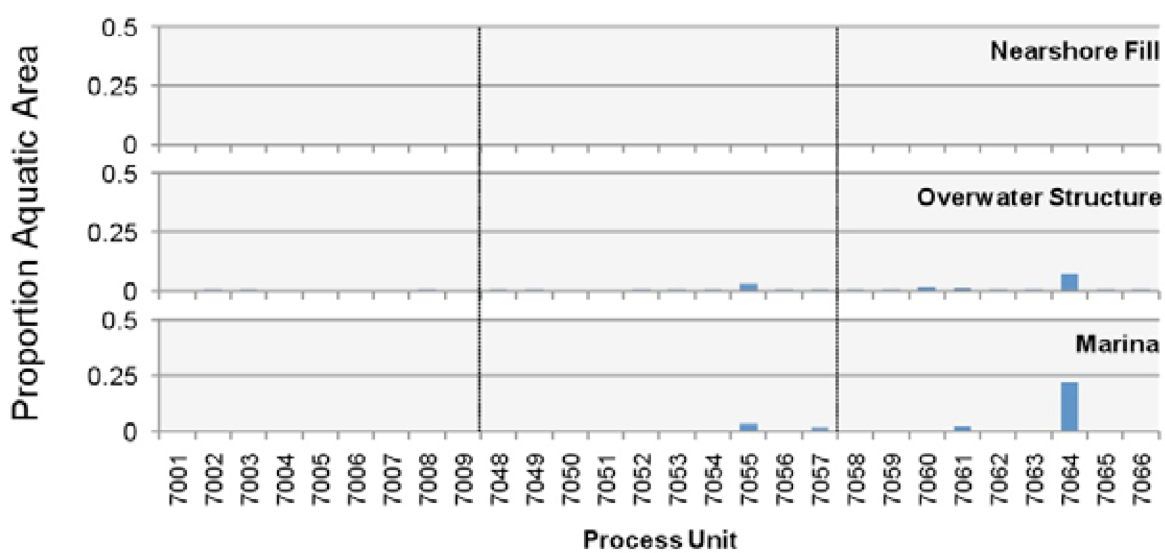


Figure 81. Shoreline alterations along sequential process units (PU) in the Orcas Island component of the San Juan Islands–Strait of Georgia Sub-Basin.

SAN JUAN ISLANDS – STRAIT OF GEORGIA (LOPEZ ISLAND) - TIER 2 SHORELINE ALTERATIONS

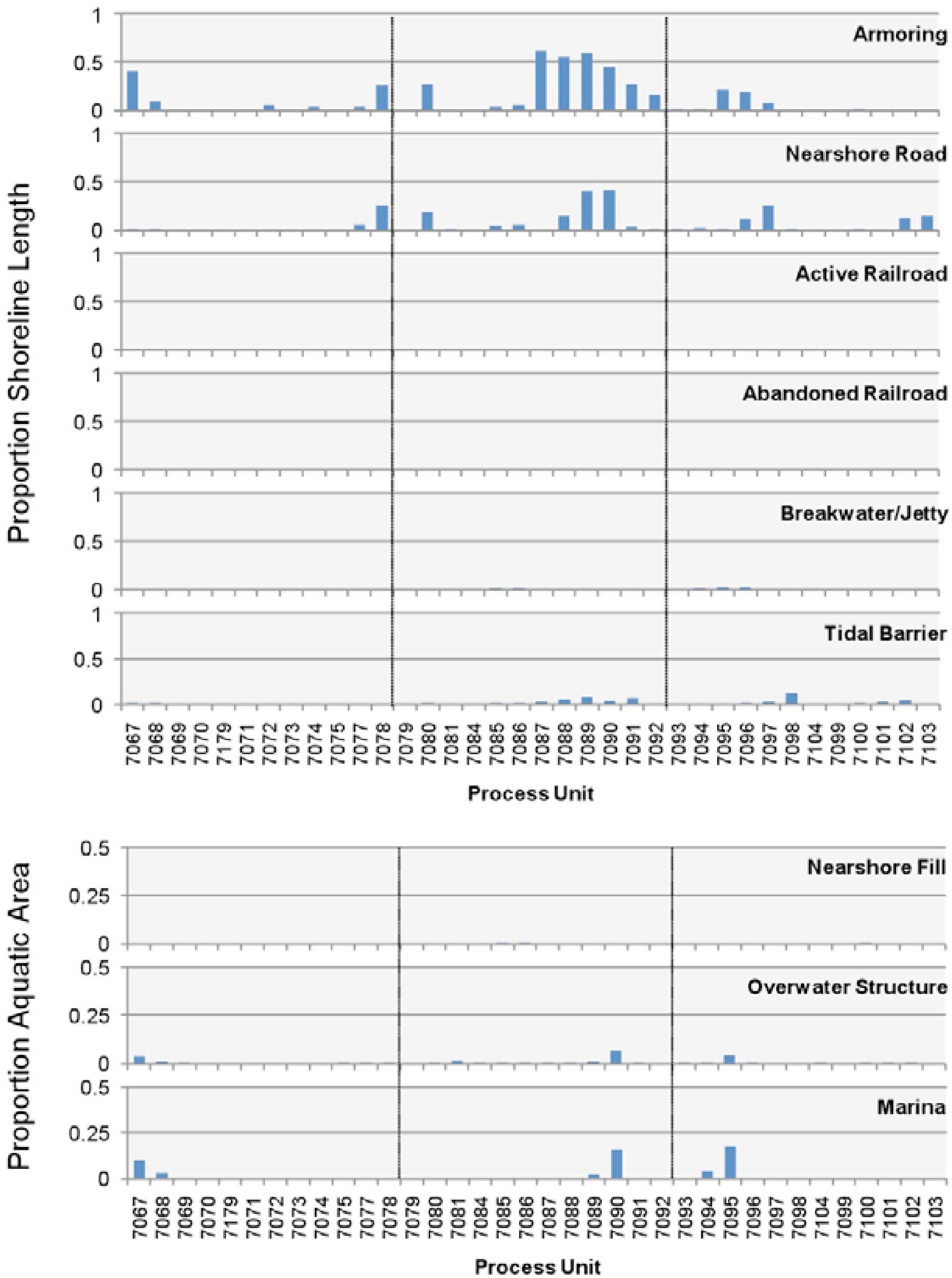


Figure 82. Shoreline alterations along sequential process units (PU) in the Lopez Island component of the San Juan Islands–Strait of Georgia Sub-Basin.

SAN JUAN ISLANDS – STRAIT OF GEORGIA (SAN JUAN ISLAND) - TIER 2 SHORELINE ALTERATIONS

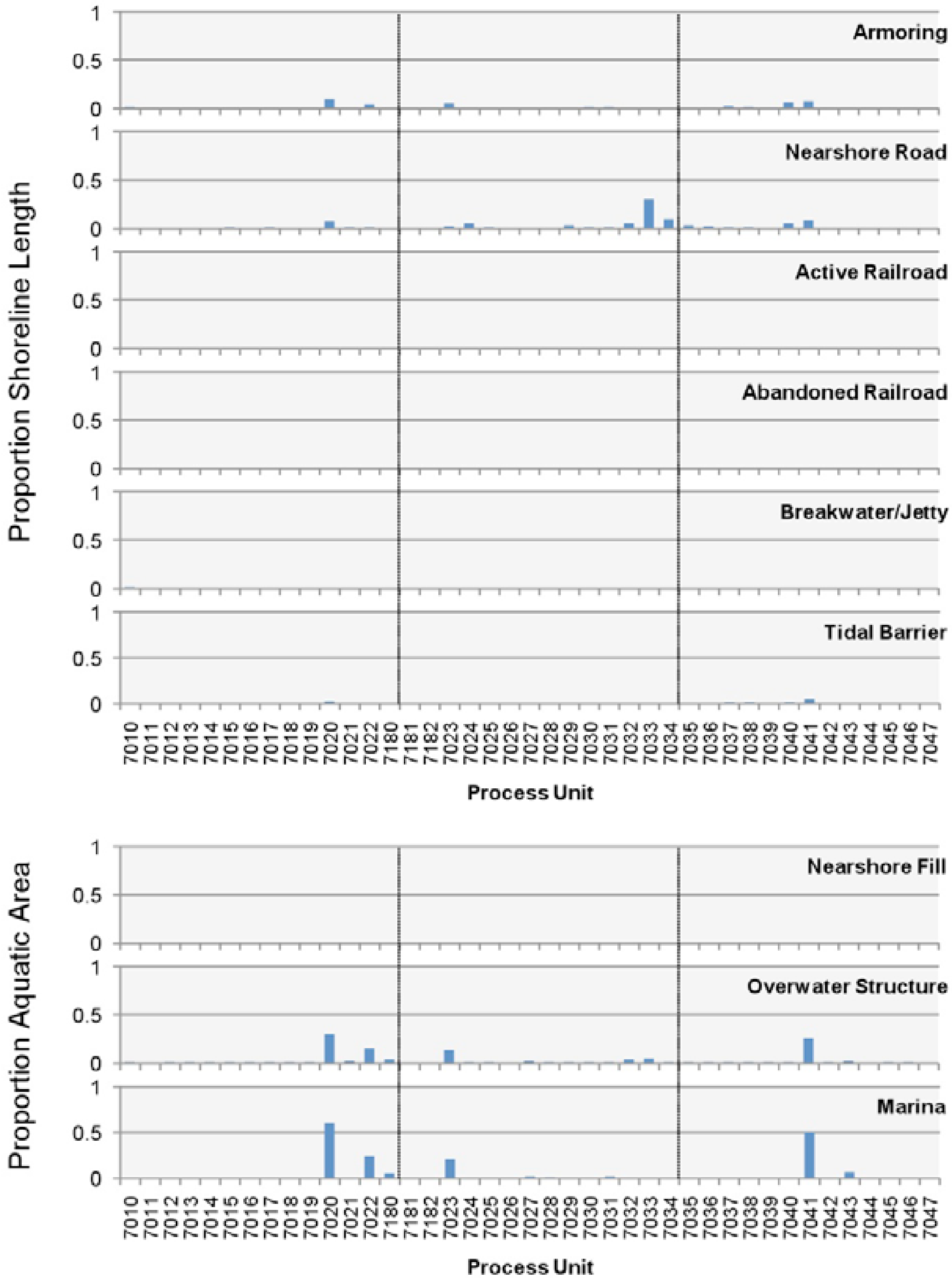


Figure 83. Shoreline alterations along sequential process units (PU) in the San Juan component of the San Juan Islands–Strait of Georgia Sub-Basin.

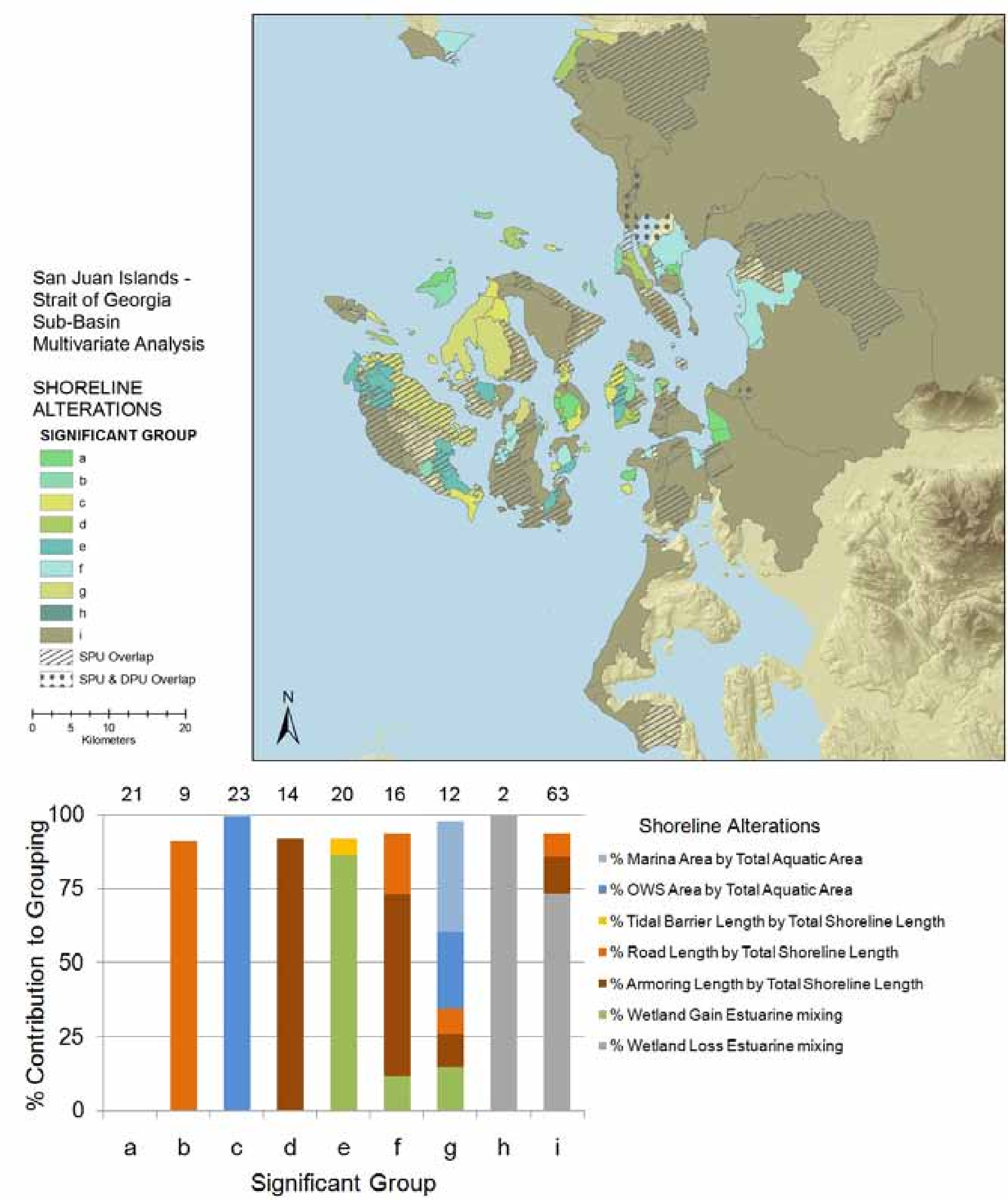


Figure 84. (Top) Process unit (PU) groups with significant similar shoreline alterations and stressors in San Juan Islands–Strait of Georgia Sub-Basin based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for shoreline alterations in the PU. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. PU in group 'a' do not have any shoreline alterations. Number above stacked histograms indicates the number of PU in each group.

Adjacent Upland and Watershed Change

Descriptive

The eastern component of the San Juan Islands–Strait of Georgia Sub-Basin is the most heavily developed area, particularly between SPU 7157–7160 (Bellingham Bay) and SPU 7167–7171 (Anacortes) (Fig. 85). The islands of the sub-basin are dominated by evergreen forest, with the exception of Lummi and Guemes Islands, which show a more mixed forest cover (Figs. 86-89).

Multivariate Analysis

Analysis of adjacent upland change shows group g (composed of 83 PU) to be common within and distributed throughout all areas of the sub-basin (Fig. 90). These process units are characterized by low to moderate development with the following categories: 10 percent impervious surface, open space and low intensity development, and roads. Group d, which includes the two deltas of the sub-basin, has a similar adjacent upland change composition as group g, but is distinguished by the additional presence of agricultural lands (i.e., hay/pasture and cultivated crops). Group i (63 PU), also common and evenly distributed. It represents minimally impacted areas; the only discriminating change variable within the adjacent upland is 10 percent impervious surface. Groups a and b (with 7 and 15 PU, respectively) contain the more highly developed process units and are concentrated in the more urbanized and residential areas.

Analysis of watershed area change shows groups f and c representing typical process units within the sub-basin (57 and 55 PU, respectively). Group f is characterized by low to moderate development and group c is minimally impacted, distinguished only by 0 to 10 percent impervious surface (Fig. 91). Group g, which includes the sub-basin's two river delta process units, is also common (32 PU) and shares many of the same discriminating variables as f (i.e., low impervious surface, open space and low intensity development, and roads), but is distinguished by the presence of hay/pasture land.

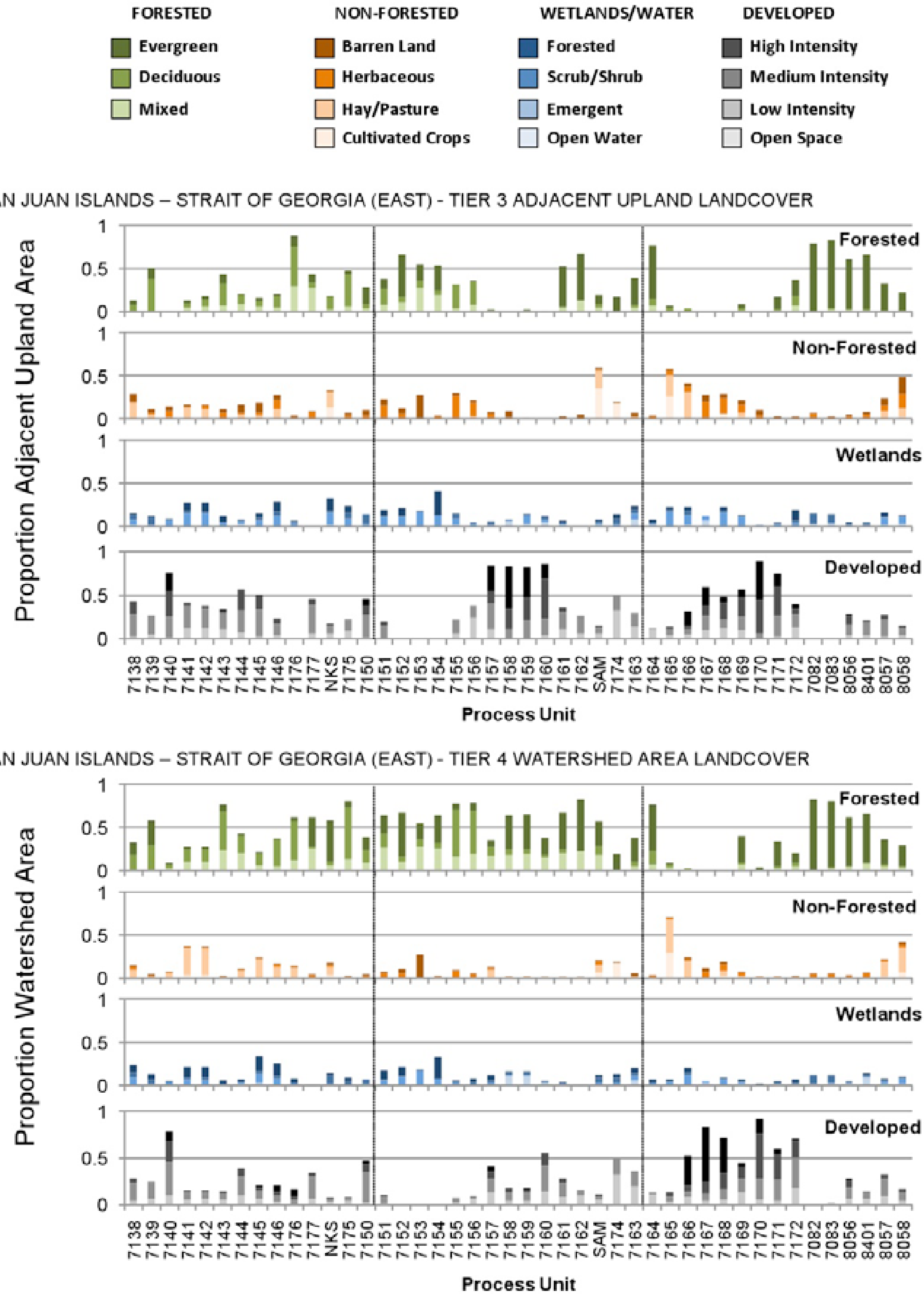


Figure 85. Land cover/land and stressors in adjacent upland (Tier 3, top) and watershed areas (Tier 4, bottom) in the eastern component of the San Juan Islands–Strait of Georgia Sub-Basin.

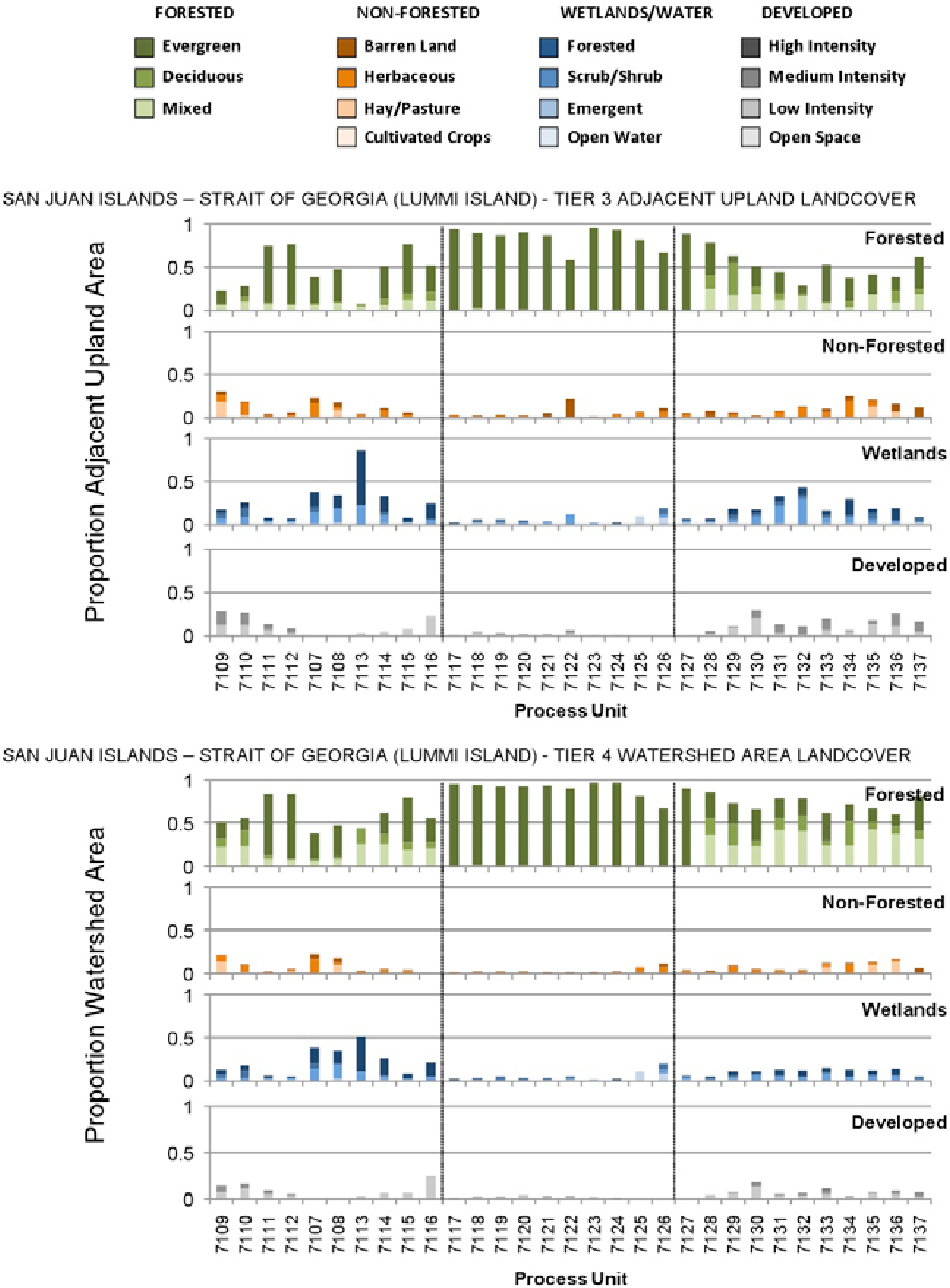


Figure 86. Land cover/land and stressors in adjacent upland (Tier 3, top) and watershed areas (Tier 4, bottom) in the central (Lummi Island) component of the San Juan Islands–Strait of Georgia Sub-Basin.

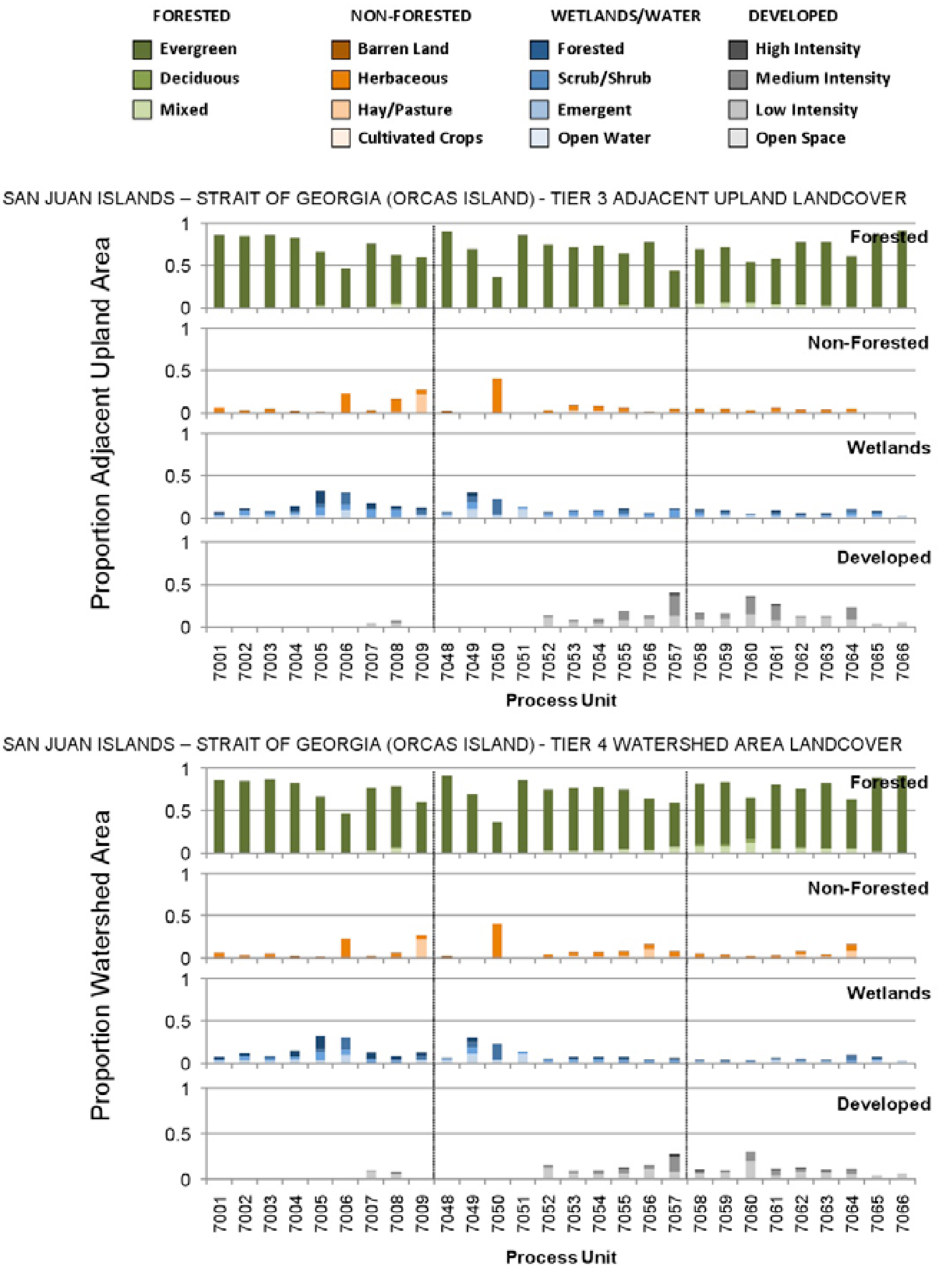


Figure 87. Land cover/land and stressors in adjacent upland (Tier 3, top) and watershed areas (Tier 4, bottom) in the Orcas Island component of the San Juan Islands–Strait of Georgia Sub-Basin.

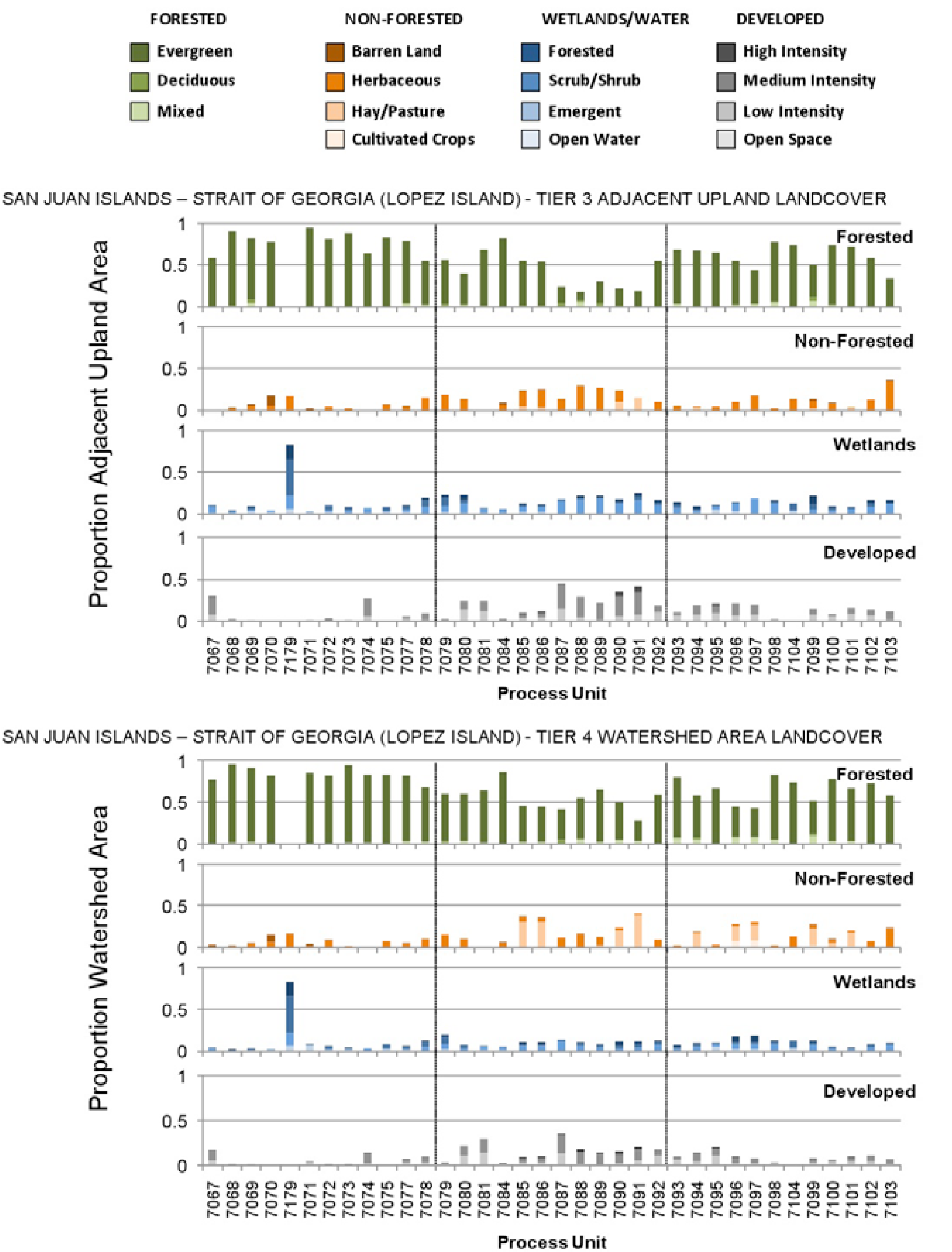


Figure 88. Land cover/land and stressors in adjacent upland (Tier 3, top) and watershed areas (Tier 4, bottom) in the Lopez Island component of the San Juan Islands–Strait of Georgia Sub-Basin.

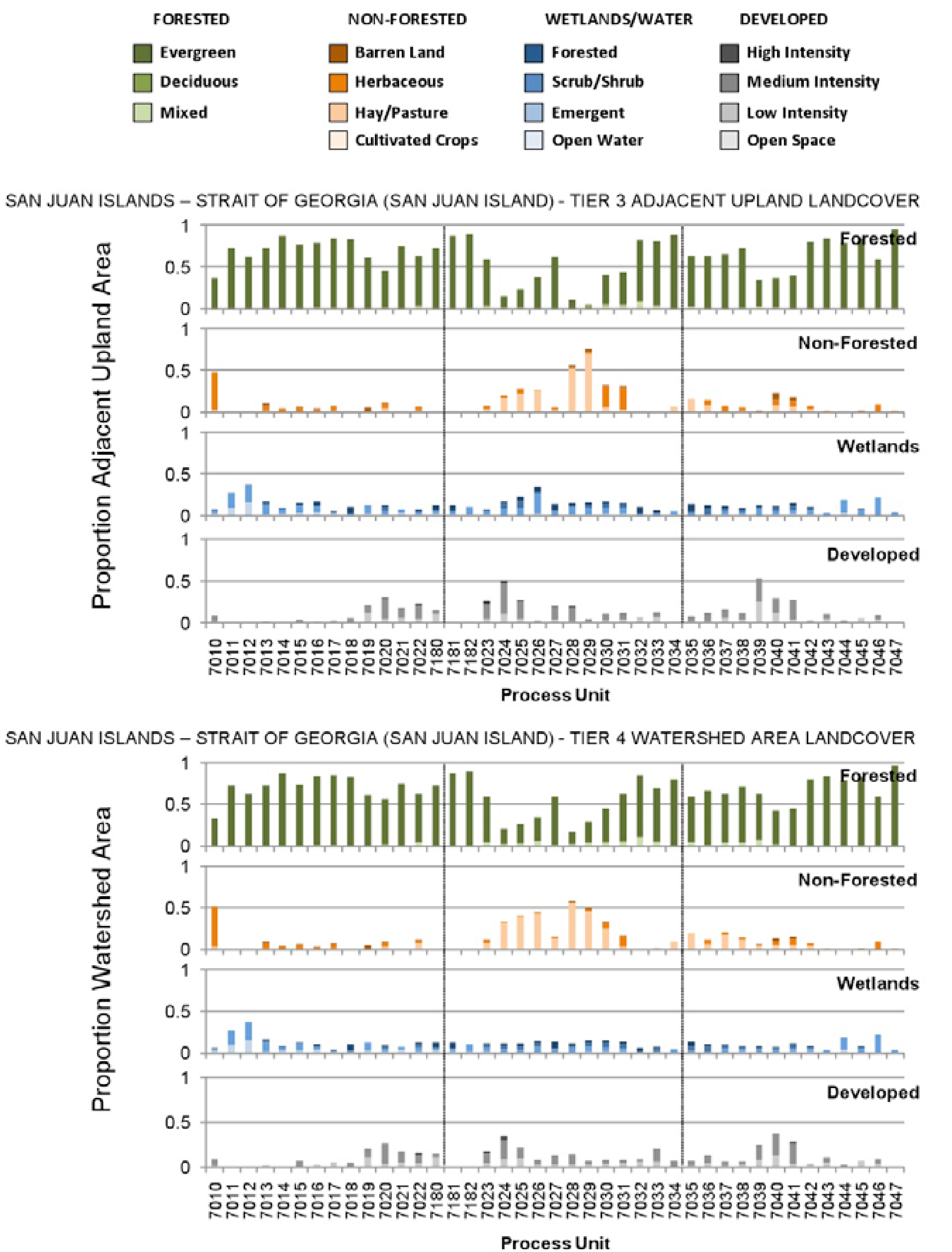


Figure 89. Land cover/land and stressors in adjacent upland (Tier 3, top) and watershed areas (Tier 4, bottom) in the San Juan Island component of the San Juan Islands–Strait of Georgia Sub-Basin.

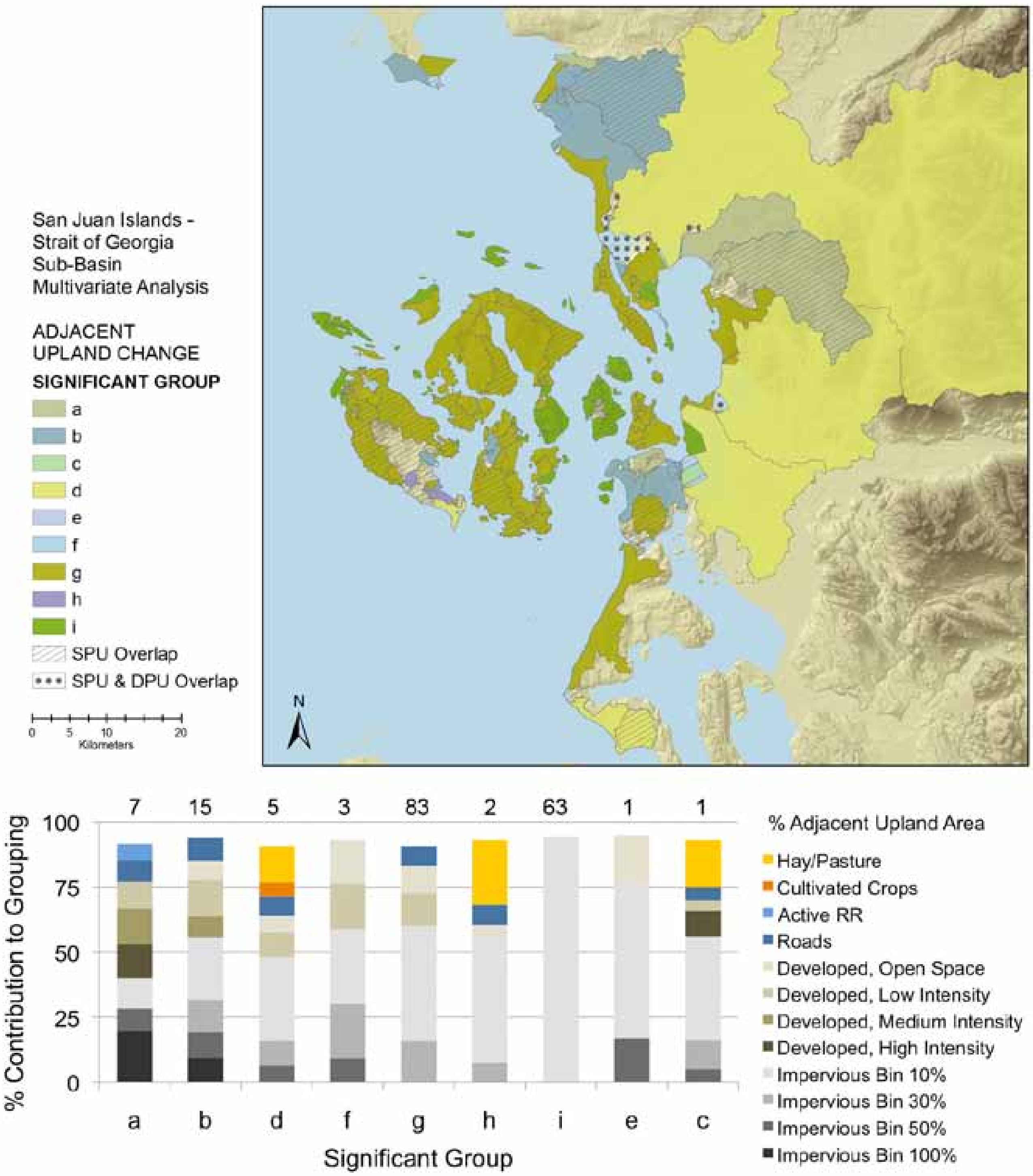


Figure 90. (Top) Distribution of process unit (PU) groups with significantly similar adjacent upland changes in San Juan Islands–Strait of Georgia Sub-Basin of Puget Sound based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for adjacent upland change in the PU. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group. Groups composed of one PU show the descriptive composition of the PU.

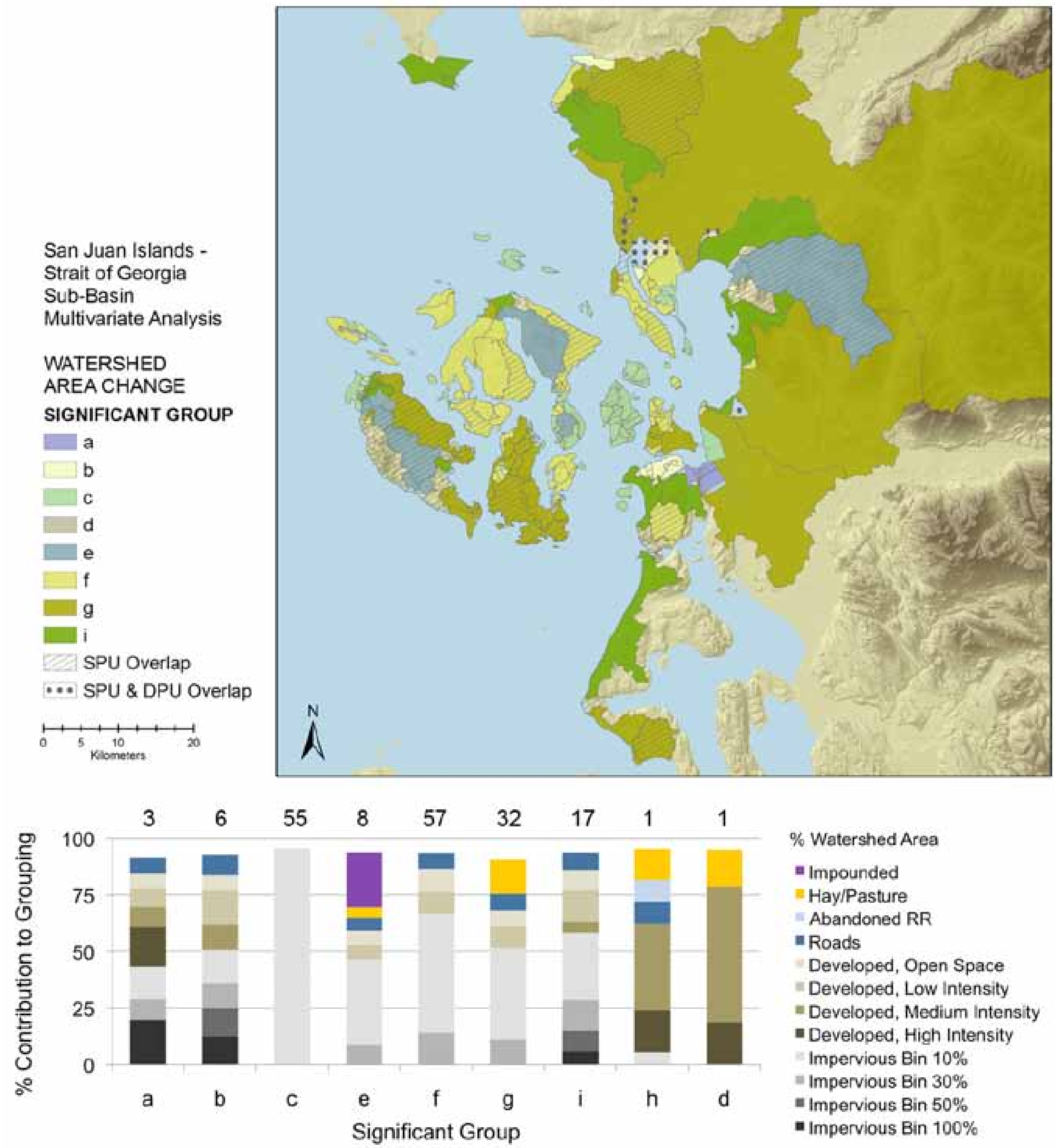


Figure 91. (Top) Distribution of process unit (PU) groups with significantly similar total watershed area changes in San Juan Islands–Strait of Georgia Sub-Basin of Puget Sound based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for watershed area change in the PU; note that group h overlaps with a DPU of another group and appears on the top map in the overlap zone. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group. Groups composed of one PU show the descriptive composition of the PU.

Hood Canal Sub-Basin

Shoreform Change and Transition

Descriptive

The Hood Canal Sub-Basin (Fig. 92) has experienced a reduction of more than 50 percent of the historical delta and open coastal inlet length, as well as losses associated with closed lagoon/marsh (approximately 36 percent), barrier estuary (approximately 25 percent), and barrier lagoon (approximately 21 percent) shoreforms (Table 4; Fig. 93).

The "artificial shoreform" and "shoreform absent" classifications dominated (89–100 percent) the transitions of almost all historical shoreforms; only historical open coastal inlets transitioned to natural shoreforms, 43 percent of which were classified as barrier estuaries under current conditions (Table 14). The three other shoreform transitions involved two barrier estuaries changing to barrier lagoon and closed lagoon/marsh, and a barrier lagoon changing to a closed lagoon/marsh, which cannot be attributed to natural or anthropogenic processes without further investigation of the specific nearshore locations.

Process unit change is described within two component areas of the Hood Canal Sub-Basin, north and south (refer to Appendix D, Figs. E.7 and E.8 for PU distribution). Several pockets of shoreform length change occur in the northern component of the Hood Canal Sub-Basin (Fig. 94). In addition to approximately 30–50 percent declines in shoreline lengths in the Dosewallips and Quilcene river deltas, the barrier estuaries and closed lagoon/marsh shoreforms surrounding much of Dabob Bay declined, particularly in the consecutive SPU 2059, 2062–2063. The northern tip and western margin of Foulweather Bluff (SPU 8220, 2077, 2099, 2076) also demonstrated large declines in barrier estuary length and moderate declines in barrier lagoon lengths along the contiguous shoreline. In southern Hood Canal, measurable reductions in SPU length were particularly notable for barrier estuaries and open coastal inlets along or close to the edges of the deltas of the Duckabush (SPU 2047), Hamma Hamma (2038), Skokomish (2032), and Union rivers (2021–2025) (Fig.95). Other notable reductions were open coastal inlet shoreline declines (SPU 2010–2013), reduced closed lagoon/marsh shoreline (2007), and reduced barrier estuary and barrier lagoon (2081–2082, 2003) on the eastern margin of the canal between Misery Point and the Great Bend.

Multivariate Analysis

Historically, PU along the Hood Canal Sub-Basin shoreline (Fig. 96) were dominated by bluff-backed beach and barrier beach (group j), bluff-backed beach, barrier beach and barrier estuary (group k) or bluff-backed beach, barrier beach, and closed lagoon/marsh (group n) shoreforms, interspersed with delta and bluff-backed beach (group b) or rocky shoreform (groups e and g) dominated PU. Under current conditions, the shoreform composition has been simplified from eight to six significant groups (not counting the one-shoreform groups), where the closed lagoon/marsh shoreform no longer contributes to a statistically distinct group of SPU and the rocky shoreforms now only constitute one group (Fig. 97). It is particularly notable that several regions historically had a mosaic of different shoreform groups where now the shore is more monotypic (for example, see the Great Bend to Lynch Cove/Union River delta). No shoreform transitions formed statistically significant groups.

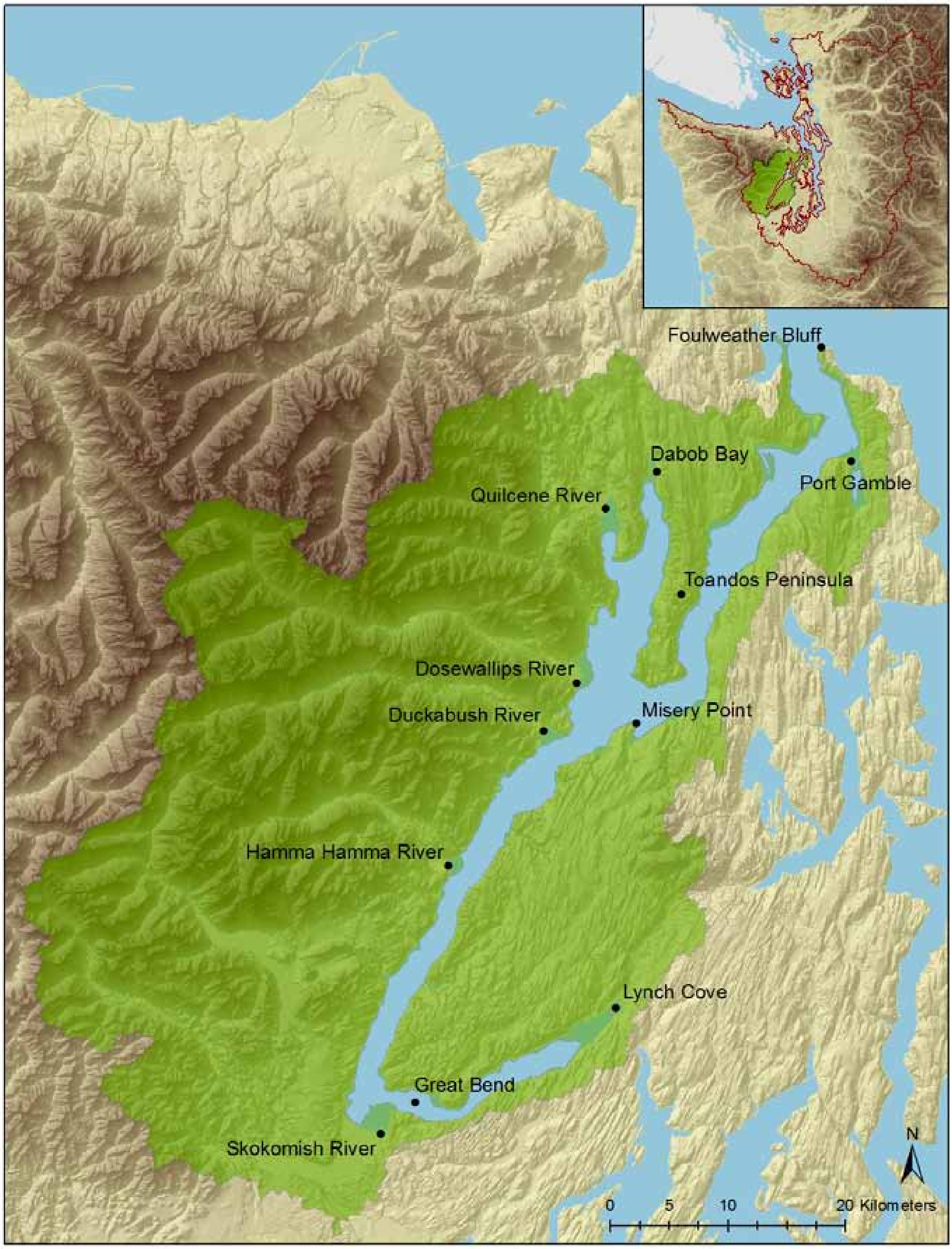


Figure 92. Hood Canal Sub-Basin.

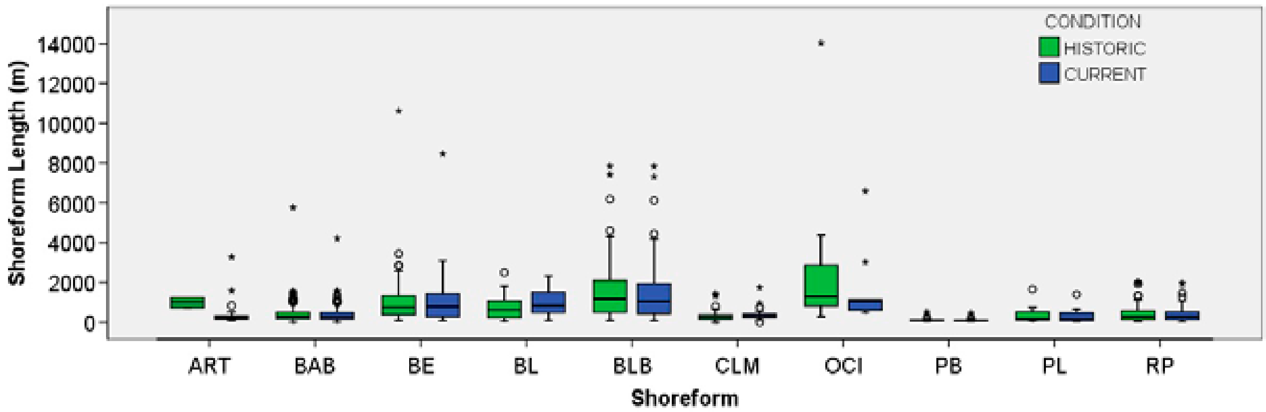


Figure 93. Historical and current contiguous shoreline length of Hood Canal shoreforms in PU (excludes delta shoreform); see Fig. 20 for shoreform codes. Each box represents the median and upper and lower quartile of the shoreform length data. The 'whiskers' (lines that extend out of the top and bottom of box) represent the highest and lowest values that are not outliers or extreme values. Outliers (values between 1.5 and 3 times the interquartile range) are marked with a circle and extreme cases (values more than 3 times the interquartile range) with an asterisk.

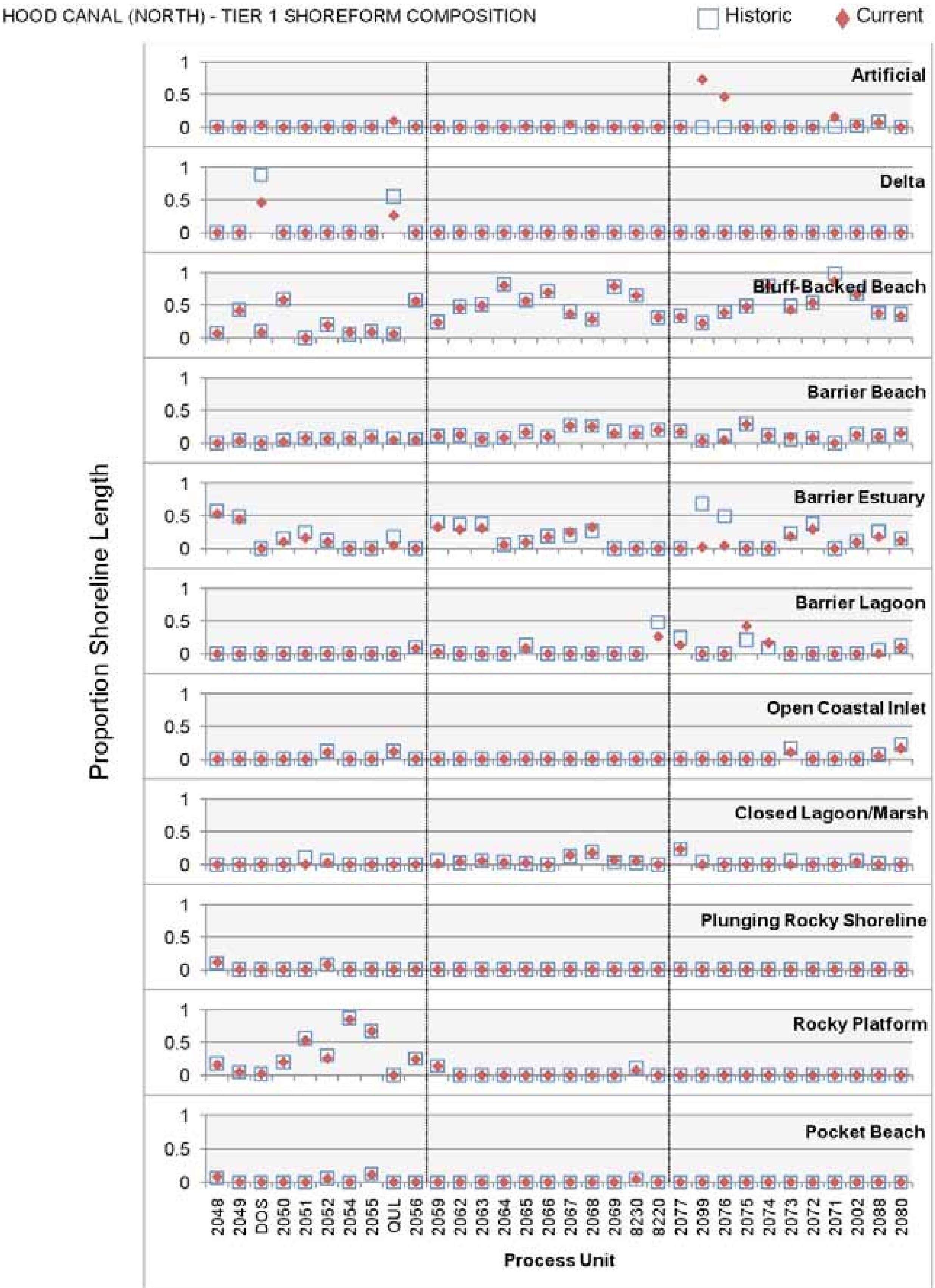


Figure 94. Proportional lengths of historical and current shoreforms along sequential process units (PU) of the northern component of the Hood Canal Sub-Basin.

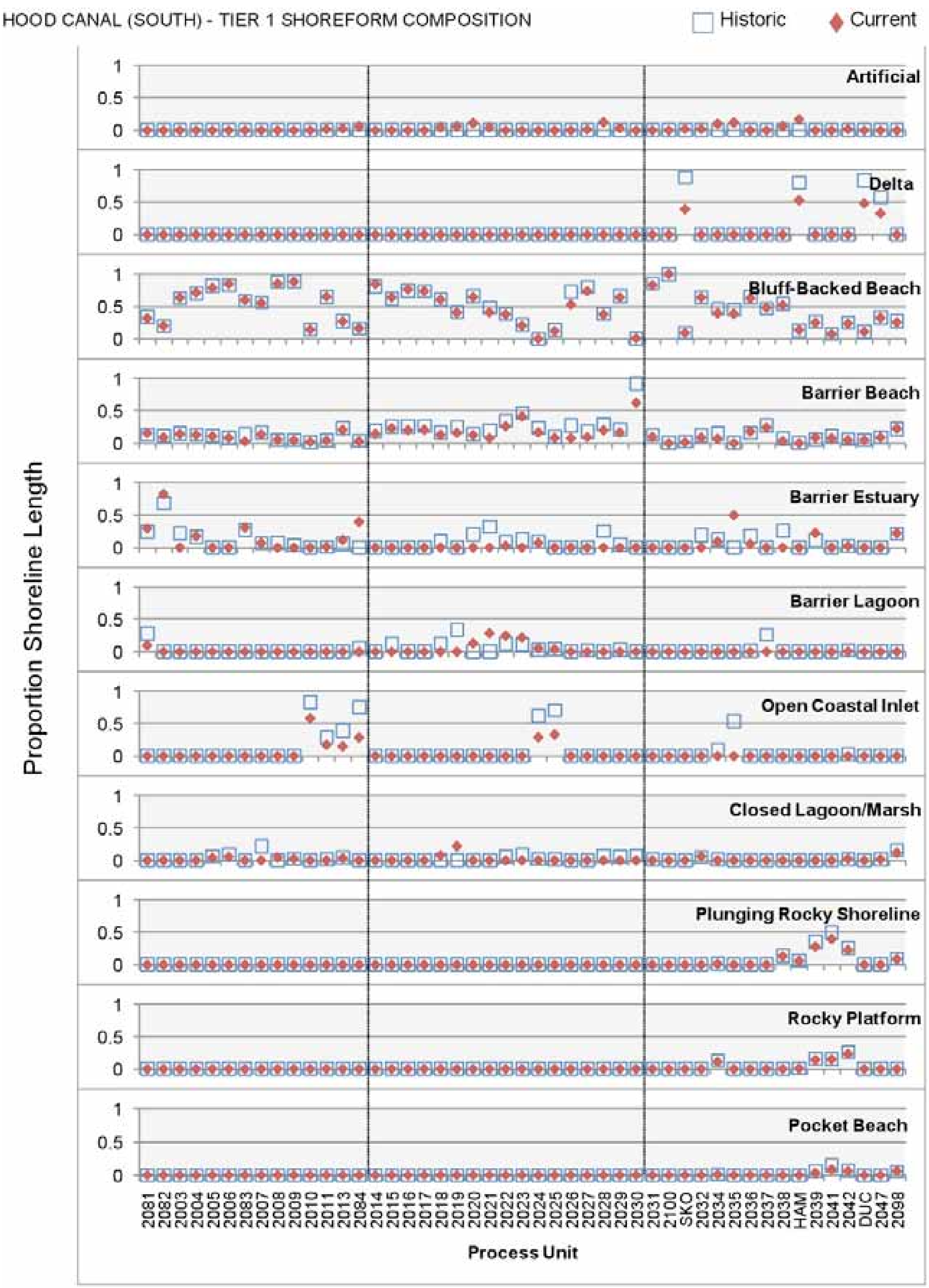


Figure 95. Historical Proportional lengths of historical and current shoreforms along sequential process units (PU) of the southern component of the Hood Canal Sub-Basin.

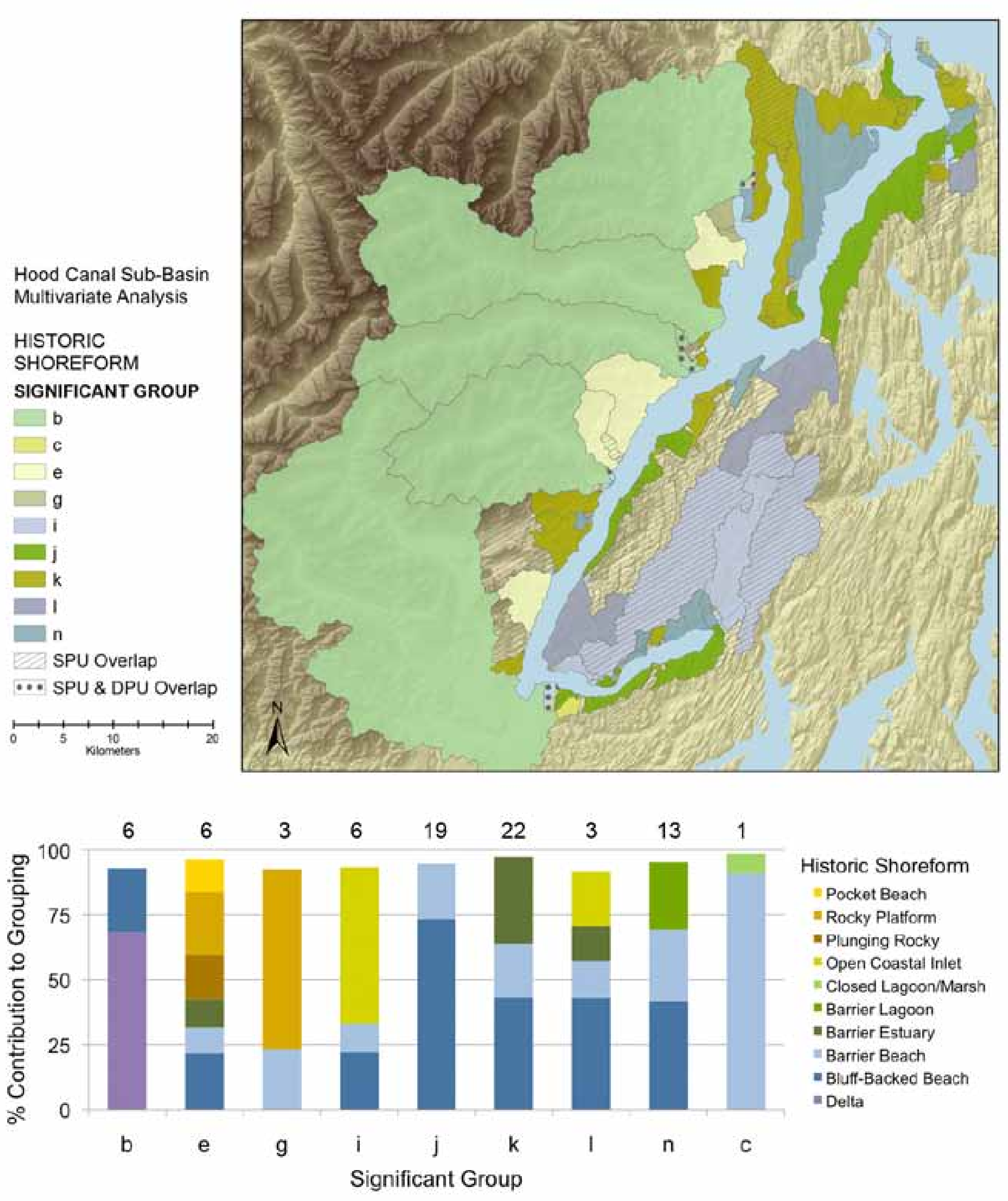
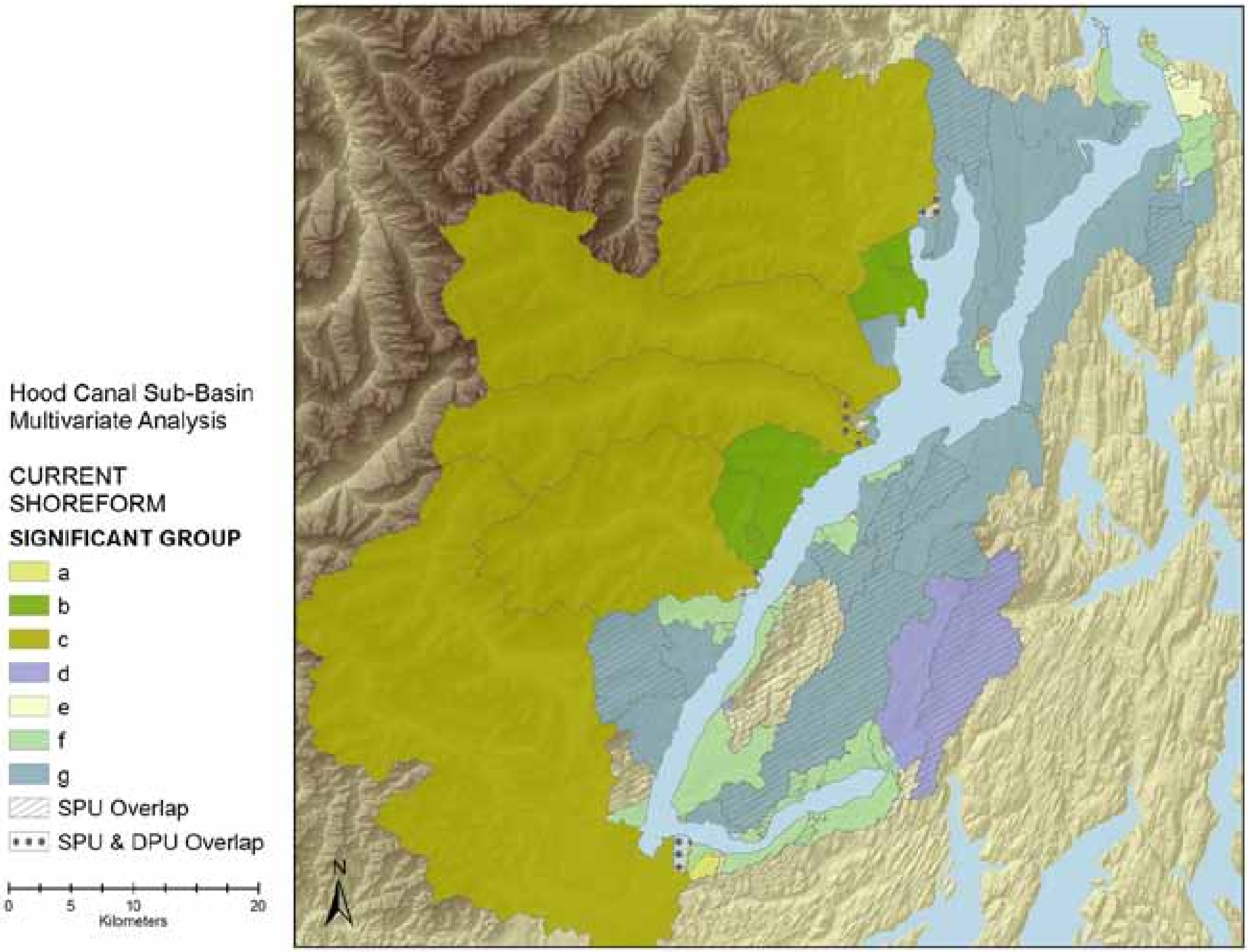


Figure 96. (Top) Distribution of process unit (PU) groups with significantly similar historical shoreform composition in Hood Canal Sub-Basin of Puget Sound based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for historical shoreform composition in the PU of the Hood Canal Sub-Basin. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group. Groups composed of one PU show the descriptive composition of the PU.



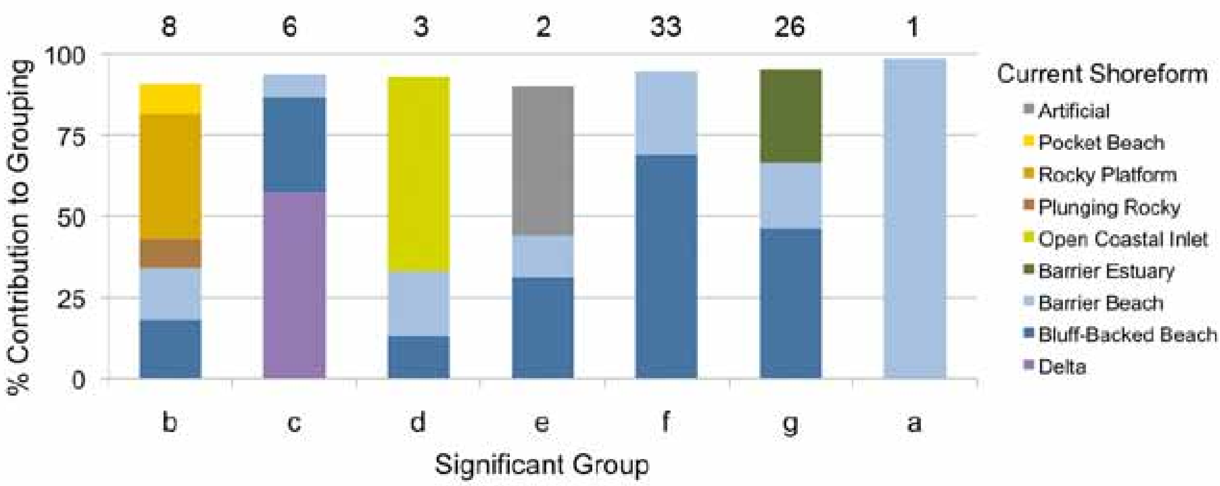


Figure 97. (Top) Distribution of process unit (PU) groups with significantly similar current shoreform composition in Hood Canal Sub-Basin of Puget Sound based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for current shoreform composition in the PU. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group. Groups composed of one PU show the descriptive composition of the PU.

Table 14. Shoreform transitions (Tier 1) of Hood Canal Sub-Basin. Highlighted numbers (diagonal line) represent the number that did not transition and are derived as the difference between the historical shoreform count and the total number of transitions.

Shoreform Transition	***Current*** ----------------------->												
Historic	Bluff-Backed Beach	Barrier Beach	Delta	Barrier Estuary	Barrier Lagoon	Closed Lagoon/ Marsh	Open Coastal Inlet	Plunging Rocky Shoreline	Rocky Platform	Pocket Beach	Artificial	Shoreform Absent	Total Transitions
Bluff-Backed Beach	137										9		9
Barrier Beach		135									12		12
Delta			4								1		1
Barrier Estuary				31	1	1					3	13	18
Barrier Lagoon					11	1					1	10	12
Closed Lagoon/Marsh						21						25	25
Open Coastal Inlet				3			4				4		7
Plunging Rocky Shoreline								22					0
Rocky Platform									37		1		1
Pocket Beach										24			0
Artificial											2		0
Shoreform Absent											1		1
Total Transitions	0	0	0	3	1	2	0	0	0	0	32	48	86

Shoreline Alterations

Descriptive

Shoreline armoring is common throughout the northern component of the Hood Canal Sub-Basin, and approaches 50 percent of the shoreline length in the western Foulweather Bluff region (Fig. 98). Nearshore roads tend to be concentrated around Dabob Bay and the eastern margin of the Toandos Peninsula. Tidal barriers are only prominent on the Quilcene and Dosewallips river deltas. However, overwater structures and marinas cover close to 50 percent of the aquatic area on the southern margin of the Dosewallips River delta (SPU 2048–2049). Extensive nearshore fill and some overwater structures and marina fill are also evident at two SPU (2099, 2076) on the western shore of Foulweather Bluff.

In contrast to the northern component, southern Hood Canal's shoreline is extensively and almost contiguously armored, particularly intensively (greater than 50 percent) inside the "Hook" along both shores around Lynch Cove (SPU 2014–2100) as well as on the southwest shore of the Canal (Fig. 99). Nearshore roads compound the armoring along much of the same shoreline, also approaching or exceeding 50 percent of the SPU length in many locations. Tidal barriers are most prominent in the Skokomish, Hamma Hamma, and Duckabush river deltas, but also within many SPU along the western shoreline.

Multivariate Analysis

The most common group of shoreline alterations (group i; 35 PU) involves a mixture of loss of estuarine mixing wetlands, armoring, and nearshore roads (Fig. 100); a group of 22 PU (group c) are characterized by the gain of estuarine mixing wetlands, armoring and nearshore roads. A group of PU (group h) that are distinguished predominantly by the loss of estuarine mixing wetlands are also distributed at several locations along the canal.

HOOD CANAL (NORTH) - TIER 2 SHORELINE ALTERATIONS

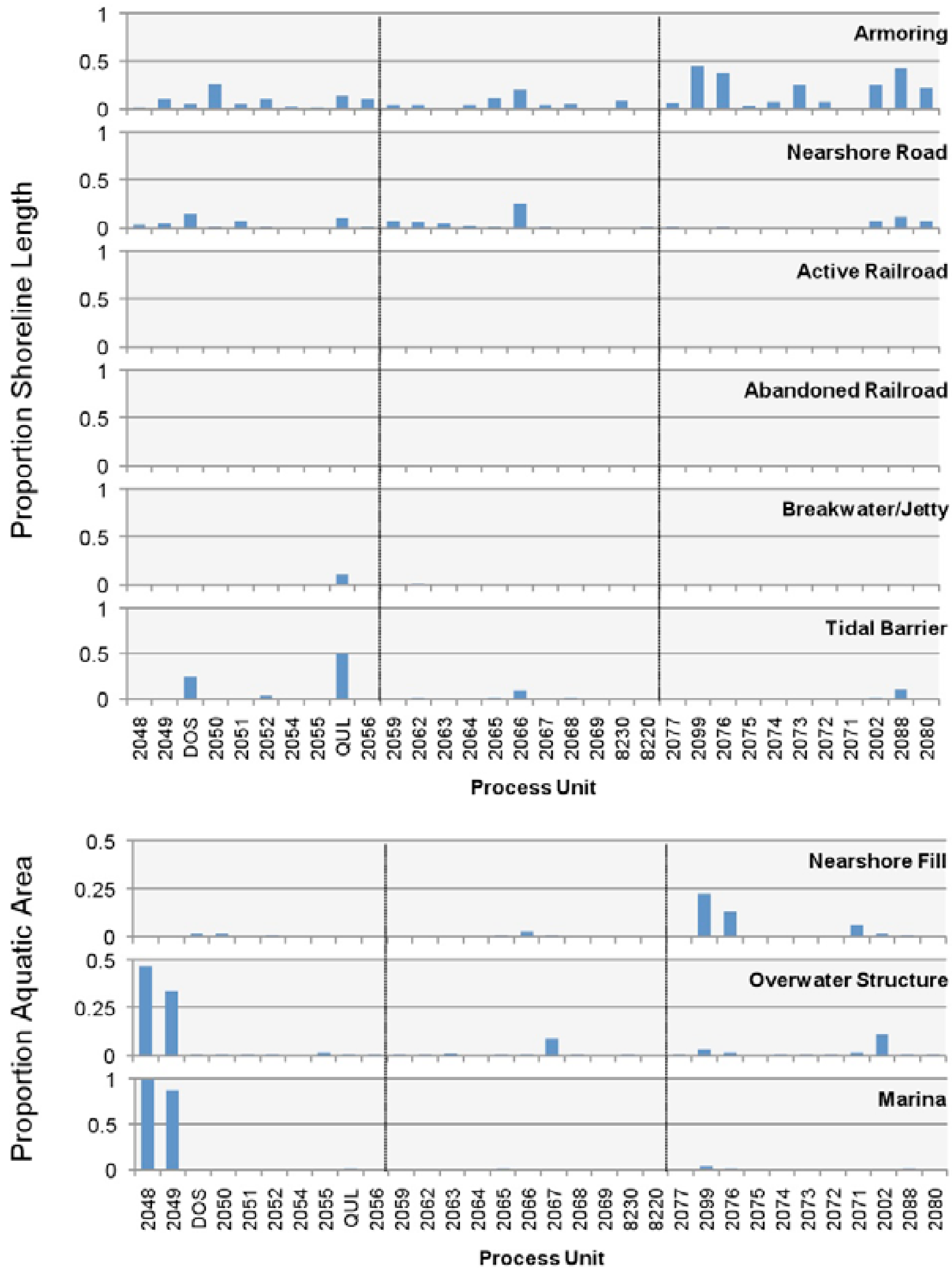
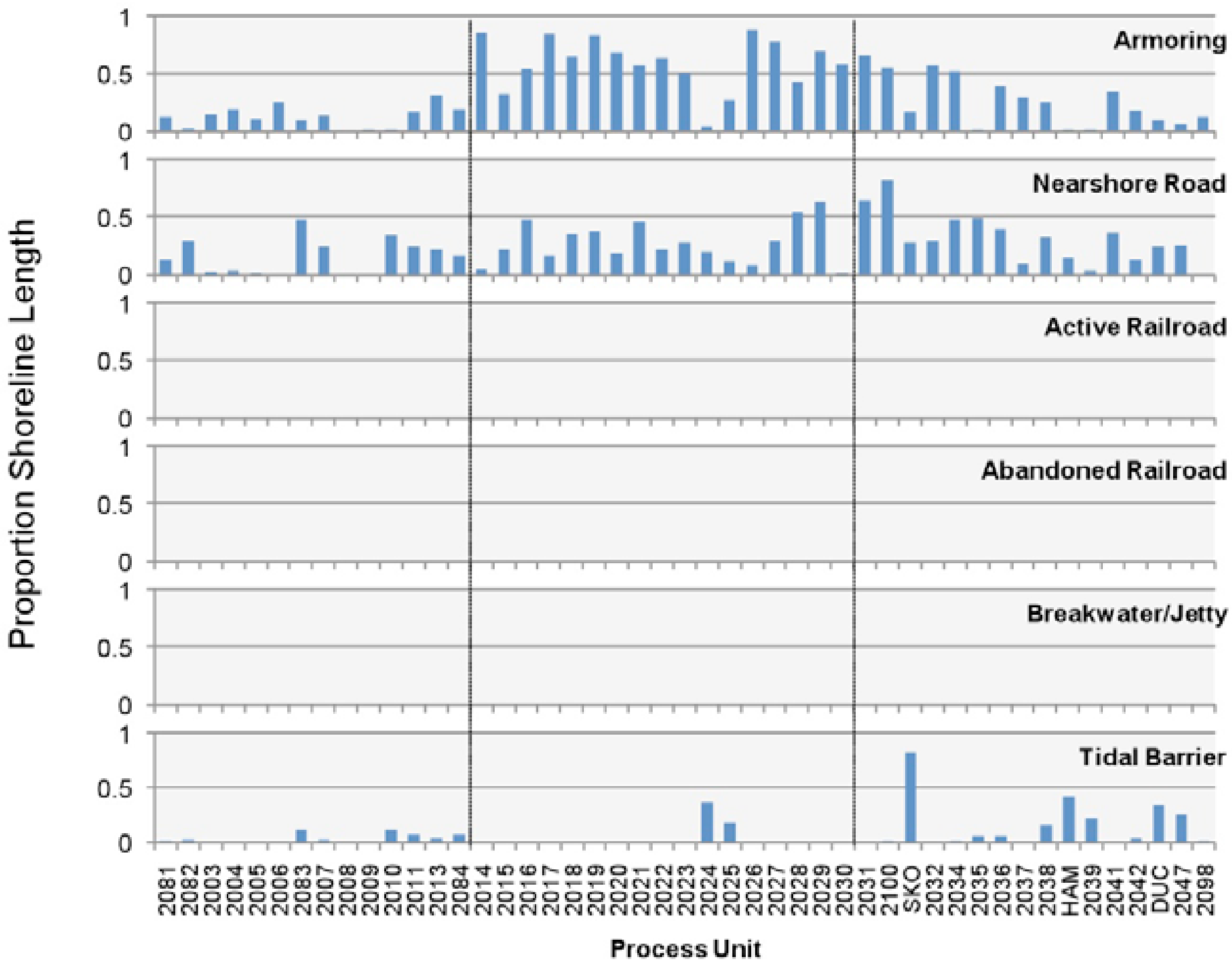


Figure 98. Shoreline alterations along sequential process units (PU) in the northern component of the Hood Canal Sub-Basin.

HOOD CANAL (SOUTH) - TIER 2 SHORELINE ALTERATIONS



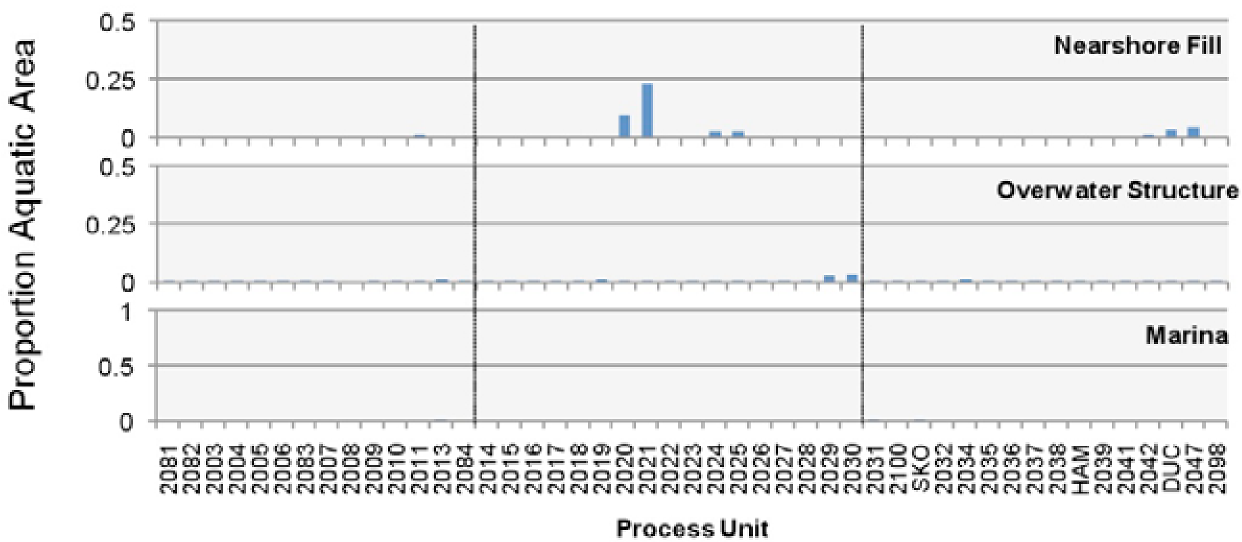


Figure 99. Shoreline alterations along sequential process units (PU) in the southern component of the Hood Canal Sub-Basin.

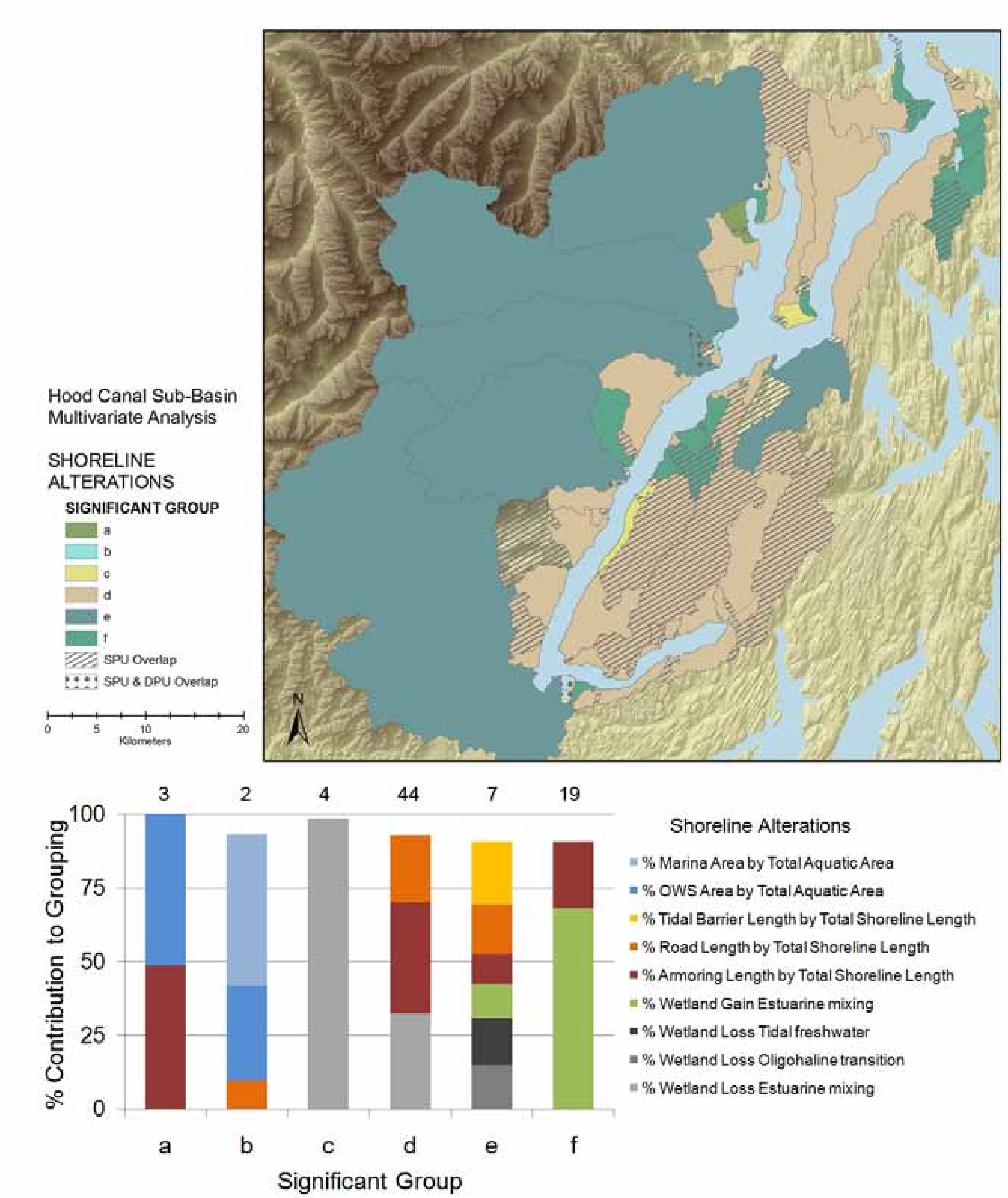


Figure 100. (Top) Process unit (PU) groups with significant similar shoreline alterations and stressors in Hood Canal Sub-Basin based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for shoreline alterations in the PU. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group. Groups composed of one PU show the descriptive composition of the PU.

Adjacent Upland and Watershed Change

Descriptive

Although the shoreline of the Hood Canal Sub-Basin was highly modified with armoring and roads, the uplands and watershed have a proportionally high natural land cover, approximately 90 percent in the adjacent upland and 95 percent in the watershed area (Table 11). This land cover is largely composed of evergreen forest, with a slightly higher proportion of mixed forest seen in the north component of the sub-basin (Fig. 101). Wetlands (categorized as both forested and emergent) are greatest in the Skokomish, Dosewallips, and Quilcene deltas, as well as in the SPU around Lynch Cove in the southern component (SPU 2024–2027) (Fig. 102). Development is minor in the watershed, with the exception of SPU 2099, a relatively small PU with about half moderately developed land cover. A contiguous stretch of SPU in the northeast section of the south component (SPU 2003–2017) remains particularly low in development impacts throughout both the adjacent upland as well as watershed area.

Multivariate Analysis

Groupings of upland change characteristics are fairly evenly distributed throughout the sub-basin, and share the dominant variable of less than 10 percent impervious surface. Varying degrees of roads, open space, and low-intensity development also distinguish the different groups (Fig. 103).

In terms of watershed change, groups g and i have the greatest numeric presence in the sub-basin with 20 and 37 PU, respectively (Fig. 104). Both are characterized as minimally developed, distinguished by the extent of low impervious surface, roads, and open space and low-intensity development. The level of impounded area distinguishes groups d and h, and PU within group j (including 4 of the 5 deltas) show very little development throughout the watershed area.

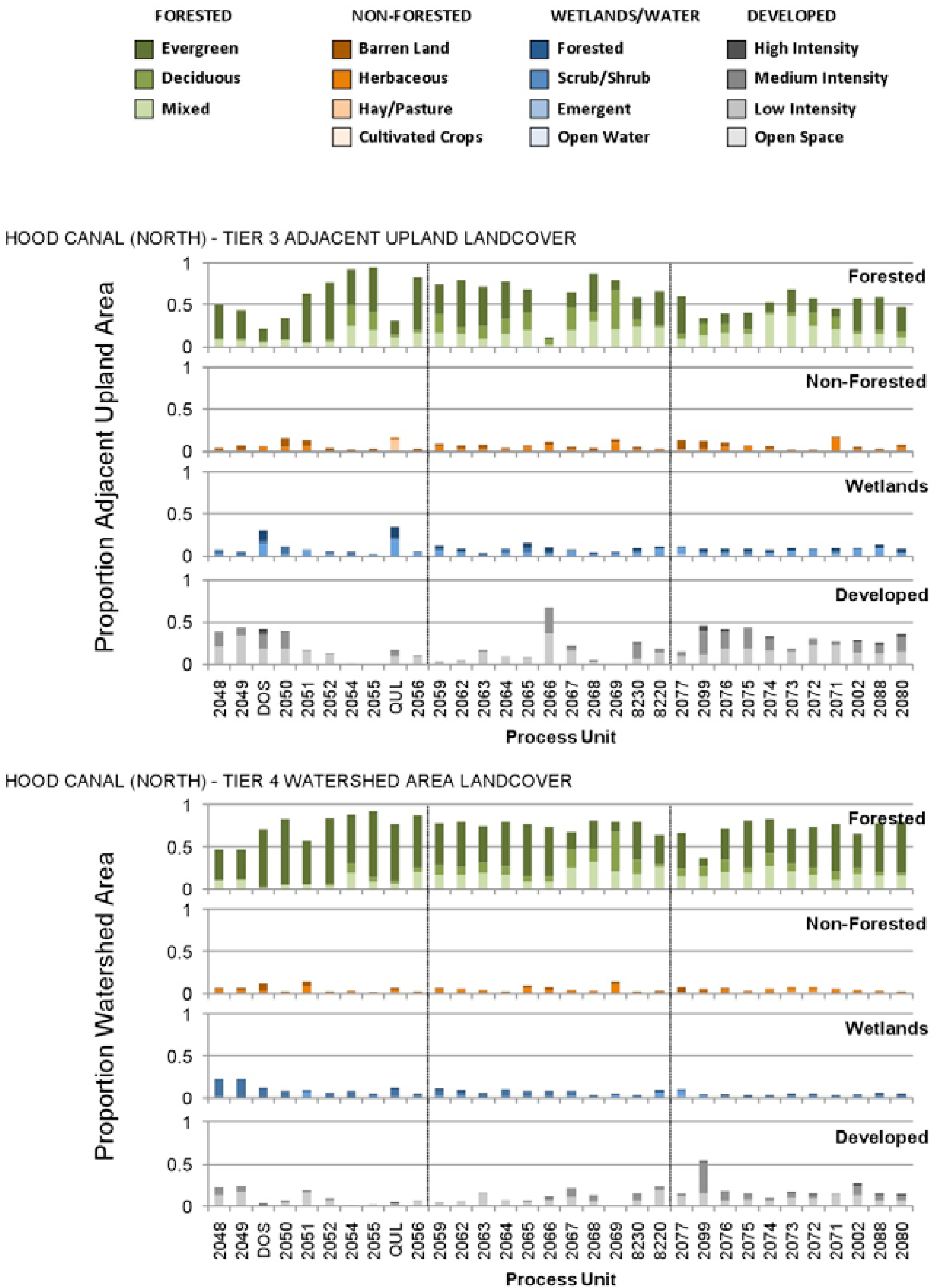


Figure 101. Land cover/land and stressors in adjacent upland (Tier 3, top) and watershed areas (Tier 4, bottom) in the northern component of the Hood Canal Sub-Basin.

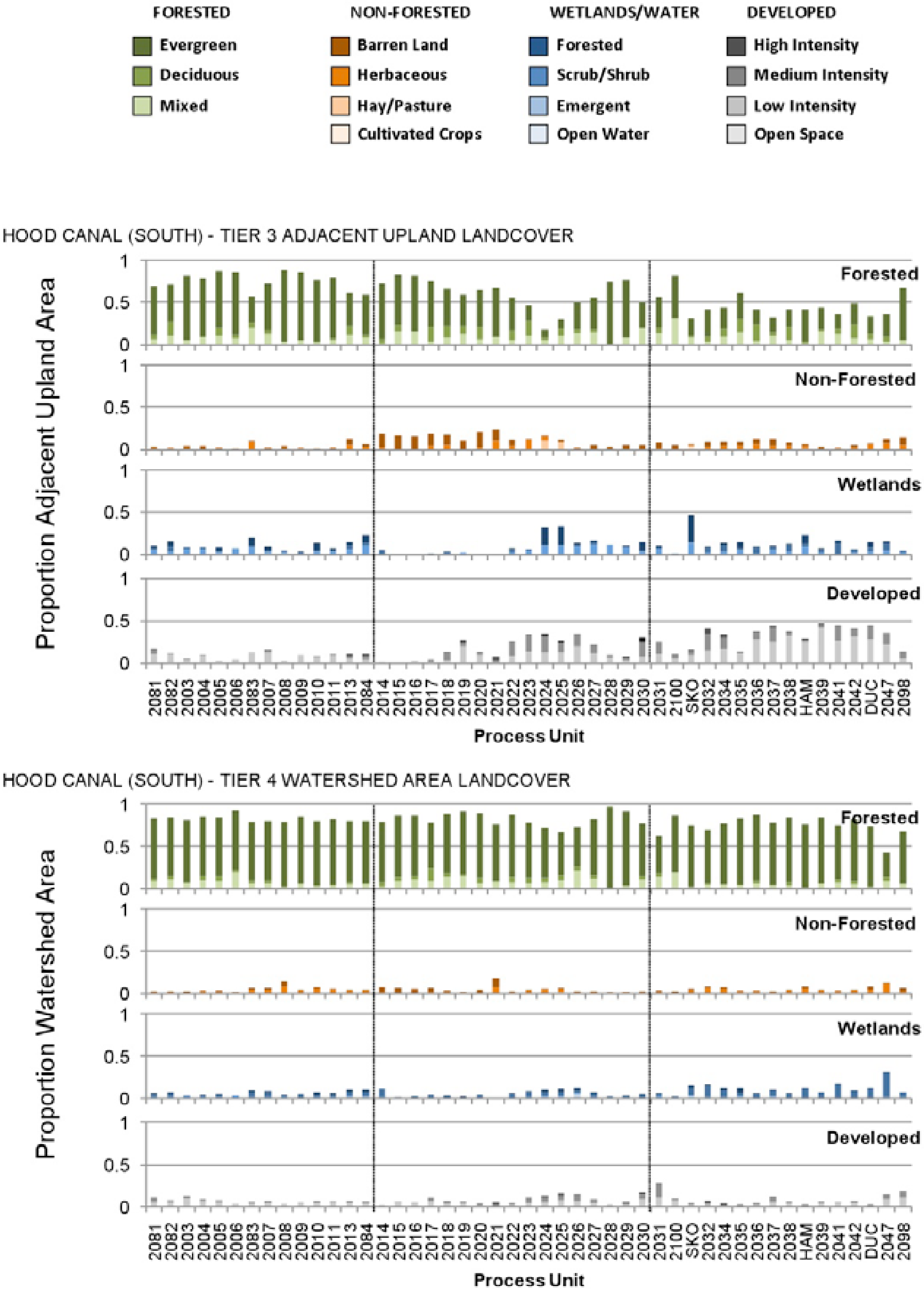


Figure 102. Land cover/land and stressors in adjacent upland (Tier 3, top) and watershed areas (Tier 4, bottom) in the southern component of the Hood Canal Sub-Basin.

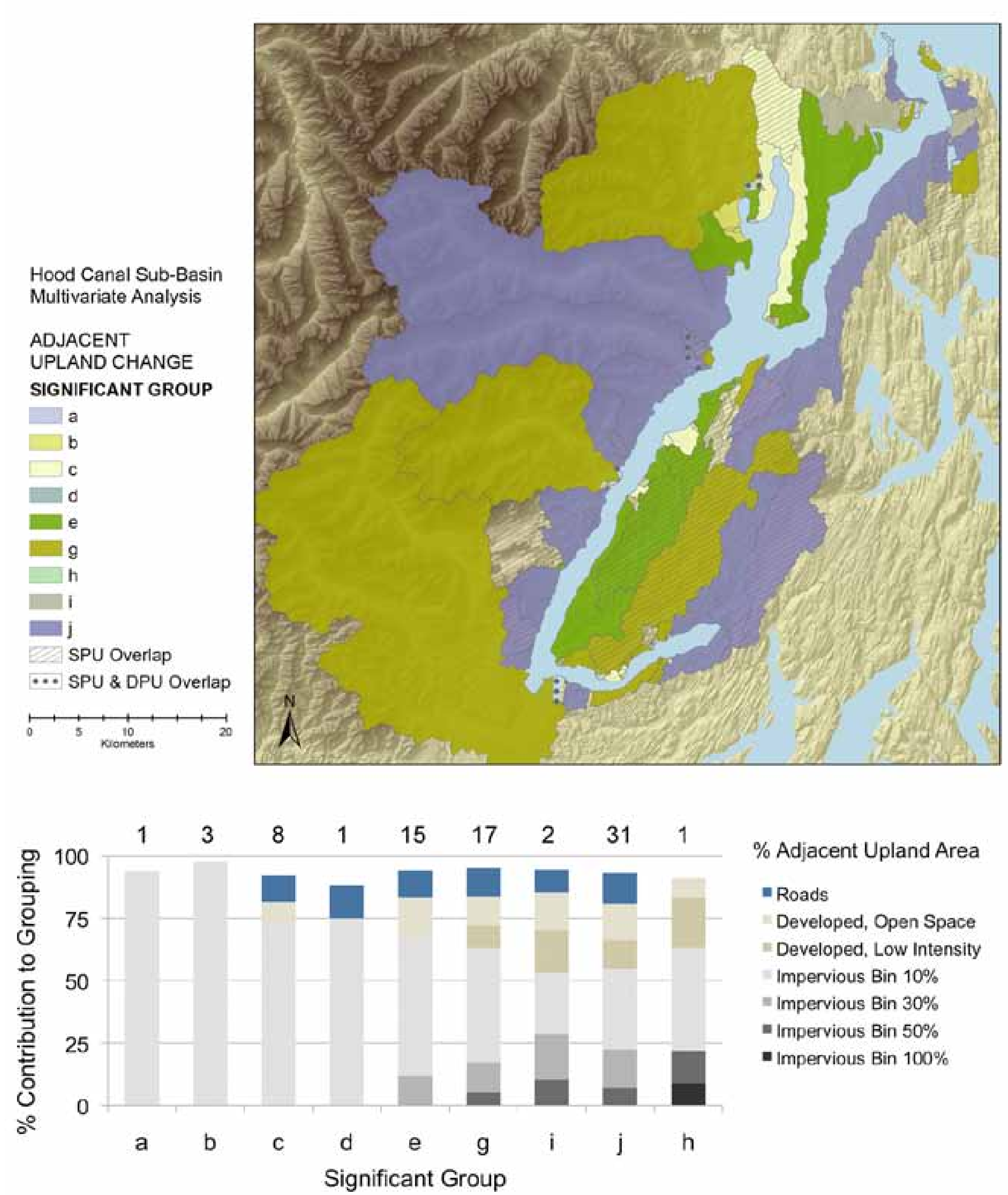


Figure 103. (Top) Process unit (PU) groups with significant similar adjacent upland change in Hood Canal Sub-Basin based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for adjacent upland change in the PU. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group. Groups composed of one PU show the descriptive composition of the PU.

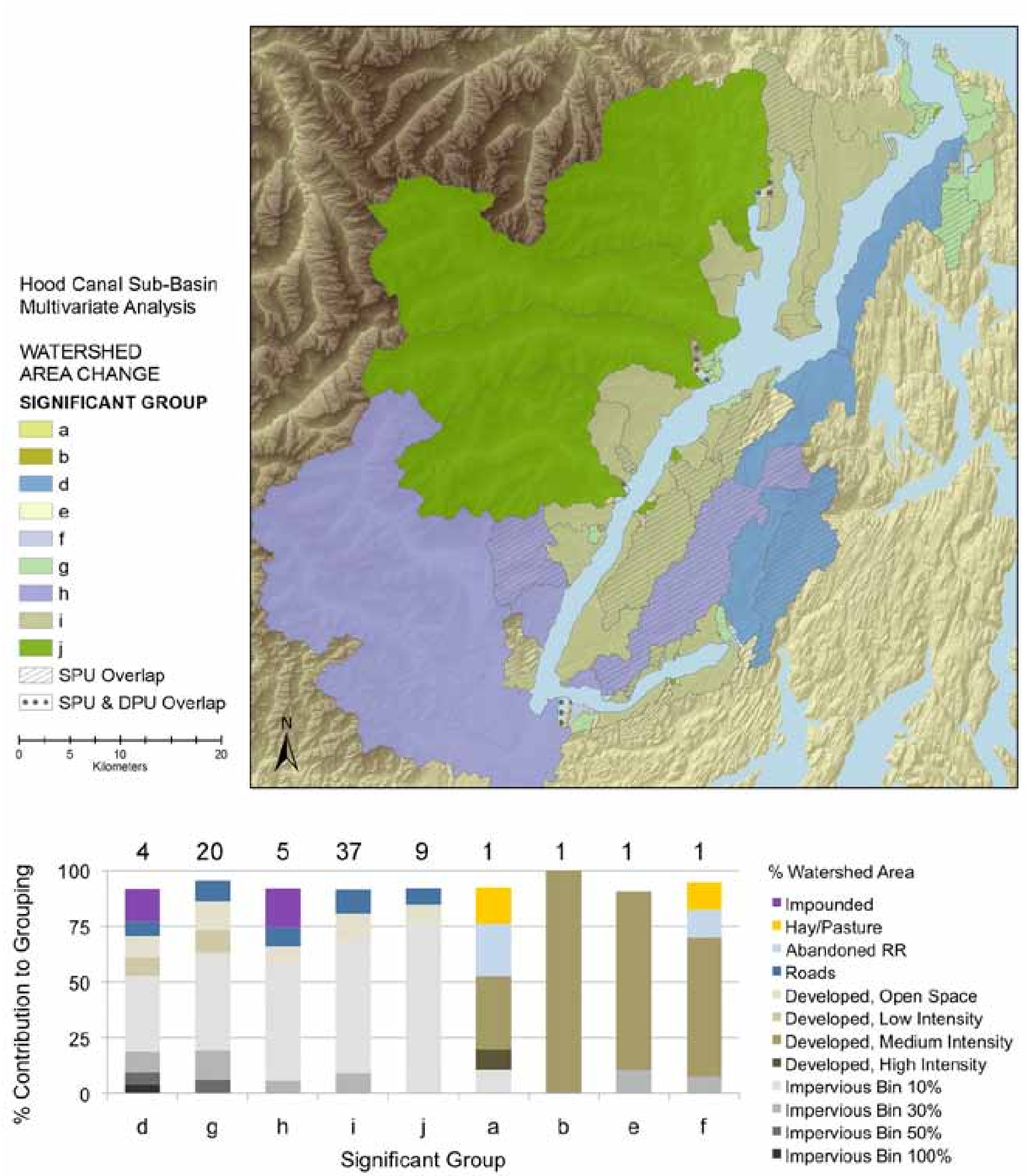


Figure 104. (Top) Process unit (PU) groups with significant similar watershed area change in Hood Canal Sub-Basin based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for watershed area change in the PU. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group. Groups composed of one PU show the descriptive composition of the PU.

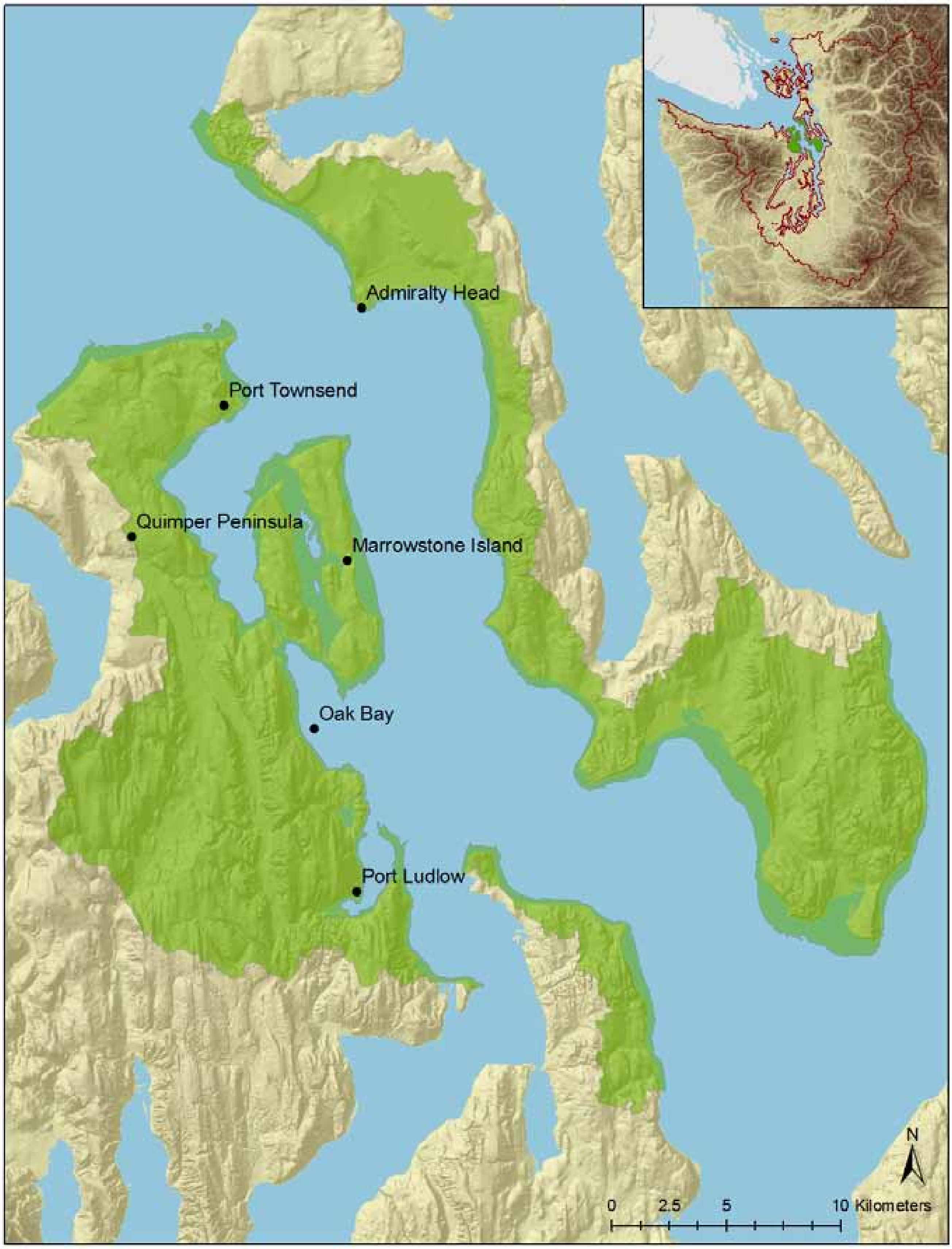


Figure 105. North Central Puget Sound Sub-Basin.

North Central Puget Sound Sub-Basin

Shoreform Change and Transition

Descriptive

Nearshore change in the North Central Puget Sound Sub-Basin (Fig. 105) is concentrated primarily on barrier estuary and barrier lagoon shoreforms (88 and 53 percent shoreline length reduction, respectively), with modest reductions in closed lagoon/marsh and open coastal inlet shorelines (22 and 27 percent, respectively) (Table 4; Fig. 106). The number of shoreform segments decreased the most for barrier estuaries (10; –3.5 percent), barrier lagoons (9; –3.1 percent), and closed lagoons/marshes (12; –4 percent) (Table 5).

Ninety-two percent of the shoreform transitions were to artificial shoreforms and shoreform absent, with only two shoreforms between bluff-backed beach and barrier beach, and two barrier lagoons transitioning to closed lagoon/marshes (Table 15). One closed lagoon/marsh appeared in the current dataset from historically absent, while 14 closed lagoon/marsh shoreforms completely disappeared from the sub-basin.

Refer to Appendix D (Fig. E.9) for PU distributions in North Central Puget Sound Sub-Basin. Barrier estuaries exhibited extensive reduction in shoreline length in various locations along the sub-basin shoreline, particularly along southwestern Whidbey Island (SPU 5030–5035, 8001) and north of Admiralty Head (8058) (Fig. 107). Barrier estuaries were also reduced at the southern end of Port Townsend Bay (SPU 5021–5022). Barrier lagoons were also reduced, most prominently along southwestern Whidbey and the northwestern end of Marrowstone Island (SPU 5010, 5016). Pocket beaches were reduced in south Port Townsend Bay and around Port Ludlow (SPU 5002–5004). Closed lagoon/marsh was measurably reduced in Port Townsend.

Multivariate Analysis

Shoreform composition of SPU was historically represented by three groups of bluff-backed and barrier beaches combined with barrier lagoons (group f), barrier estuaries (group c), or both (group e) (Fig. 108). One or more of the three rocky shoreforms distinguish other groups. The complexity of shoreform composition is reduced by half under current conditions, with the disappearance of barrier lagoons and barrier estuaries, and the addition of artificial shoreforms (Fig. 109). A vast majority of the sub-basin's shoreline has been reduced to comparatively simple bluff-backed and barrier beach PU. This is illustrated in the predominant transition group (group c), which involves a mixture of lost shoreforms that now characterize most of the sub-basin's shorelines, except for the region south of Oak Bay (Fig. 110).

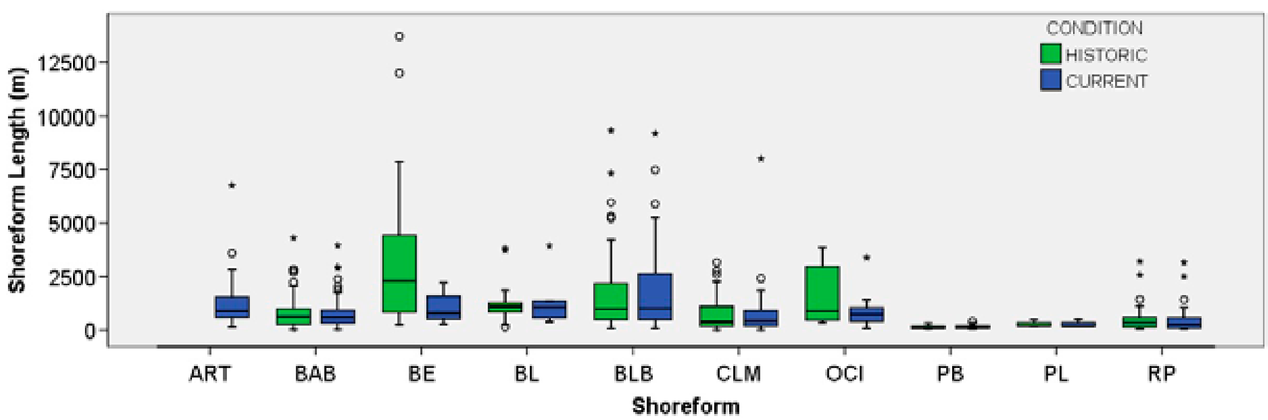


Figure 106. Historical and current contiguous shoreline length of North Central Puget Sound shoreforms in PU (excludes delta shoreform); see Fig. 20 for shoreform codes. Each box represents the median and upper and lower quartile of the shoreform length data. The 'whiskers' (lines that extend out of the top and bottom of box) represent the highest and lowest values that are not outliers or extreme values. Outliers (values between 1.5 and 3 times the interquartile range) are marked with a circle and extreme cases (values more than 3 times the interquartile range) with an asterisk.

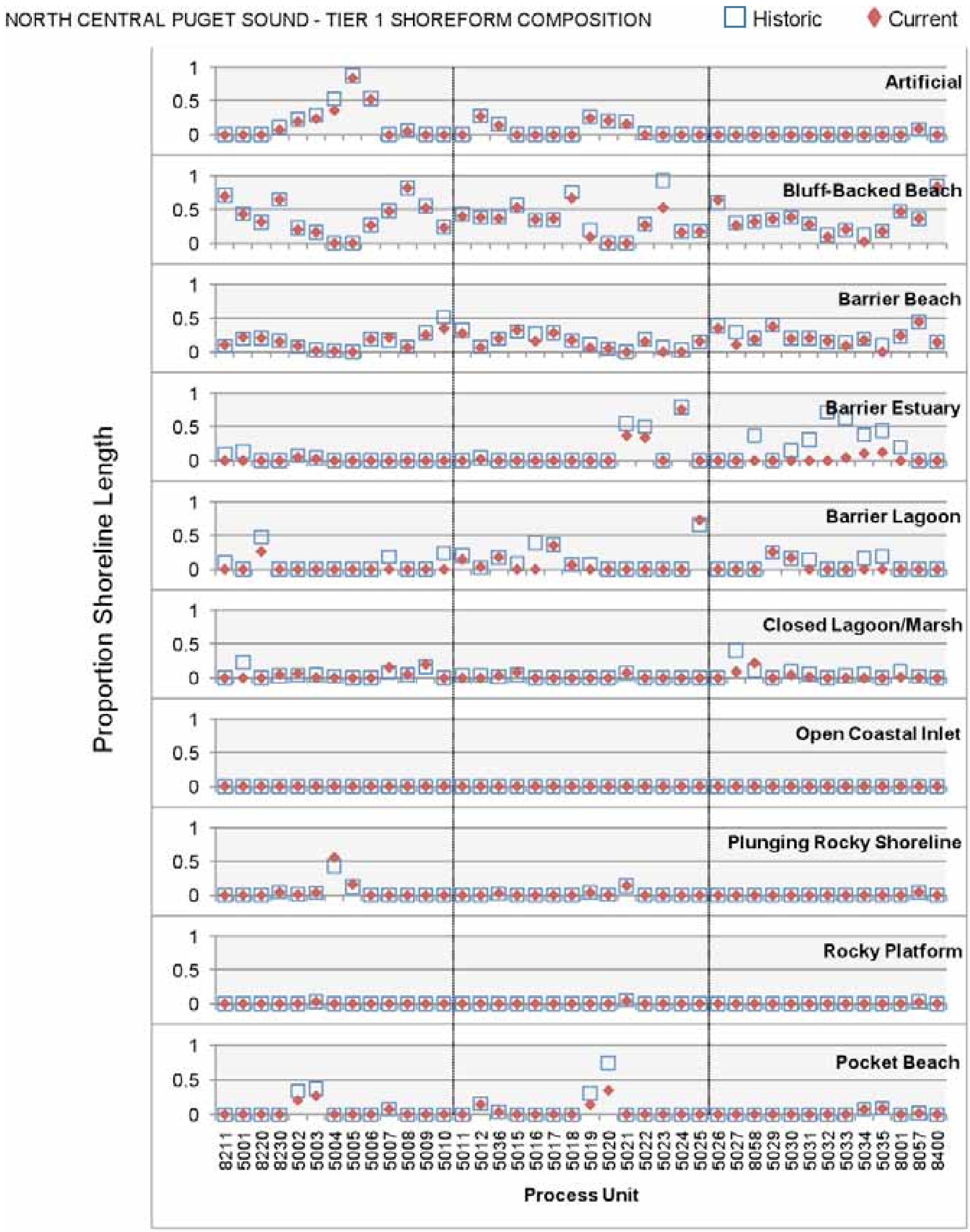


Figure 107. Proportional lengths of historical and current shoreforms along sequential process units (PU) of the North Central Puget Sound Sub-Basin.

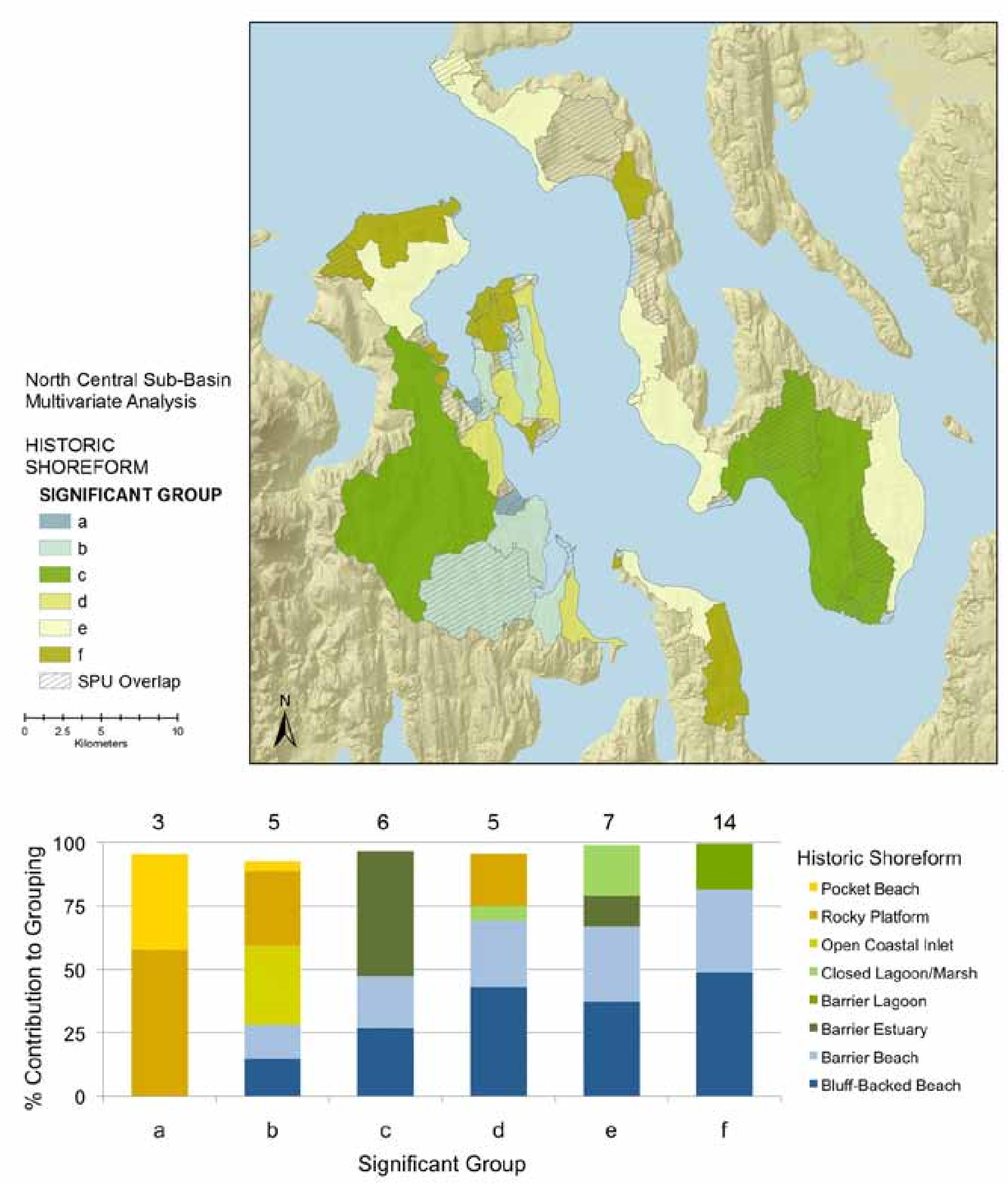


Figure 108. (Top) Distribution of process unit (PU) groups with significantly similar historical shoreform composition in North Central Sub-Basin of Puget Sound based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for historical shoreform composition in the PU. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group.

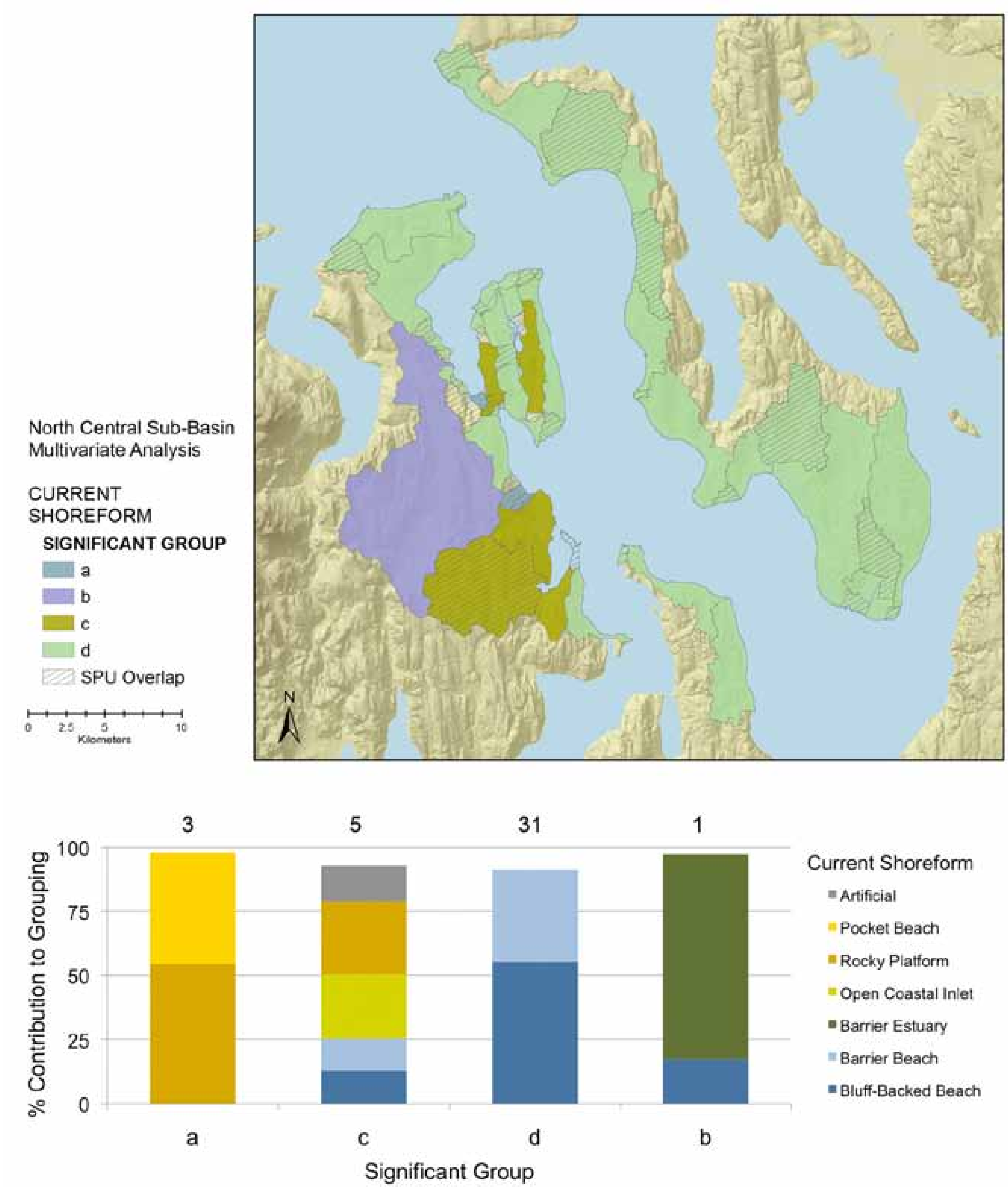


Figure 109. (Top) Distribution of process unit (PU) groups with significantly similar current shoreform composition in North Central Sub-Basin of Puget Sound based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for current shoreform composition in the PU. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group. Groups composed of one PU show the descriptive composition of the PU.

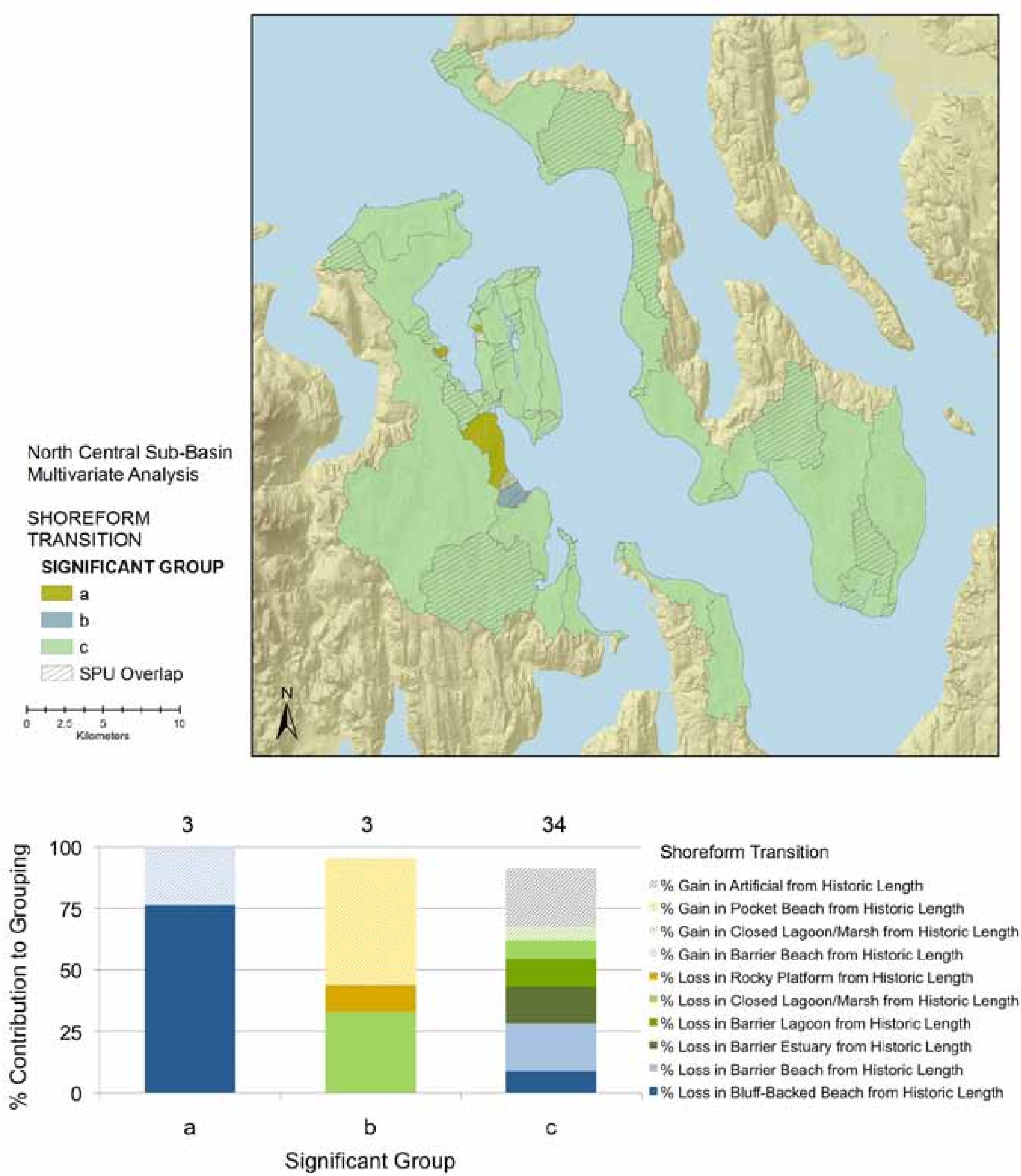


Figure 110. (Top) Distribution of process unit (PU) groups with significantly similar shoreform transitions in North Central Sub-Basin of Puget Sound based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for shoreform transitions in the PU. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group.

Table 15. Shoreform transitions (Tier 1) of North Central Puget Sound Sub-Basin. Highlighted numbers (diagonal line) represent the number that did not transition and are derived as the difference between the historical shoreform count and the total number of transitions.

Shoreform Transition	*Current* ------------------------>											
Historic	Bluff-Backed Beach	Barrier Beach	Barrier Estuary	Barrier Lagoon	Closed Lagoon/ Marsh	Open Coastal Inlet	Plunging Rocky Shoreline	Rocky Platform	Pocket Beach	Artificial	Shoreform Absent	Total Transitions
Bluff-Backed Beach	57	1								5		6
Barrier Beach	1	57								12		13
Barrier Estuary			5							3	9	12
Barrier Lagoon				9	2					1	5	8
Closed Lagoon/Marsh					15					1	14	15
Open Coastal Inlet						5				4		4
Plunging Rocky Shoreline							3					0
Rocky Platform								39		1		1
Pocket Beach									19			0
Artificial										0		0
Shoreform Absent					1					1		2
Total Transitions	1	1	0	0	3	0	0	0	0	28	28	61

Shoreline Alterations

Descriptive

The North Central Puget Sound Sub-Basin shoreline is not extensively armored, but armoring does occur to some extent in 75 percent of the PU (Fig. 111); roads are coincident in about half of the PU. While not associated with large river deltas, tidal barriers are persistent along the shoreline, approaching or exceeding 25 percent of the shoreline length, especially around the southern end of Port Townsend Bay (SPU 5016–5020) and southern Whidbey Island (SPU 5032-8001).

Multivariate Analysis

The dominant groupings of PU alterations are loss of estuarine mixing wetlands, armoring. and nearshore roads and/or tidal barrier (groups c [20 PU] and d [14 PU]), with the latter group of PU concentrated on the western margin of the sub-basin, around the Quimper Peninsula (Fig. 112).

NORTH CENTRAL PUGET SOUND - TIER 2 SHORELINE ALTERATIONS

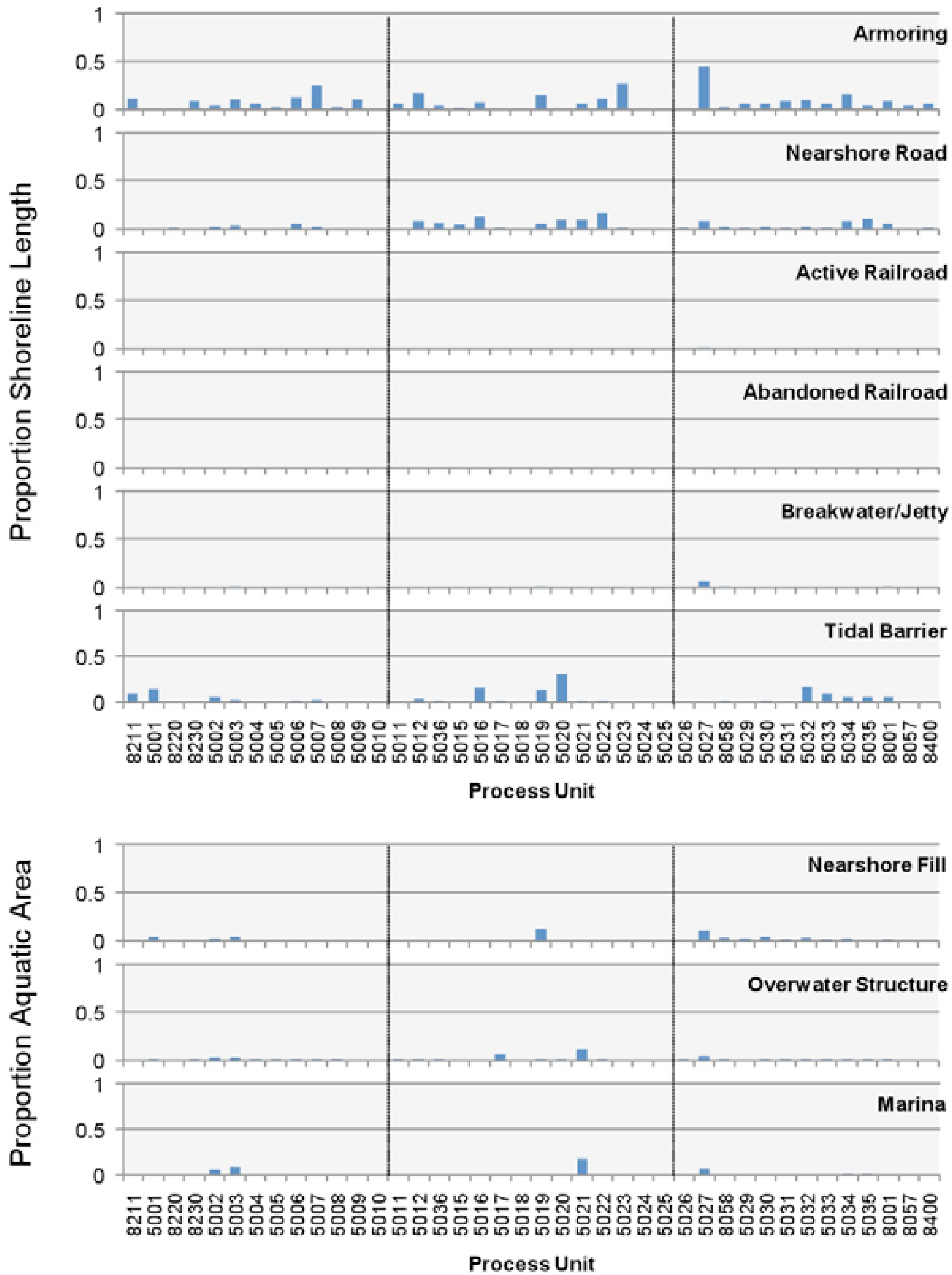


Figure 111. Shoreline alterations along sequential process units (PU) of the North Central Sub-Basin.

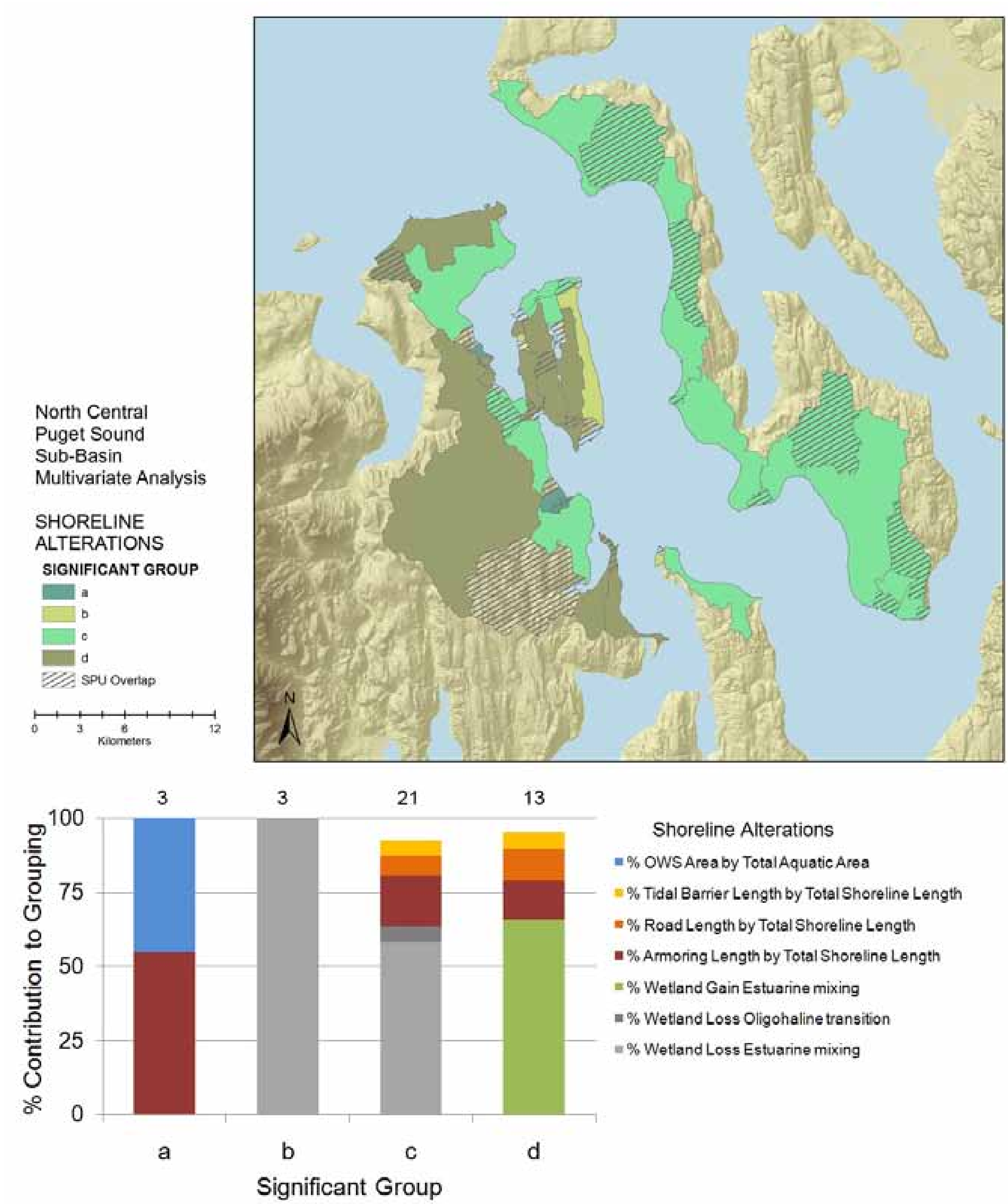


Figure 112. (Top) Process unit (PU) groups with significant similar shoreline alterations and stressors in North Central Sub-Basin based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for shoreline alterations in the PU. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group.

Adjacent Upland and Watershed Change

Descriptive

The landscape of the North Central Puget Sound Sub-Basin is largely forested with some herbaceous land cover in the adjacent upland area. Development is focused around the east side of Port Townsend Bay (Fig. 113).

Multivariate Analysis

Analysis of the adjacent upland area change shows low-intensity development and minimal impervious surface common to all groups in the North Central Puget Sound Sub-Basin, which are fairly evenly distributed numerically (Fig. 114).

Process unit groups of watershed area change in this sub-basin are generally focused over distinct regions, with the exception of group e, which is distributed throughout the sub-basin (Fig. 115). Low intensity development and low impervious surface are the dominant variables across all groups, with varying levels of higher intensity development distinguishing one from another. Group h, in the northern section of the sub-basin, includes two PU of moderate development with the additional presence of hay/pasture land and cultivated crops.

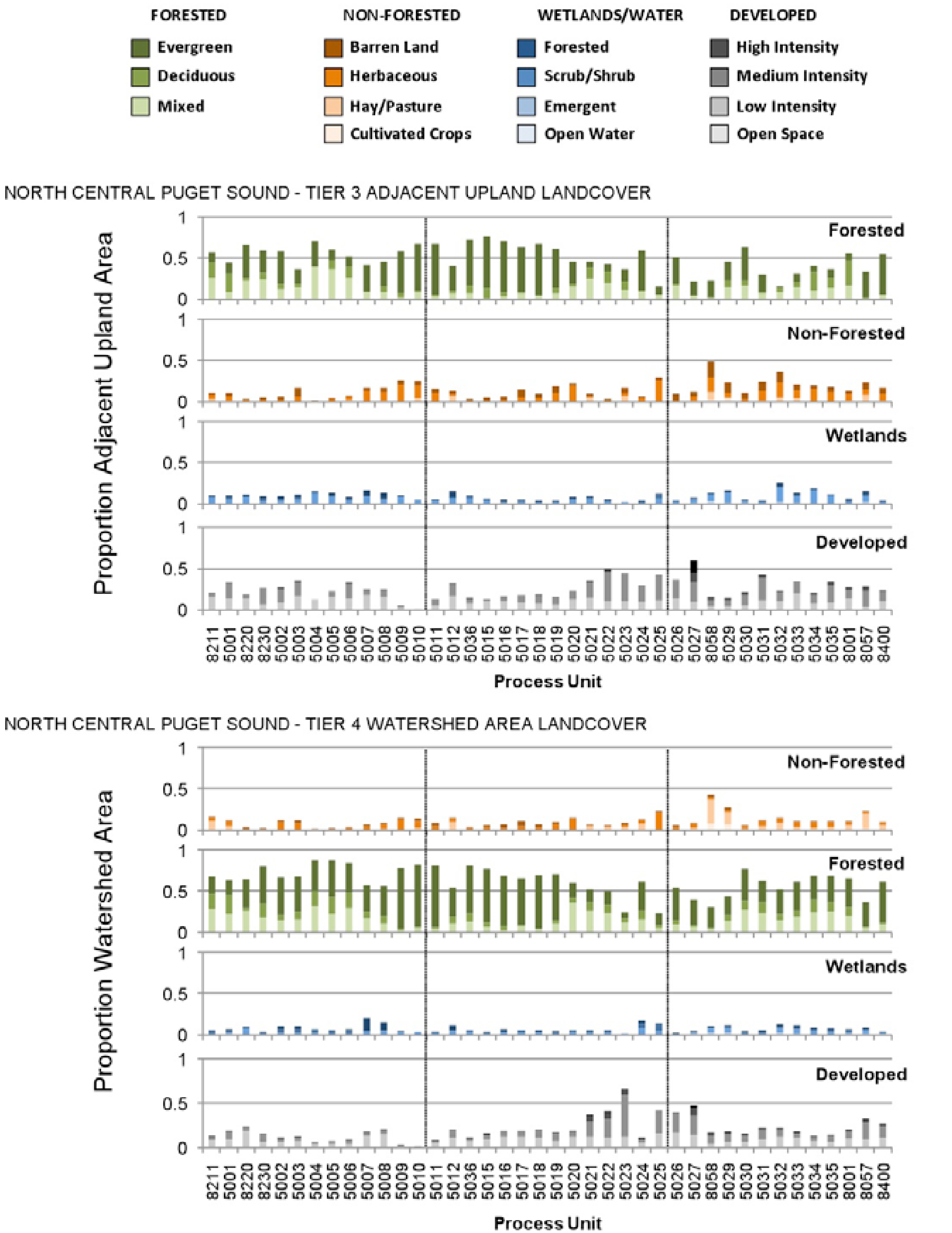
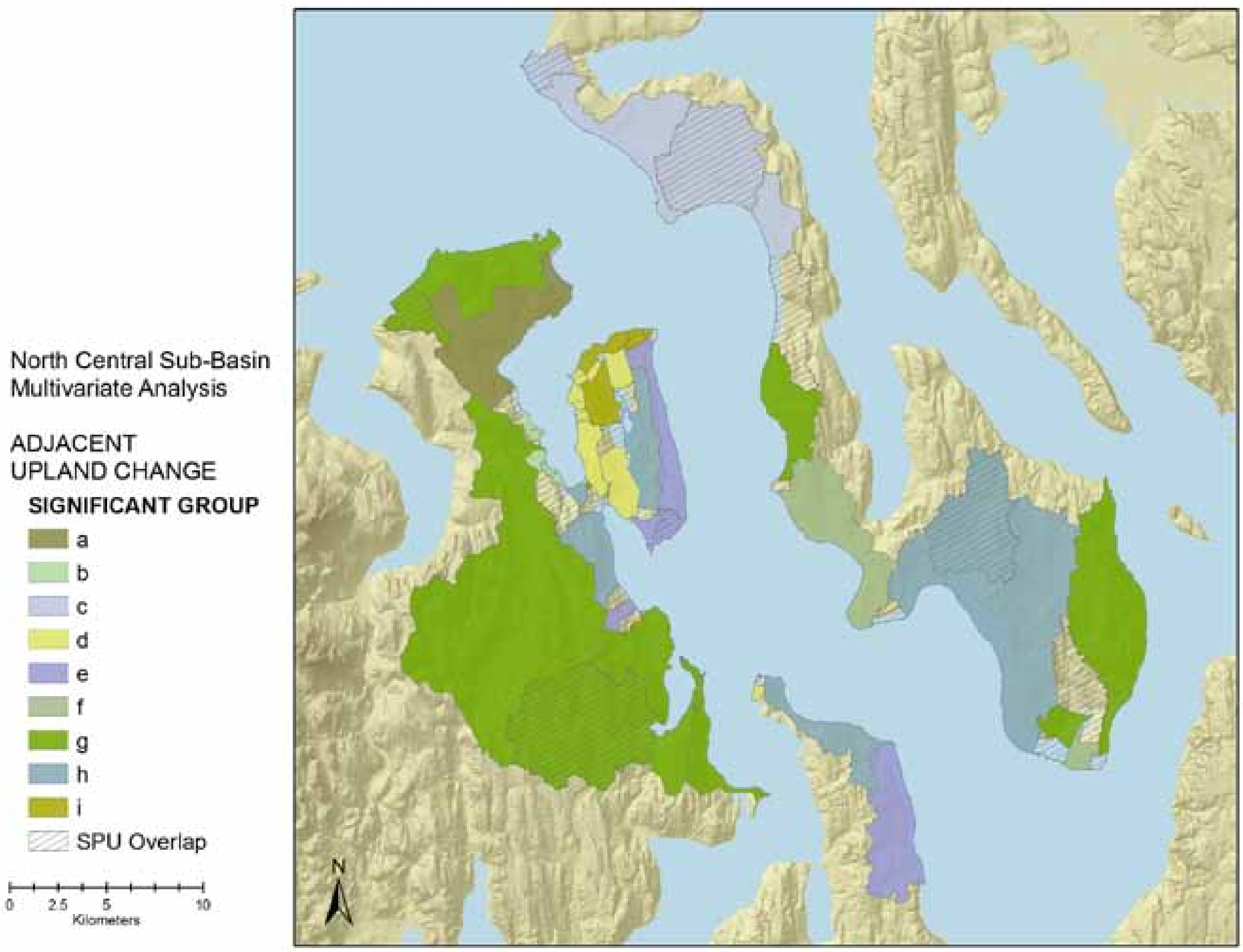


Figure 113. Land cover/land and stressors in adjacent upland (Tier 3, top) and watershed areas (Tier 4, bottom) of the North Central Puget Sound Sub-Basin.



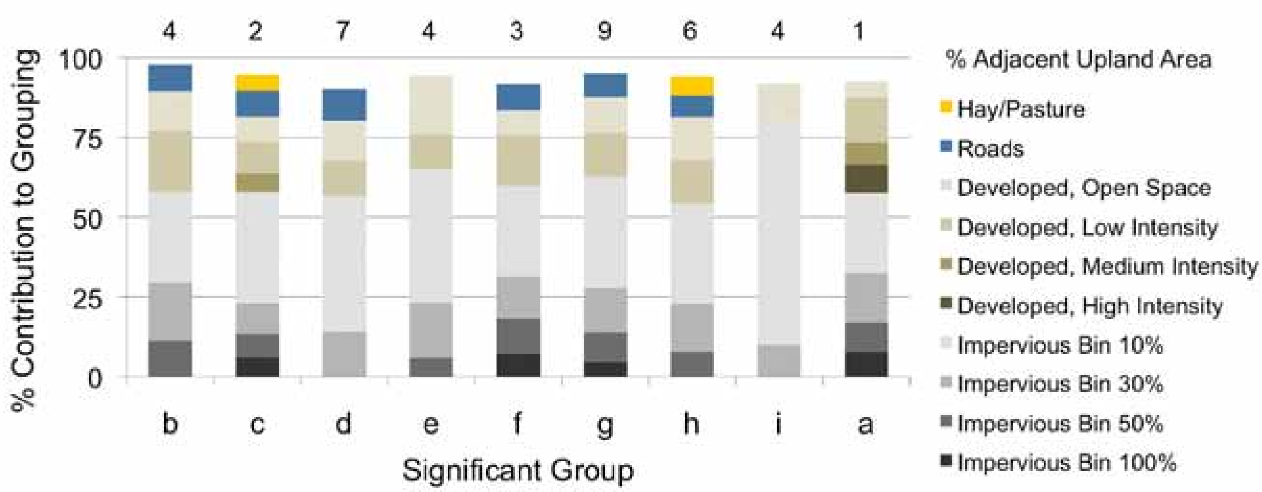


Figure 114. (Top) Distribution of process unit (PU) groups with significantly similar adjacent upland changes in North Central Sub-Basin of Puget Sound based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for adjacent upland change in the PU. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group. Groups composed on one PU show the descriptive composition of the PU.

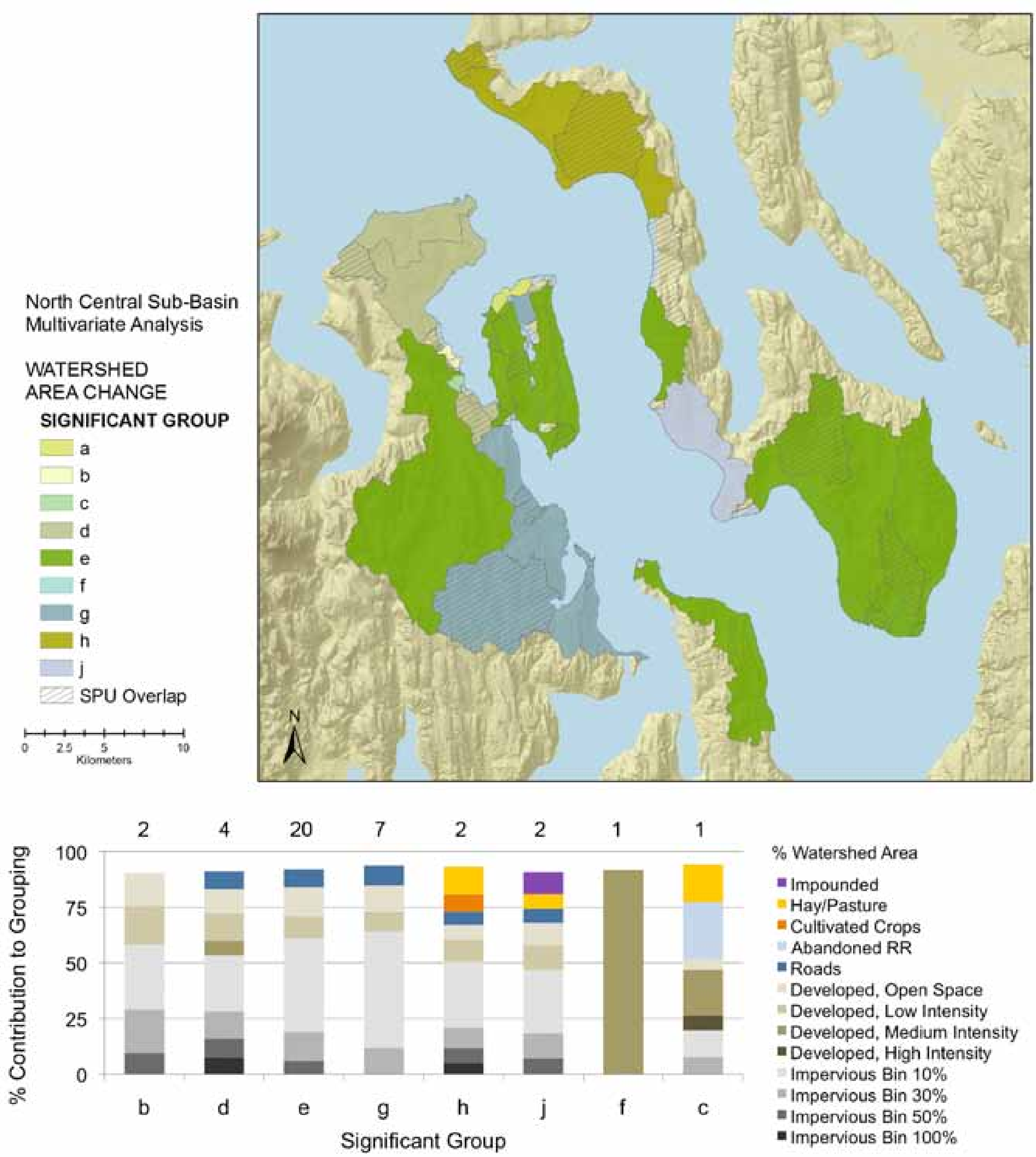


Figure 115. (Top) Distribution of process unit (PU) groups with significantly similar total watershed area changes in North Central Sub-Basin of Puget Sound based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for watershed area change in the PU. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group. Groups composed of one PU show the descriptive composition of the PU.

Whidbey Sub-Basin

Shoreform Change and Transition

Descriptive

Much of the Whidbey Sub-Basin (Fig. 116) nearshore change is due to simplification of barrier estuary, barrier lagoon, and closed lagoon/marsh shoreline lengths (reductions of 50–64 percent) and modest reductions in delta shoreline length (–37 percent) (Table 4; Fig. 117). Other shoreform changes involved less than 15 percent reduction in shoreline length. Relative changes in the number of different shoreforms were similarly manifested in barrier estuary (–7), barrier lagoon (–9), and closed lagoon/marsh (–19) (Table 5).

Shoreform transitions are dominated by changes to artificial and shoreform absent (79 percent) except for eight transitions of bluff-backed beach to barrier beach and barrier beach to bluff-backed beach (Table 16). Two barrier lagoons and four closed lagoon/marsh shoreforms that were in the current data apparently had not been detected during the historical survey, or they were formed in the interim.

We have partitioned the sub-basin into two components (see Appendix D, Figs. E.10–E.11 for PU distributions) in order to examine the contiguous shoreline for concentrations of shoreline length change (Figs. 118–119). In addition to the 20 to 50 percent reductions in delta shoreline lengths, the most notable concentrations of reduced shoreform length in the eastern portion of the Whidbey Sub-Basin are reduced barrier estuary complexity around Similk Bay (SPU 6033–6034), barrier estuary and coastal lagoon/marsh reductions between the Skagit and Stillaquamish river deltas (SPU 6048–6050), barrier estuary reductions around Tulalip Bay (SPU 6053–6054) and closed lagoon/marsh reductions around Gedney Island (SPU 6057–6059) (Fig. 118). The western component of the Whidbey Sub-Basin illustrates one of the few significant reductions in the length of bluff-backed beach shoreform in the region, in the Rocky Point (SPU 6005–6006) and Crescent Harbor (SPU 6025) areas of Whidbey Island (Fig. 119). Barrier lagoon and closed lagoon/marsh shoreforms were reduced to some degree in the shoreline surrounding Penn Cove (SPU 6013–6019), the southern end of Holmes Harbor (SPU 6007–6008), and western Similk Bay (SPU 6031–6032).

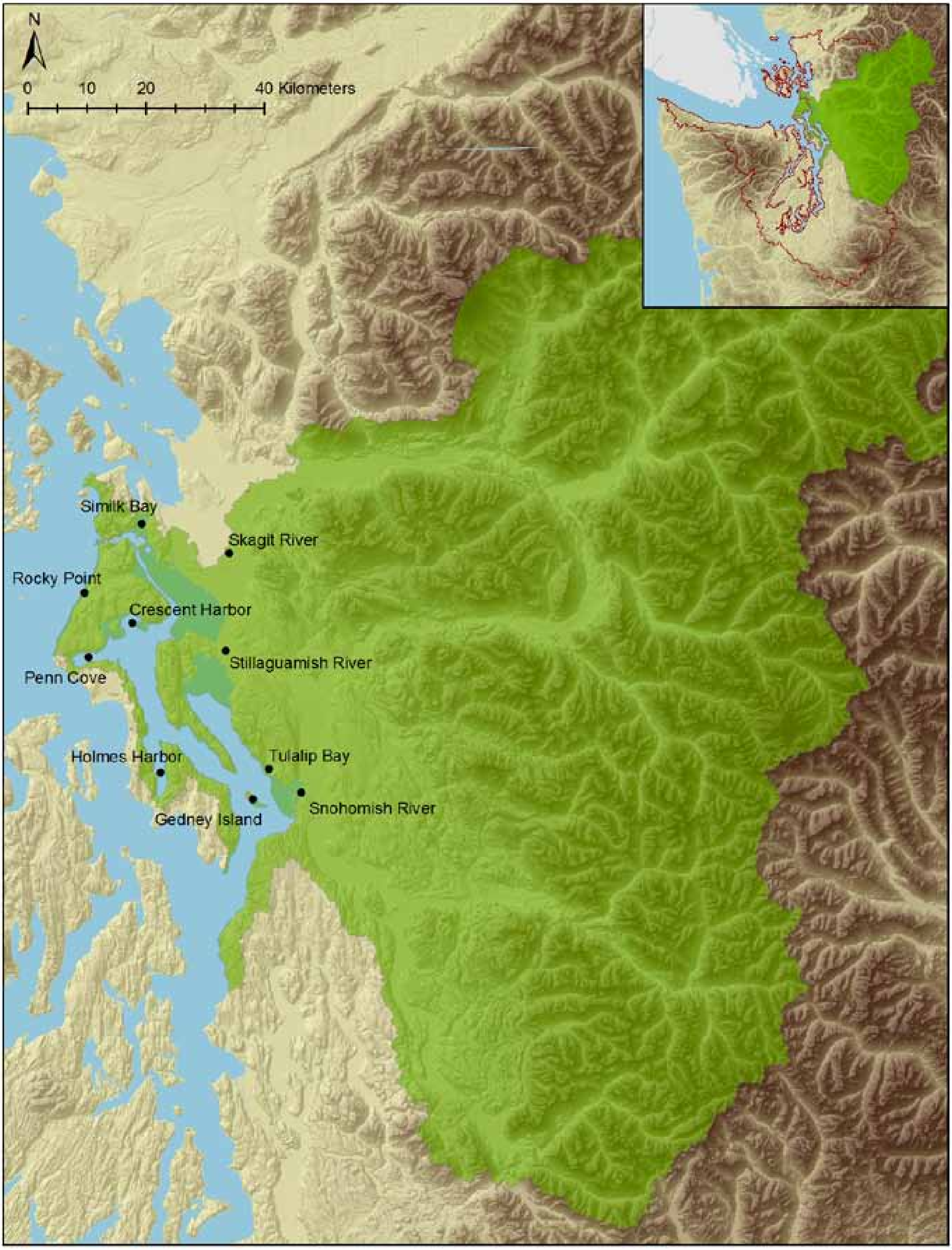


Figure 116. Whidbey Sub-Basin.

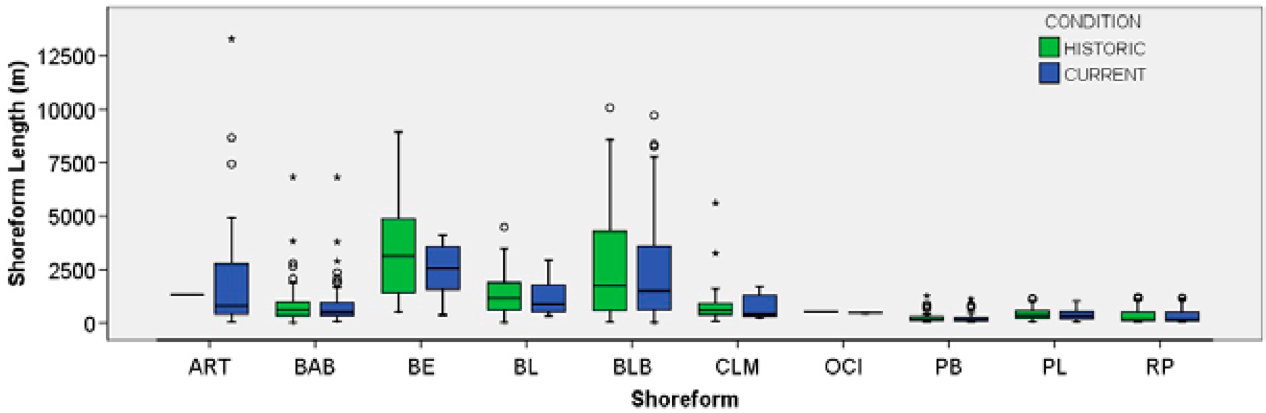


Figure 117. Historical and current contiguous shoreline length of Whidbey Sub-Basin shoreforms in PU (excludes delta shoreform); see Fig. 20 for shoreform codes. Each box represents the median and upper and lower quartile of the shoreform length data. The 'whiskers' (lines that extend out of the top and bottom of box) represent the highest and lowest values that are not outliers or extreme values. Outliers (values between 1.5 and 3 times the interquartile range) are marked with an asterisk.

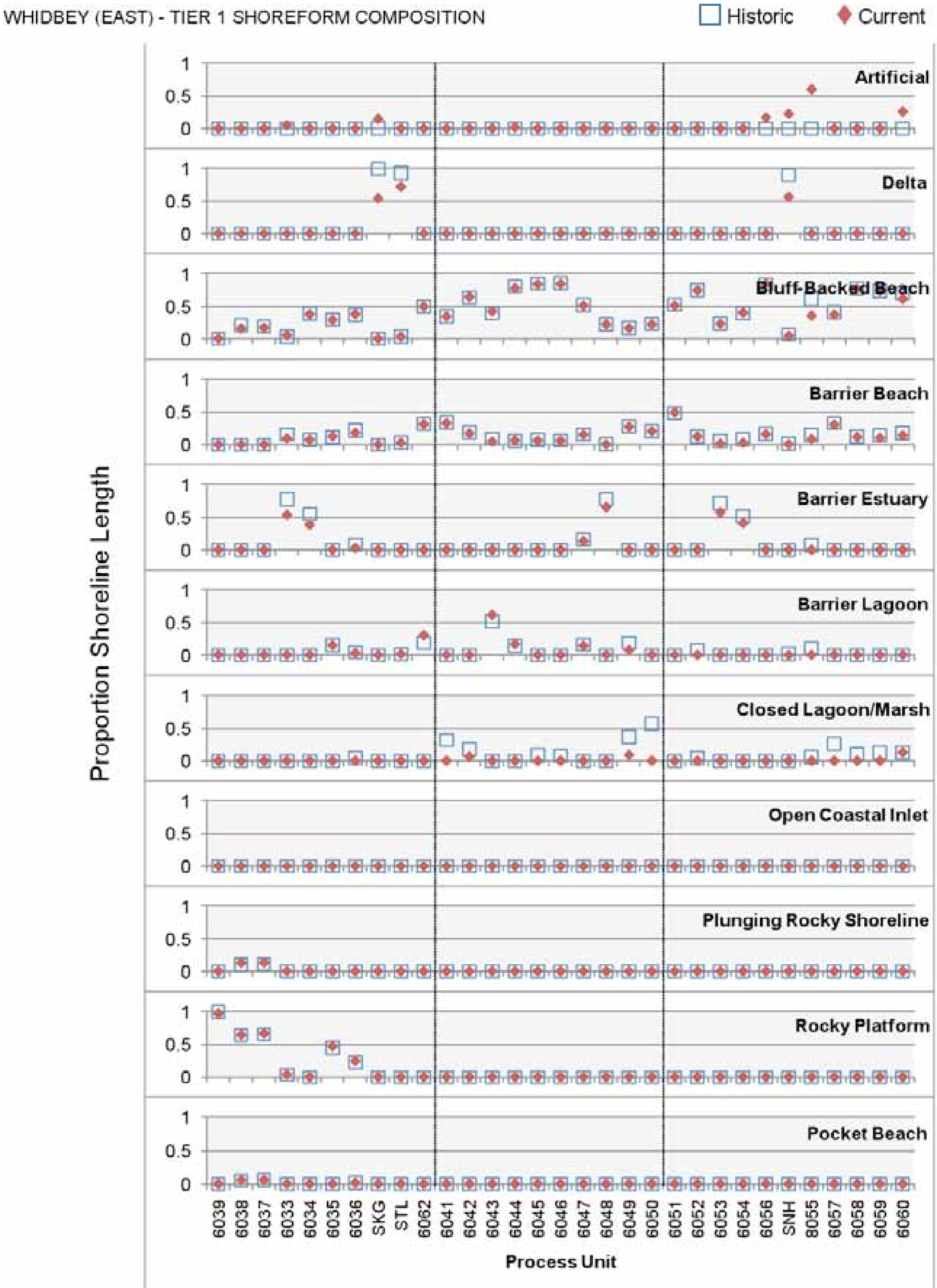


Figure 118. Historical Proportional lengths of historical and current shoreforms along sequential process units (PU) of the eastern component of the Whidbey Sub-Basin.

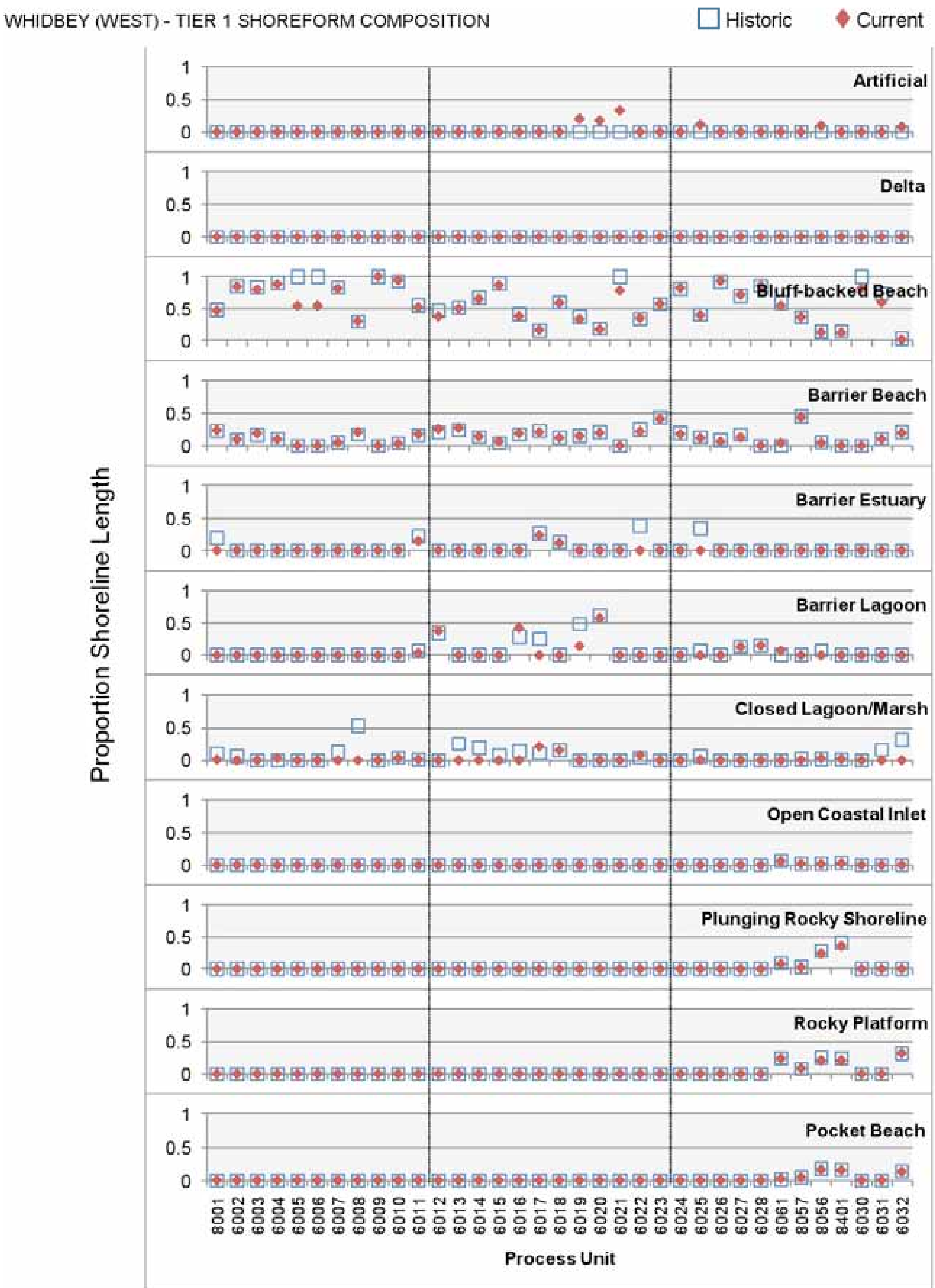


Figure 119. Proportional lengths of historical and current shoreforms along sequential process units (PU) of the western component of the Whidbey Sub-Basin.

Multivariate Analysis

The historical shoreform composition of PU in the Whidbey Sub-Basin consisted of a variety of permutations on different embayment shoreforms with bluff-backed beaches and barrier beaches (Fig. 120). The dominant groups were characterized by bluff-backed beaches and barrier beaches alone (group m) and bluff-backed beaches, barrier beaches, barrier estuaries, barrier lagoons, and closed lagoons/marshes (group n). Groups i-l were composed of five to eight PU with bluff-backed beaches and barrier beaches with one of the embayment shoreforms. One group (group c) of nine PU included all three rocky shoreforms integrated with bluff-backed and barrier beaches. The current shoreform composition is roughly parallel with the historical, but with reduced numbers of PU represented in the groups as well as the addition of artificial shoreforms contributing to the similarity of PU in two groups (Fig. 121). The most prominent transitions involved insertion of artificial shoreforms with the loss of bluff-backed and barrier beaches and barrier estuaries (group e), the reduction in bluff-backed beach and closed lagoon/marsh (group d), and gains in either bluff-backed or barrier beaches (groups b, h) (Fig. 122).

Shoreline Alterations

Descriptive

The Whidbey Sub-Basin shoreline is pervasively armored in both the eastern and western components, but more extensively so (approaching and surpassing 50 percent of PU) on the eastern margin (Figs. 123–124). Nearshore roads are coincident along much of the same shoreline, although approaching 50 percent of PU length in only a few cases. Although tidal barriers do occur in the western component, they are very common, and often extensive (approaching 100 percent), in and around the deltas (Skagit, Stillaguamish, and Snohomish).

Multivariate Analysis

The pervasive combined alterations among the PU are loss of estuarine mixing wetlands, armoring and nearshore roads throughout the sub-basin (group j; 42 PU), and gain of estuarine mixing wetlands, armoring, and nearshore roads (group h; 11 PU), the latter of which are concentrated around Similk Bay and around the northeastern corner of Holmes Harbor (Fig. 125).

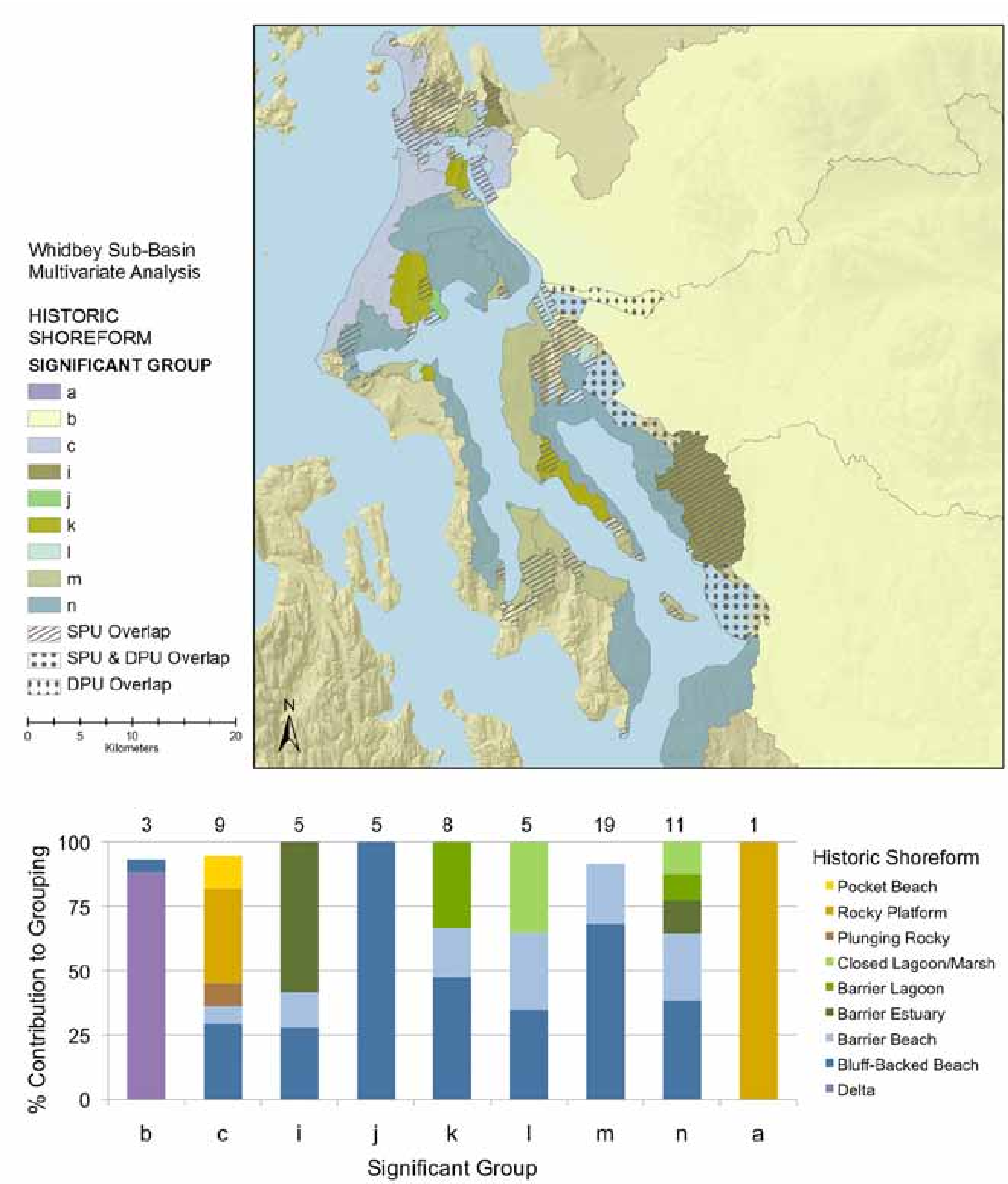


Figure 120. (Top) Distribution of process unit (PU) groups with significantly similar historical shoreform composition in Whidbey Sub-Basin of Puget Sound based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for historical shoreform composition in the PU of the Whidbey Sub-Basin. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group. Groups composed of one PU show the descriptive composition of the PU.

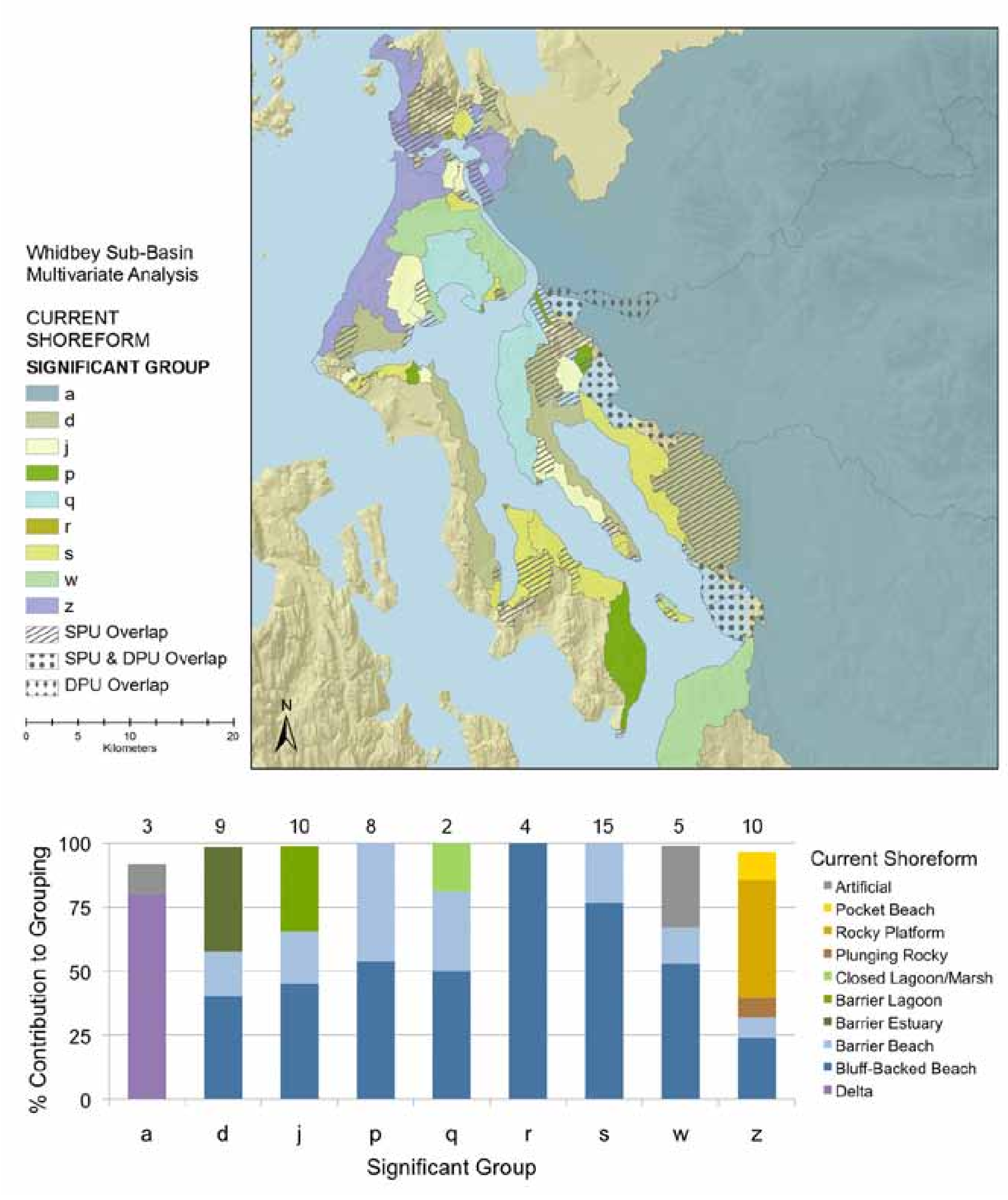


Figure 121. (Top) Distribution of process unit (PU) groups with significantly similar current shoreform composition in Whidbey Sub-Basin of Puget Sound based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for current shoreform composition in the PU of the Whidbey Sub-Basin. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group.

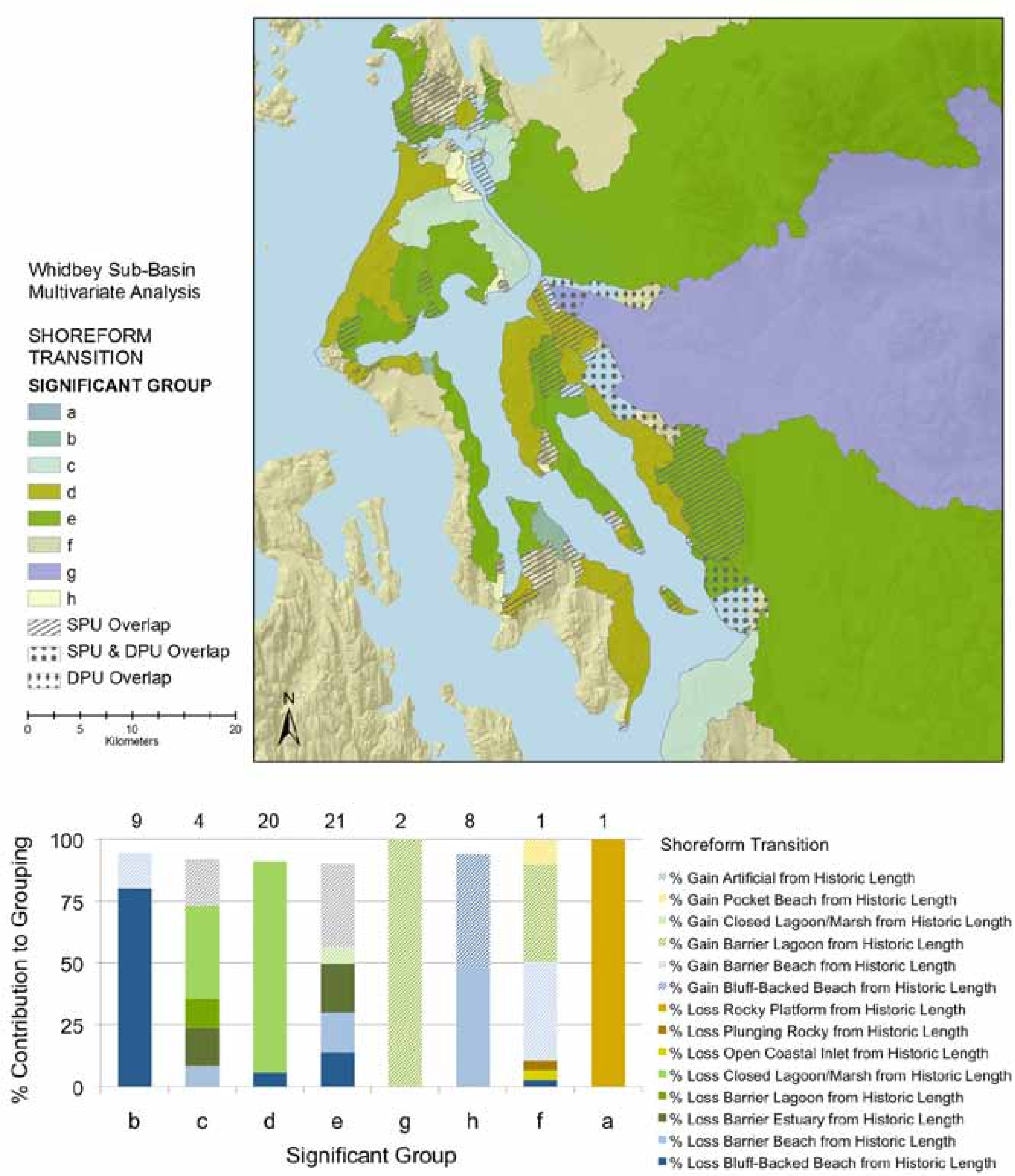


Figure 122. (Top) Distribution of process unit (PU) groups with significantly similar shoreform transitions in Whidbey Sub-Basin of Puget Sound based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for shoreform transitions in the PU of the Whidbey Sub-Basin. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group. Groups composed of one PU show the descriptive composition of the PU.

Table 16. Shoreform transitions (Tier 1) of Whidbey Sub-Basin. Highlighted numbers (diagonal line) represent the number that did not transition and are derived as the difference between the historical shoreform count and the total number of transitions.

Shoreform Transition	***Current* ------------------------>**												
Historic	Bluff-Backed Beach	Barrier Beach	Delta	Barrier Estuary	Barrier Lagoon	Closed Lagoon/ Marsh	Open Coastal Inlet	Plunging Rocky Shoreline	Rocky Platform	Pocket Beach	Artificial	Shoreform Absent	Total Transitions
Bluff-Backed Beach	71	7									13		20
Barrier Beach	1	89									6		7
Delta			0								3		3
Barrier Estuary				7								7	7
Barrier Lagoon					9	1					5	9	15
Closed Lagoon/Marsh						8					1	23	24
Open Coastal Inlet							2						0
Plunging Rocky Shoreline								23					0
Rocky Platform									56				0
Pocket Beach										30			0
Artificial											1		0
Shoreform Absent					2	4			1		5		12
Total Transitions	3	8	0	0	2	5	0	0	1	0	33	39	91

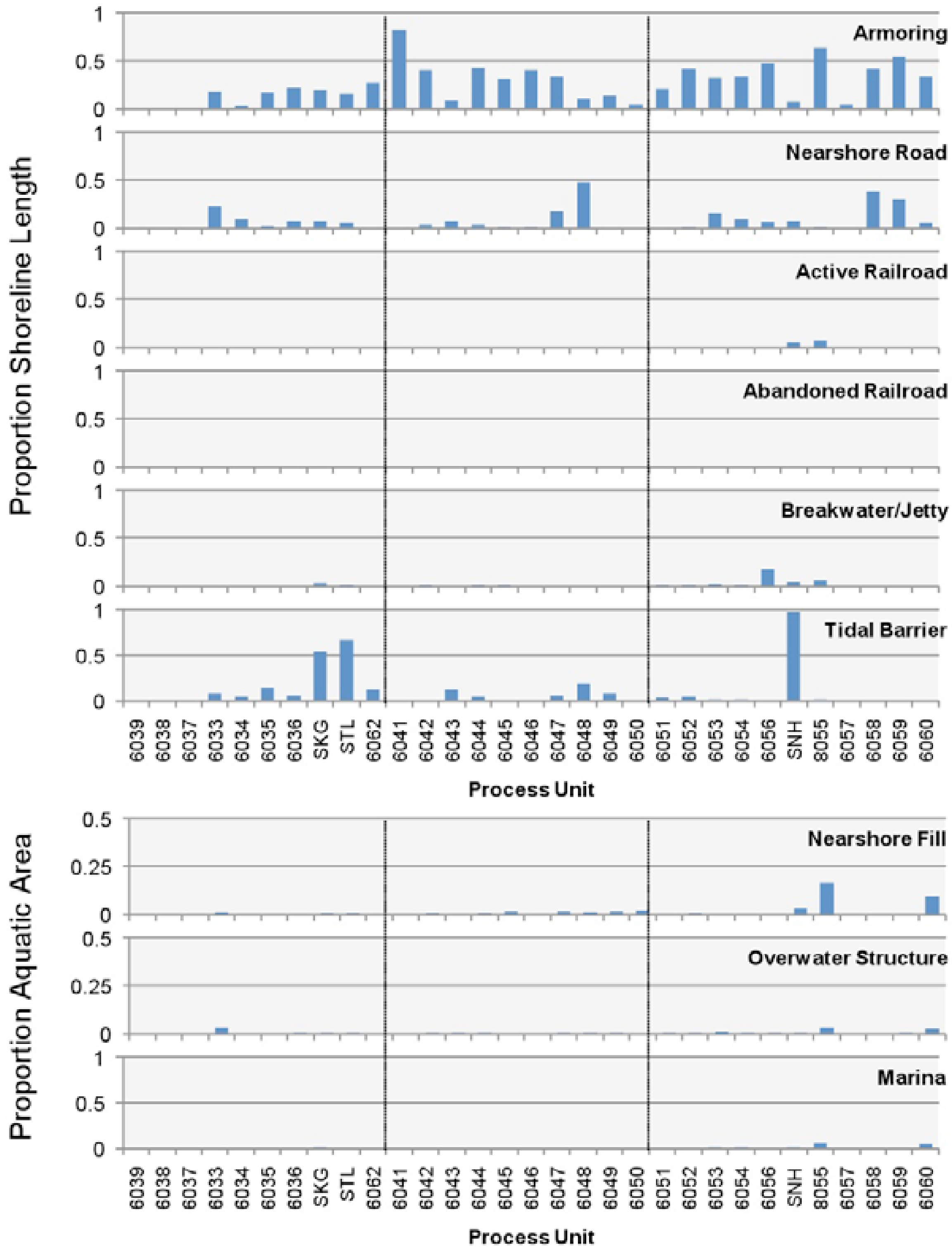


Figure 123. Shoreline alterations along sequential process units (PU) in the eastern component of the Whidbey Sub-Basin.

WHIDBEY (WEST) - TIER 2 SHORELINE ALTERATIONS

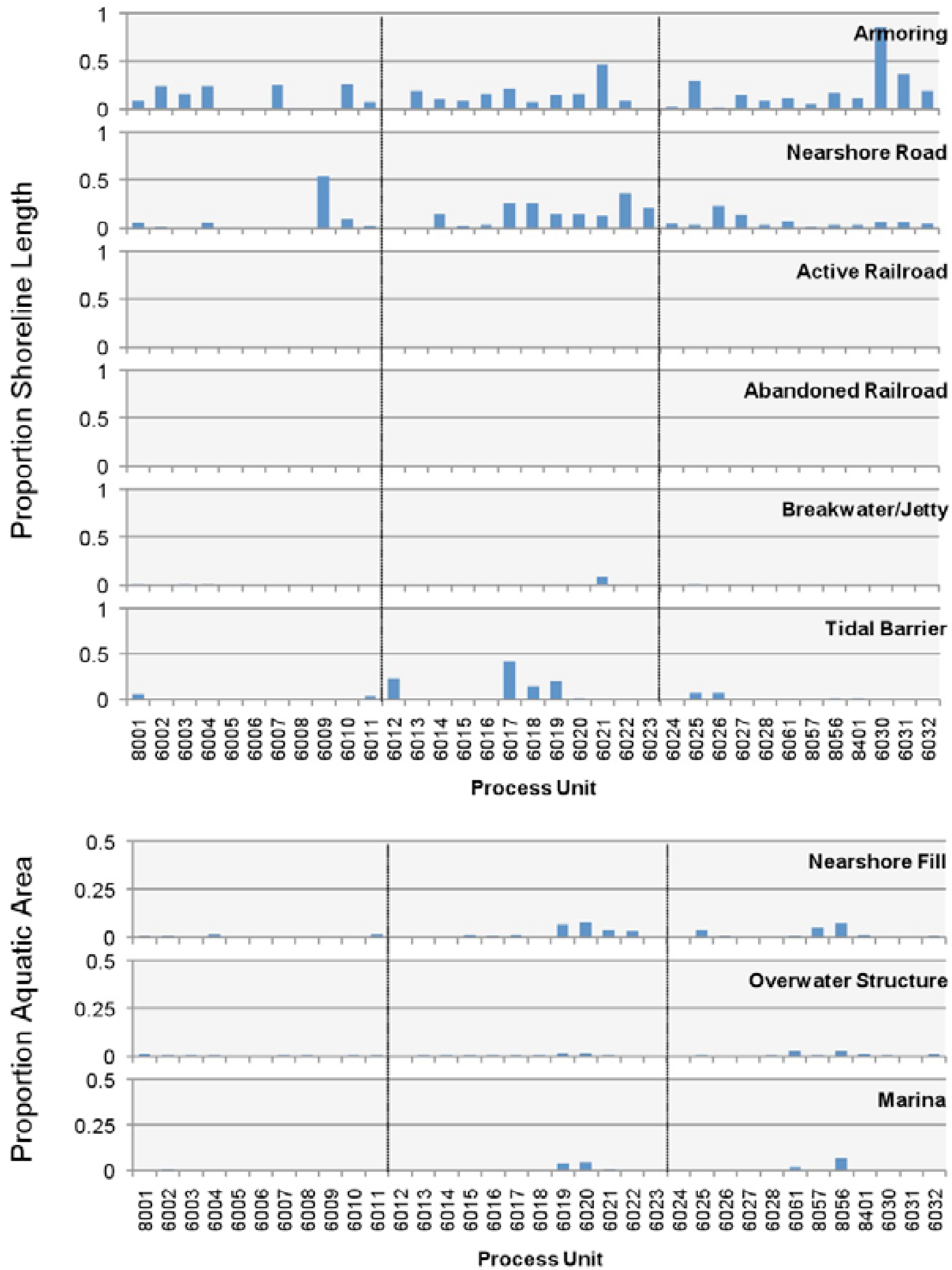


Figure 124. Shoreline alterations along sequential process units (PU) in the western component of the Whidbey Sub-Basin.

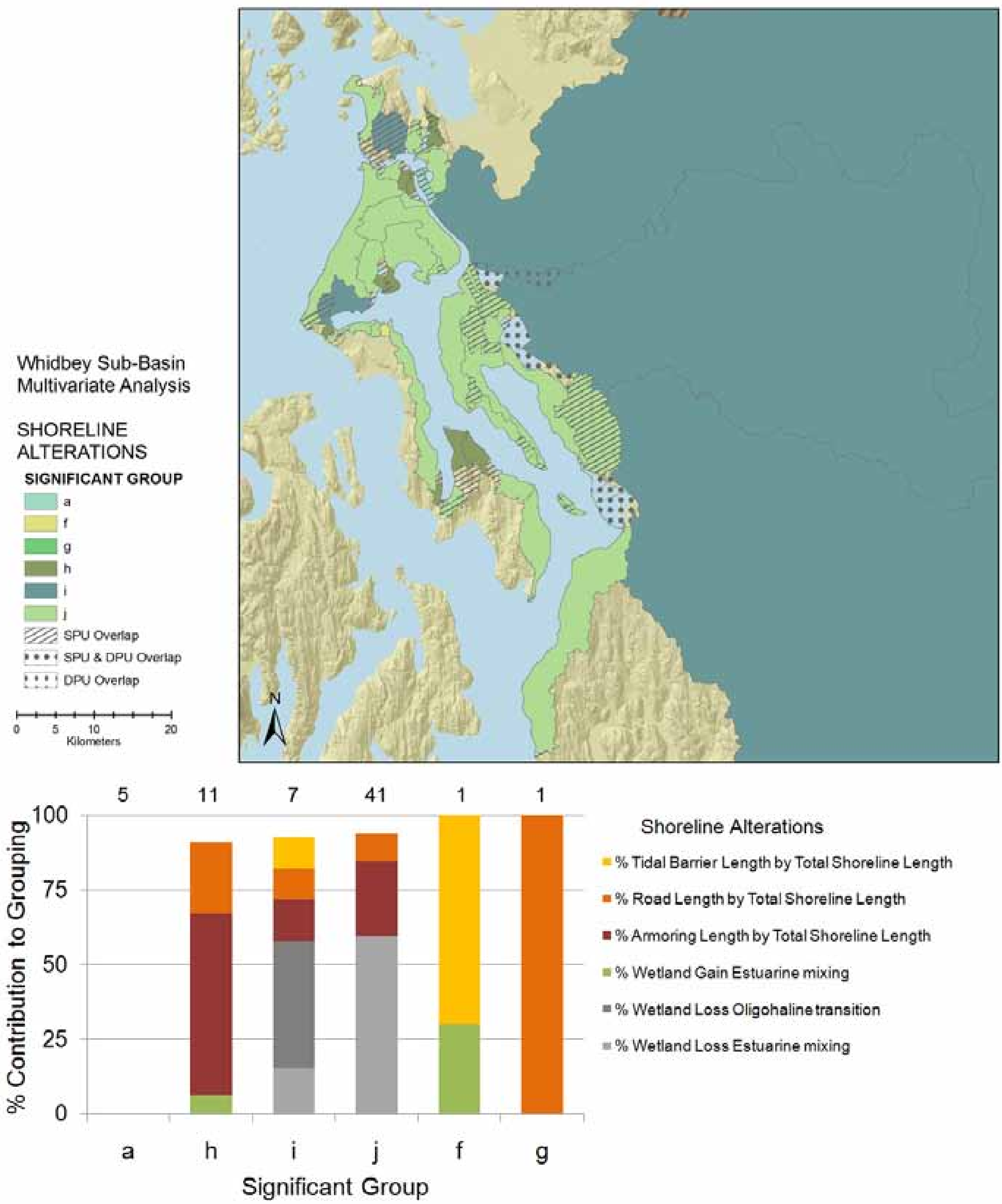


Figure 125. (Top) Process unit (PU) groups with significant similar shoreline alterations and stressors in Whidbey Sub-Basin based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for shoreline alterations in the PU of the Whidbey Sub-Basin. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group. Groups composed of one PU show the descriptive composition of the PU. Group 'a' does not contain any shoreline alterations.

Adjacent Upland and Watershed Change

Descriptive

As on the shoreline, development is fairly pervasive throughout the adjacent upland and in many areas of the watershed area of the Whidbey Sub-Basin (Figs. 126–127). High-intensity development makes up a considerable proportion of the watershed area around Oak Harbor (SPU 6019–6021) as well as throughout the relatively large SPU 8055, connecting the cities of Everett and Seattle. Much land is devoted to agriculture (hay/pasture) around the Skagit and Stillaguamish deltas.

Multivariate Analysis

Analysis of adjacent upland change show groups h and j to be numerically the most common (23 and 16 PU, respectively), and are both characterized by a range of impervious surface and low intensity development (Fig. 128). Group g, located around Oak Harbor and SPU 8055, contains the process units with greatest concentrations of high-intensity development. Groups b and f (within which are the three large deltas) are distinguished by the presence of hay/pasture land interspersed with low to moderate development.

Considering watershed area change, group i (21 PU) is characterized by moderate development in the Whidbey Sub-Basin (Fig. 129). Group f is distinguished by hay/pasture land, which speaks to the agricultural presence in the sub-basin. As seen in changes to the adjacent upland, process units around Oak Harbor as well as SPU 8055 form a group based on high contributions of high intensity development. The Skagit and Snohomish DPU are distinguished as group d, based on the level of impounded area.

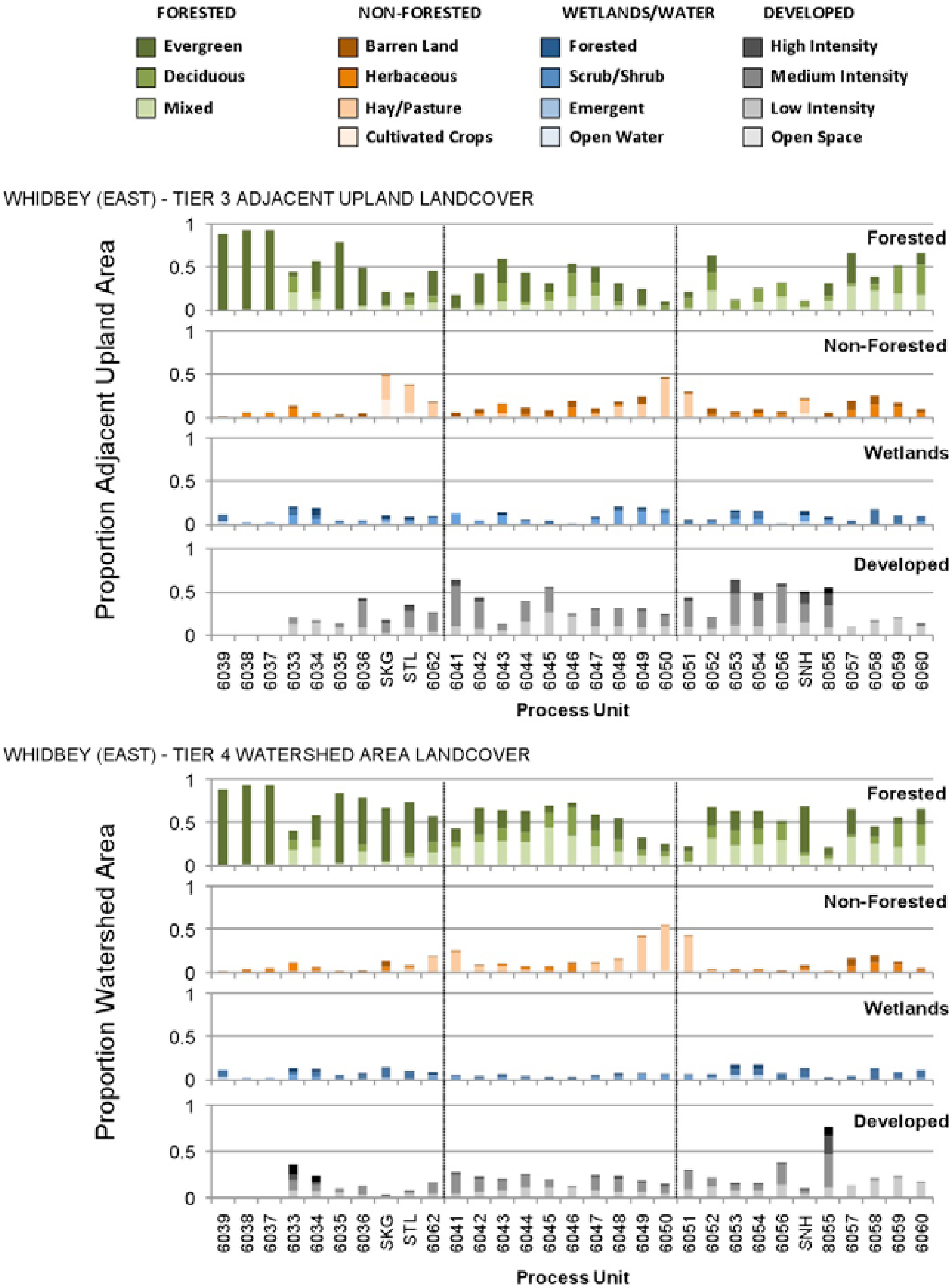


Figure 126. Land cover/land and stressors in adjacent upland (Tier 3, top) and watershed areas (Tier 4, bottom) in the eastern component of the Whidbey Sub-Basin.

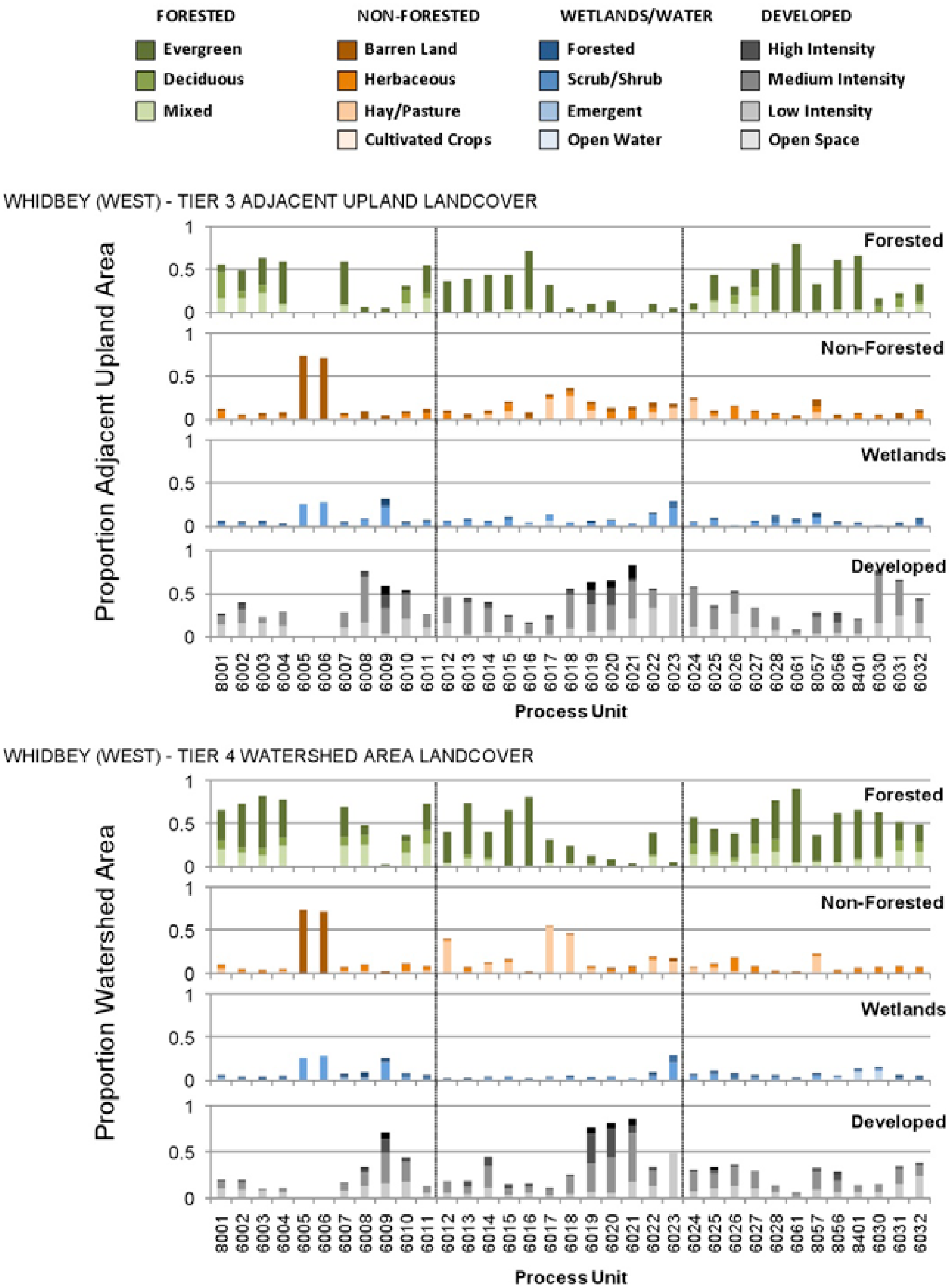


Figure 127. Land cover/land and stressors in adjacent upland (Tier 3, top) and watershed areas (Tier 4, bottom) in the western component of the Whidbey Sub-Basin.

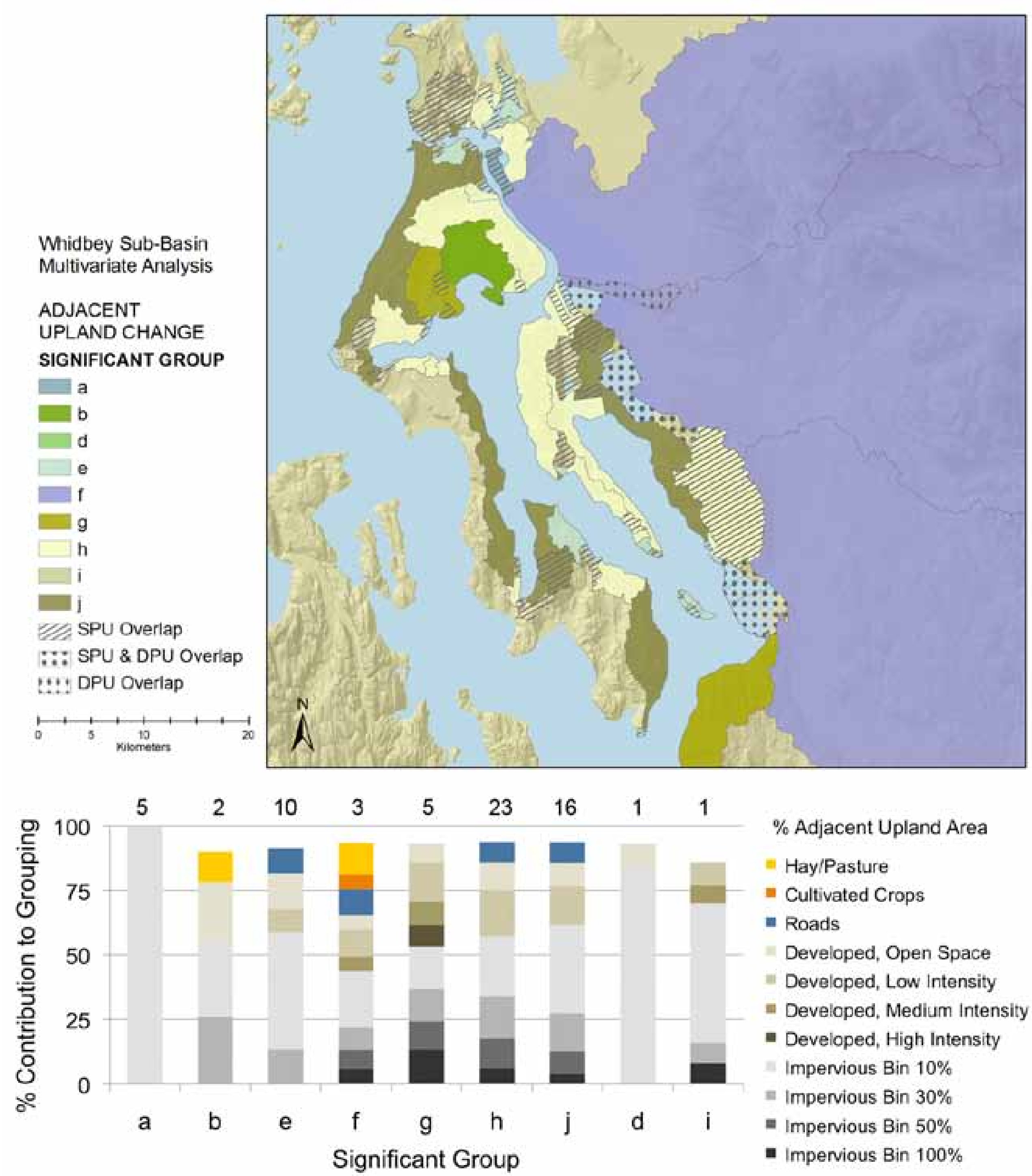


Figure 128. (Top) Distribution of process unit (PU) groups with significantly similar adjacent upland changes in Whidbey Sub-Basin of Puget Sound based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for adjacent upland change in the PU of the Whidbey Sub-Basin. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group. Groups composed of one PU show the descriptive composition of the PU.

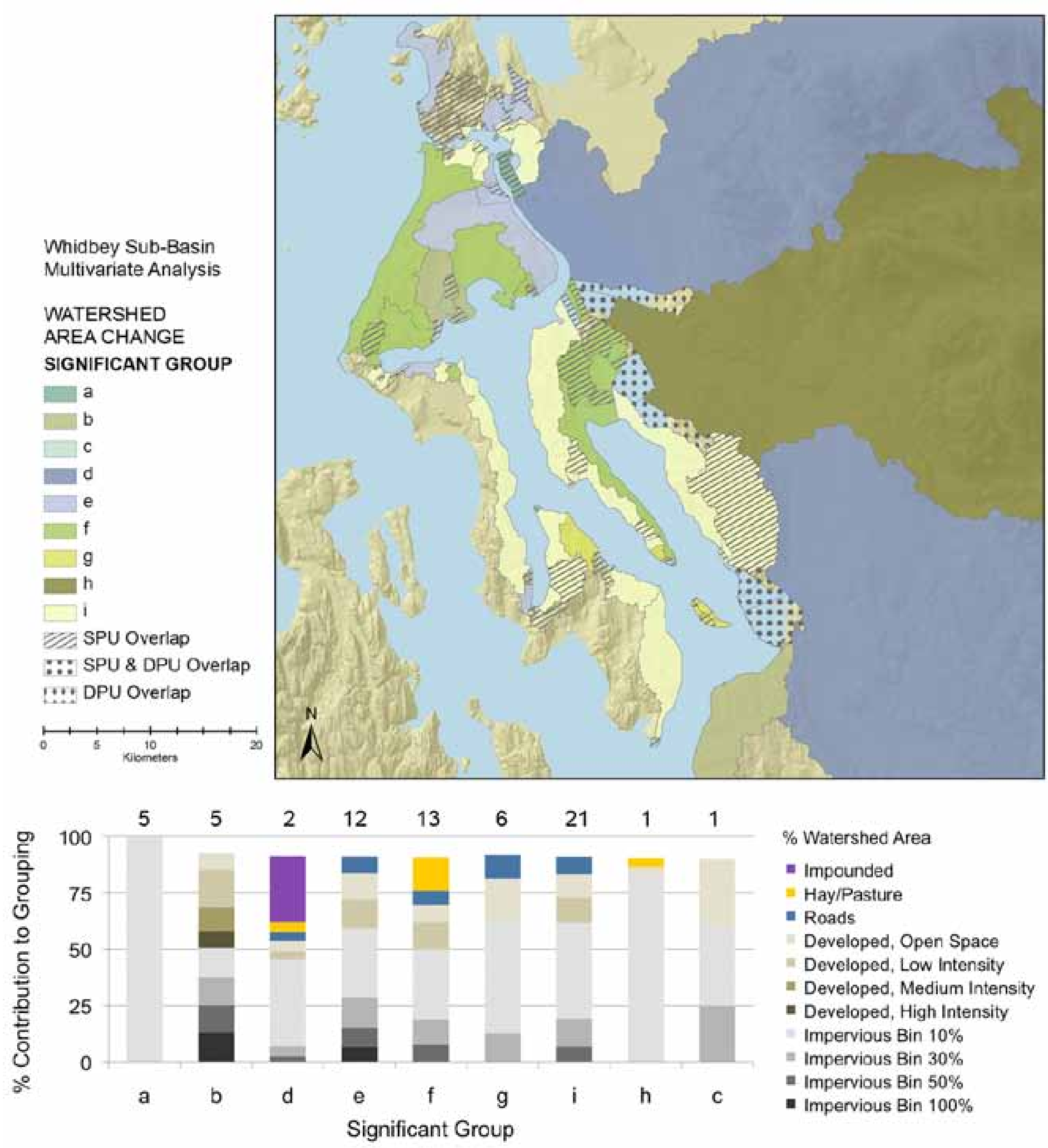


Figure 129. (Top) Distribution of process unit (PU) groups with significantly similar total watershed area changes in Whidbey Sub-Basin of Puget Sound based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for watershed area change in the PU of the Whidbey Sub-Basin. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group. Groups composed of one PU show the descriptive composition of the PU.

South Central Puget Sound Sub-Basin

Shoreform Change and Transition

Descriptive

Likely the most developed nearshore region of Puget Sound, the South Central Puget Sound Sub-Basin (Fig. 130) has lost considerable proportions (41 to 89 percent) of its barrier estuary, barrier lagoon, closed lagoon/marsh, and open coastal inlet shoreline length, and virtually 100 percent of its delta (Duwamish and Puyallup rivers) shoreline (Table 4; Fig. 131). The largest losses of shoreform segments involve closed lagoons/marshes (39) and barrier lagoons (21). Additionally, the South Central Sub-Basin has lost 21 barrier beach segments, more than any of the other sub-basins (Table 5).

As in other sub-basins, shoreform transitions in South Central Puget Sound are dominated (92.8 percent) by artificial or shoreform absent transitions (Table 17). This is particularly notable for bluff-backed beaches (34 percent of original shoreform segments became artificial), barrier beaches (approximately 22 percent became artificial), and open coastal inlets (approximately 68 percent became artificial). Six bluff-backed or barrier beaches transitioned between these two forms, but two bluff-backed beaches and one barrier beach transitioned to barrier estuaries. Four open coastal inlets transitioned to barrier estuaries.

We have partitioned the sub-basin into four components (see Appendix D, Figs. E.12-E.15 for PU distributions) in order to examine the contiguous shoreline for concentrations of shoreline length change (Figs. 132-135). Reductions in shoreform length along the contiguous shoreline of the eastern component of the South Central Sub-Basin indicate pervasive decreases in natural shoreforms, especially bluff-backed beaches, barrier estuaries, barrier lagoons, and open coastal inlets, accompanied by increases in artificial shoreforms (Fig. 132). Bluff-backed beach decrease is particularly notable from Elliott Bay south to Seahurst, and along the southern margin of Commencement Bay. Although not as dramatically changed, the South Kitsap component demonstrates significantly reduced open coastal inlet and barrier beach shoreline, especially around Gig Harbor, and pervasive reductions in bluff-backed beach, barrier estuary, open coastal inlet, barrier beach, and barrier lagoon around Sinclair Inlet and the eastern margin of Port Orchard (Fig. 133). The western shore of Port Orchard from Liberty Bay to Burke Bay (SPU 4064-4074) illustrates the most change in the North Kitsap component, with large declines in open coastal inlet shoreline lengths and reductions in barrier estuaries and bluff-backed beaches (Fig. 134). The east side of Bainbridge Island (SPU 4132–4133) shows declines in barrier lagoon and closed lagoon/marsh shoreforms. Changes in the Vashon Island component include reductions of barrier estuaries and barrier lagoons in the region of Tramp Harbor (SPU 4095–4097) and Quartermaster Harbor (SPU 4111), and barrier beaches on the eastern shore of Blake Island (SPU 4085–4086) and Quartermaster Harbor (Figs. 135).

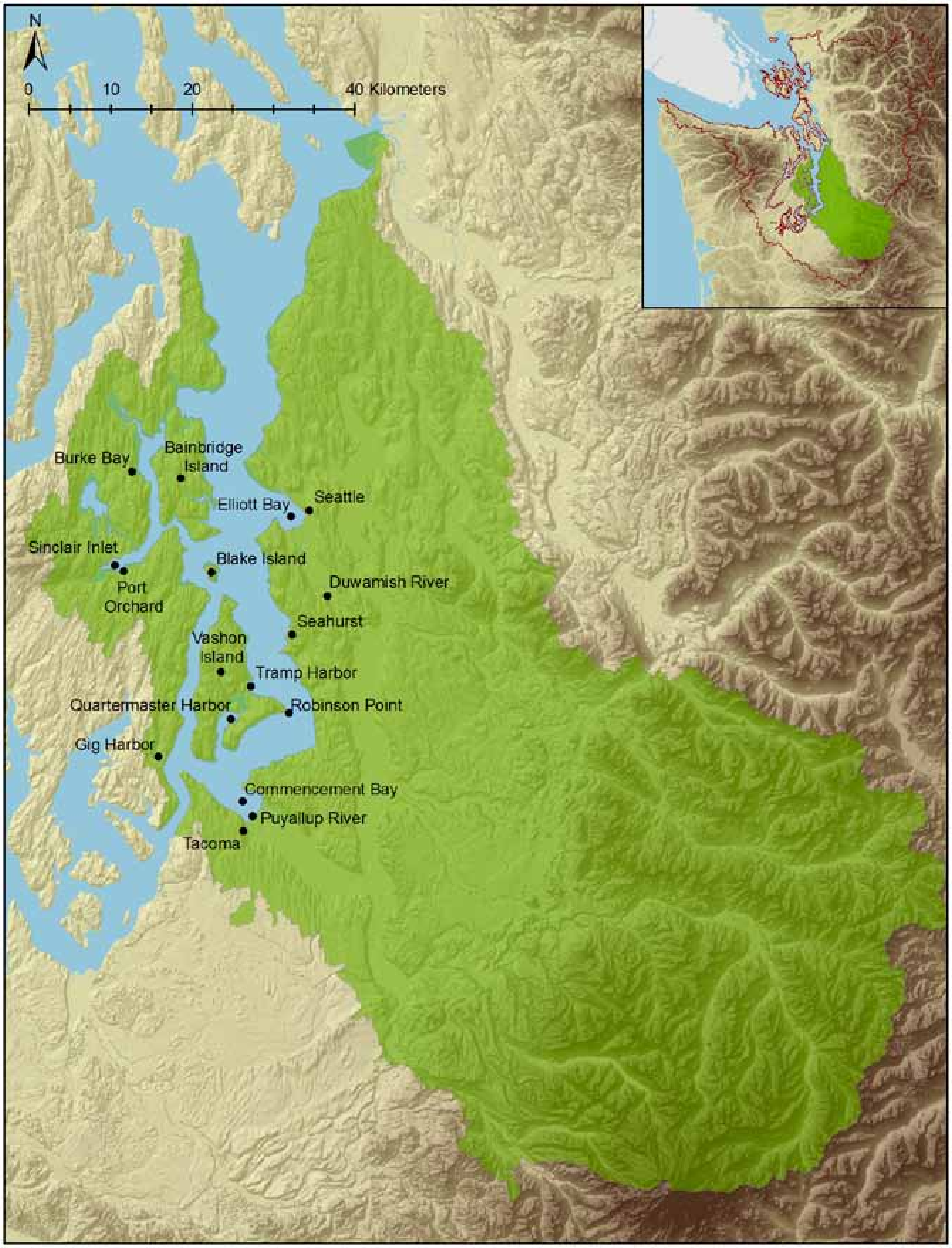


Figure 130. South Central Puget Sound Sub-Basin.

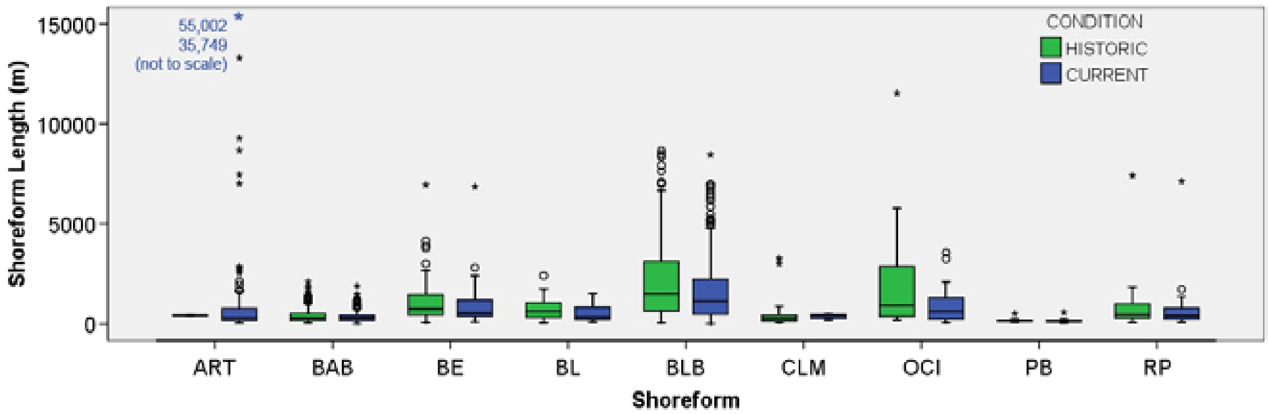


Figure 131. Historical and current contiguous shoreline length of South Central Puget Sound shoreforms in PU (excludes delta shoreform); see Fig. 20 for shoreform codes. Each box represents the median and upper and lower quartile of the shoreform length data. The 'whiskers' (lines that extend out of the top and bottom of box) represent the highest and lowest values that are not outliers or extreme values. Outliers (values between 1.5 and 3 times the interquartile range) are marked with a circle and extreme cases (values more than 3 times the interquartile range) with an asterisk. Extreme cases not shown to scale are indicated with the shoreform length (m) measurement.

Multivariate Analysis

Historical shoreform composition in the South Central Puget Sub-Basin was dominated by large groups of bluff-backed beach and barrier beach (group i), bluff-backed beach, barrier beach and barrier estuary (group j), or bluff-backed beach and open coastal inlet (group m) process units (Fig. 136). Under current conditions, bluff-backed beach and barrier beach PU (group h) still dominate, but other groups are totally (group a) or partially artificial (group g) (Fig. 137). The shoreform transition groups are dominated by three groups (encompassing 73 PU) that include gains in artificial shoreforms (Fig. 138).

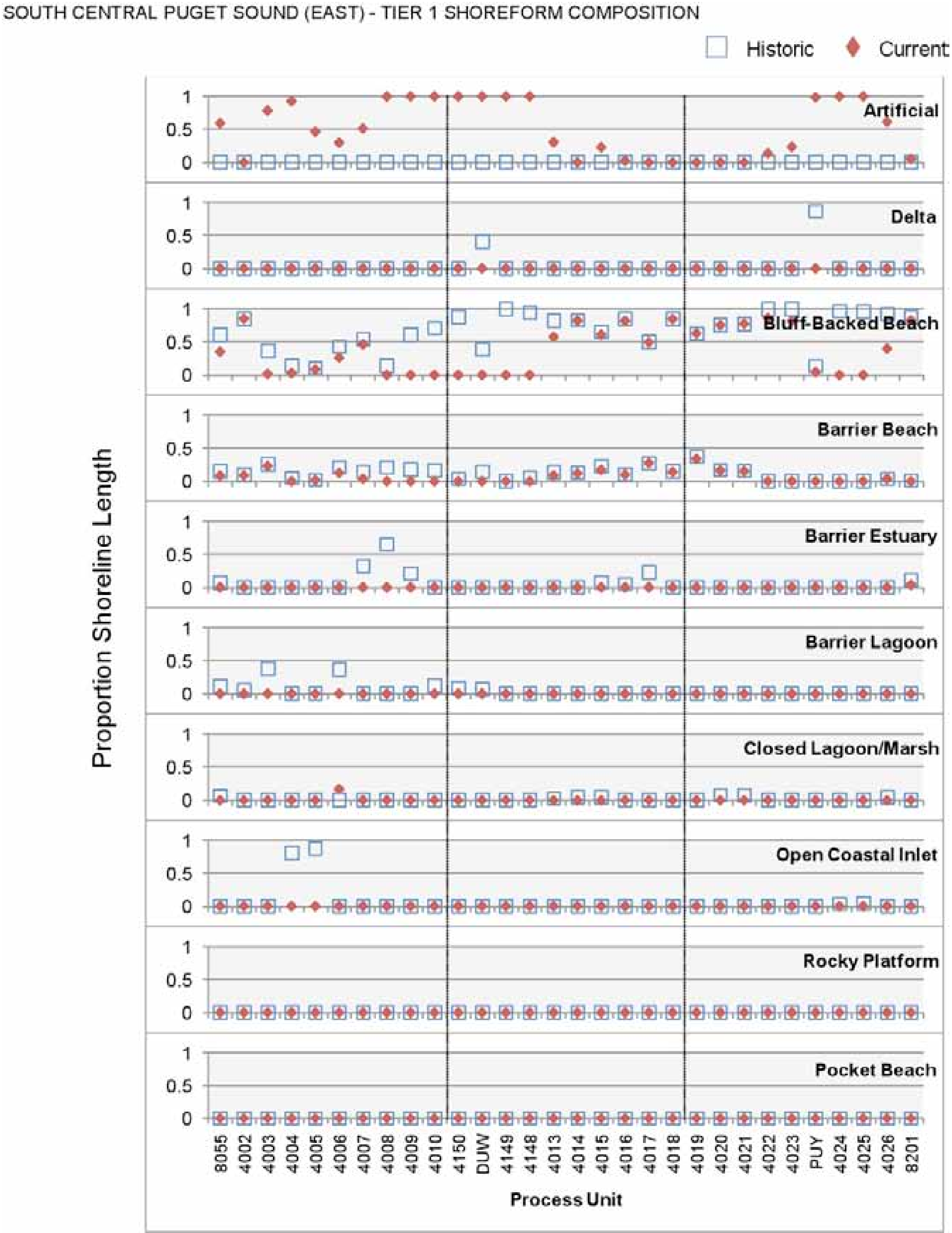


Figure 132. Proportional lengths of historical and current shoreforms along sequential process units (PU) of the eastern component of the South Central Puget Sound Sub-Basin.

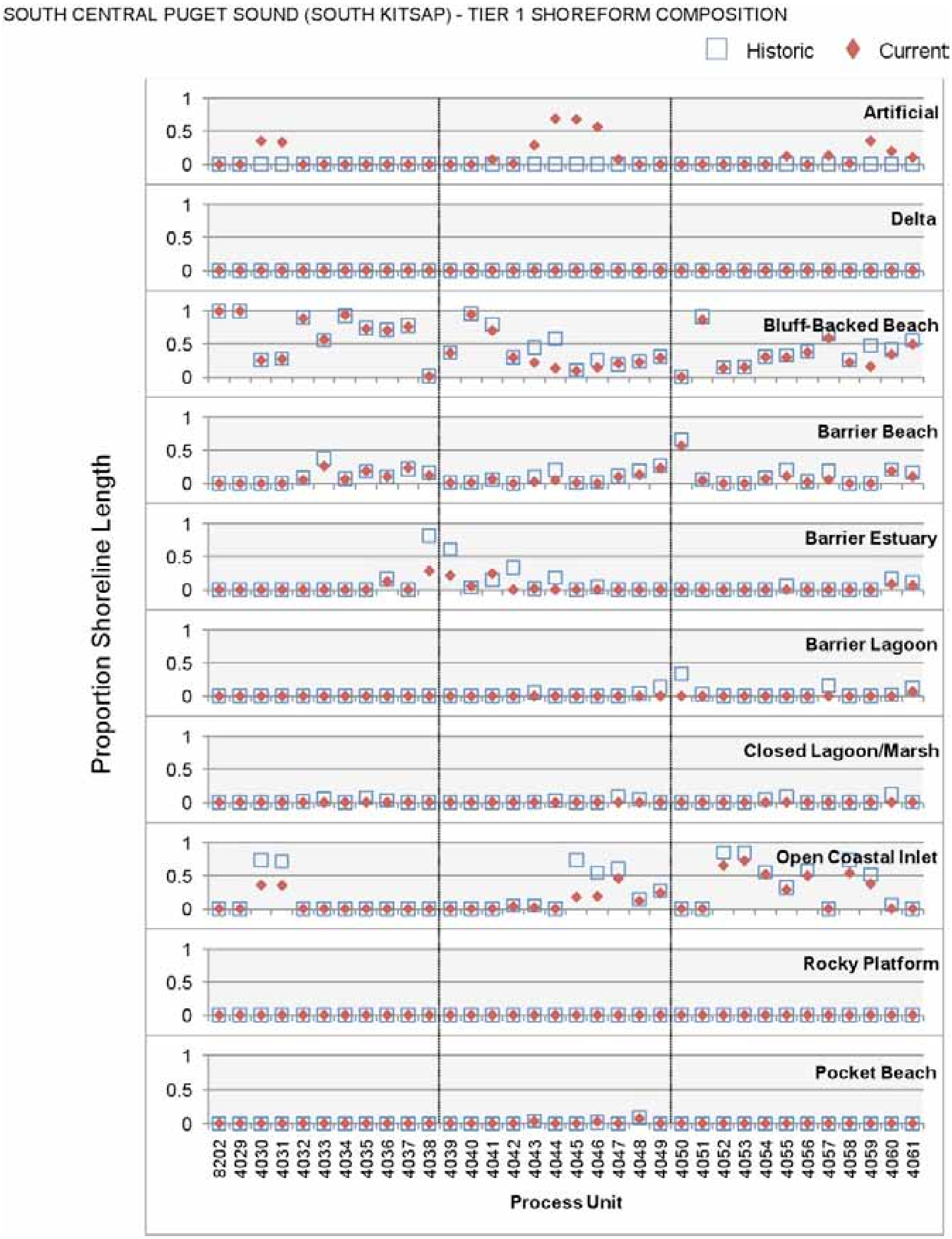


Figure 133. Proportional lengths of historical and current shoreforms along sequential process units (PU) of the South Kitsap component of the South Central Puget Sound Sub-Basin.

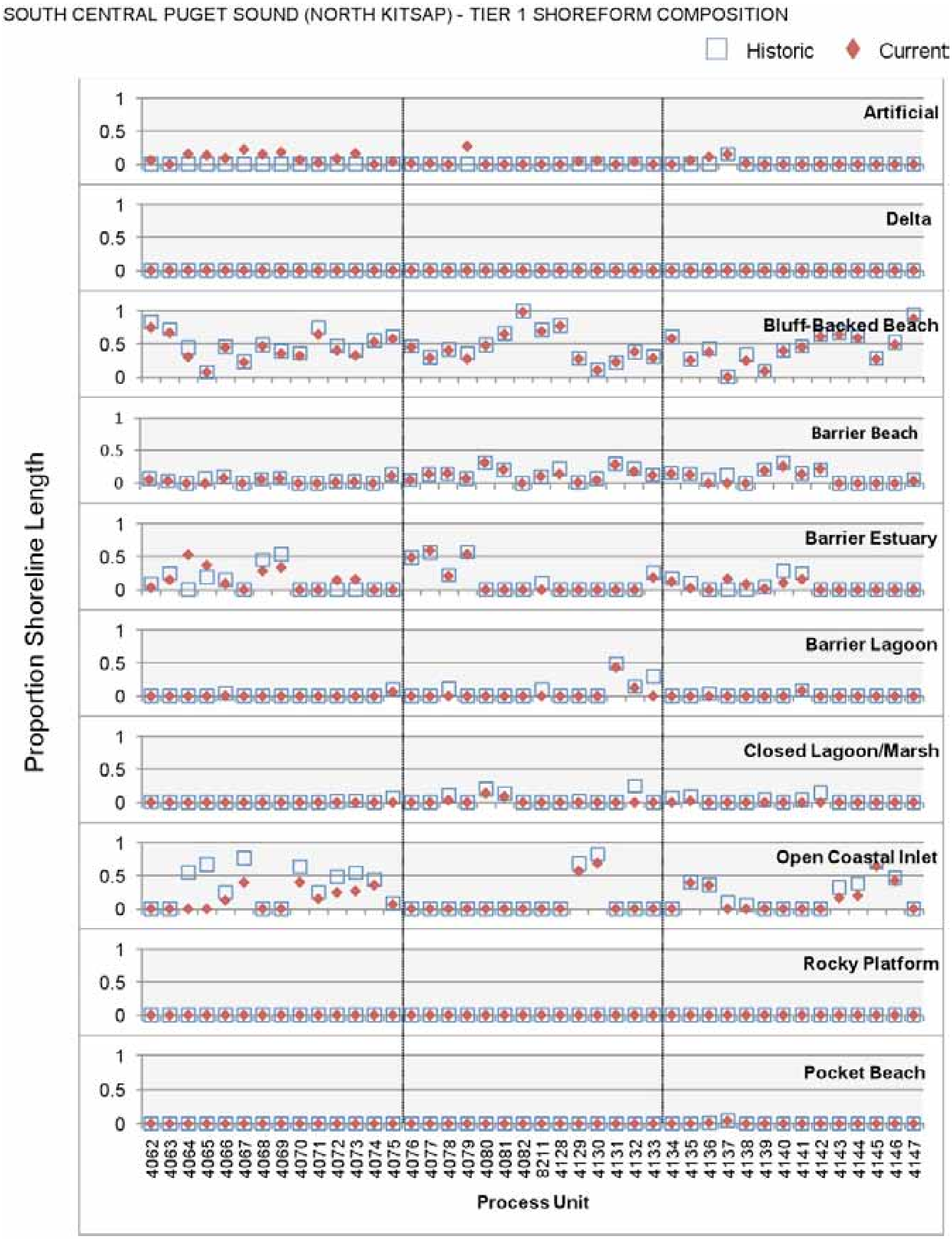


Figure 134. Proportional lengths of historical and current shoreforms along sequential process units (PU) of the North Kitsap component of the South Central Puget Sound Sub-Basin.

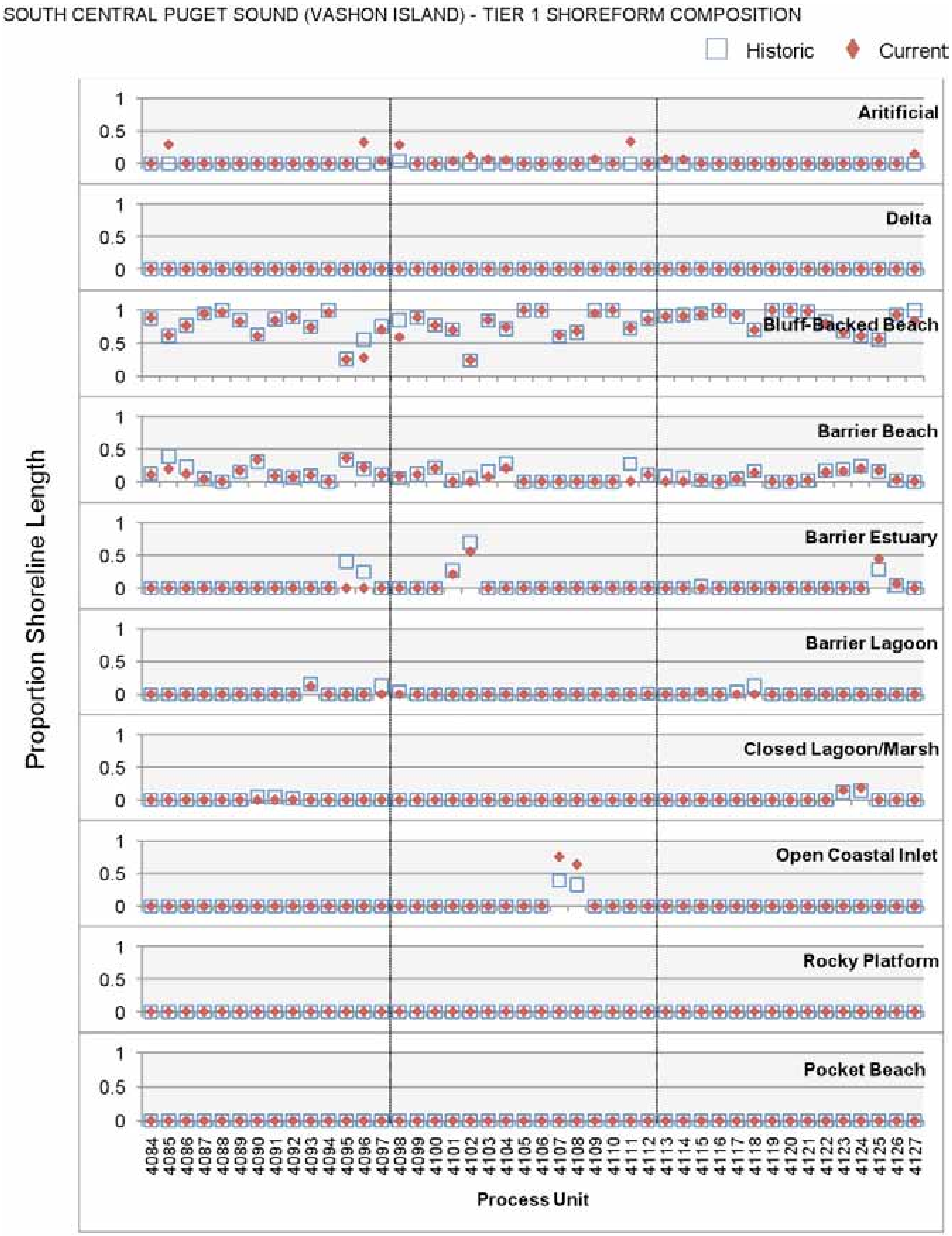


Figure 135. Proportional lengths of historical and current shoreforms along sequential process units (PU) of the Vashon Island component of the South Central Puget Sound Sub-Basin.

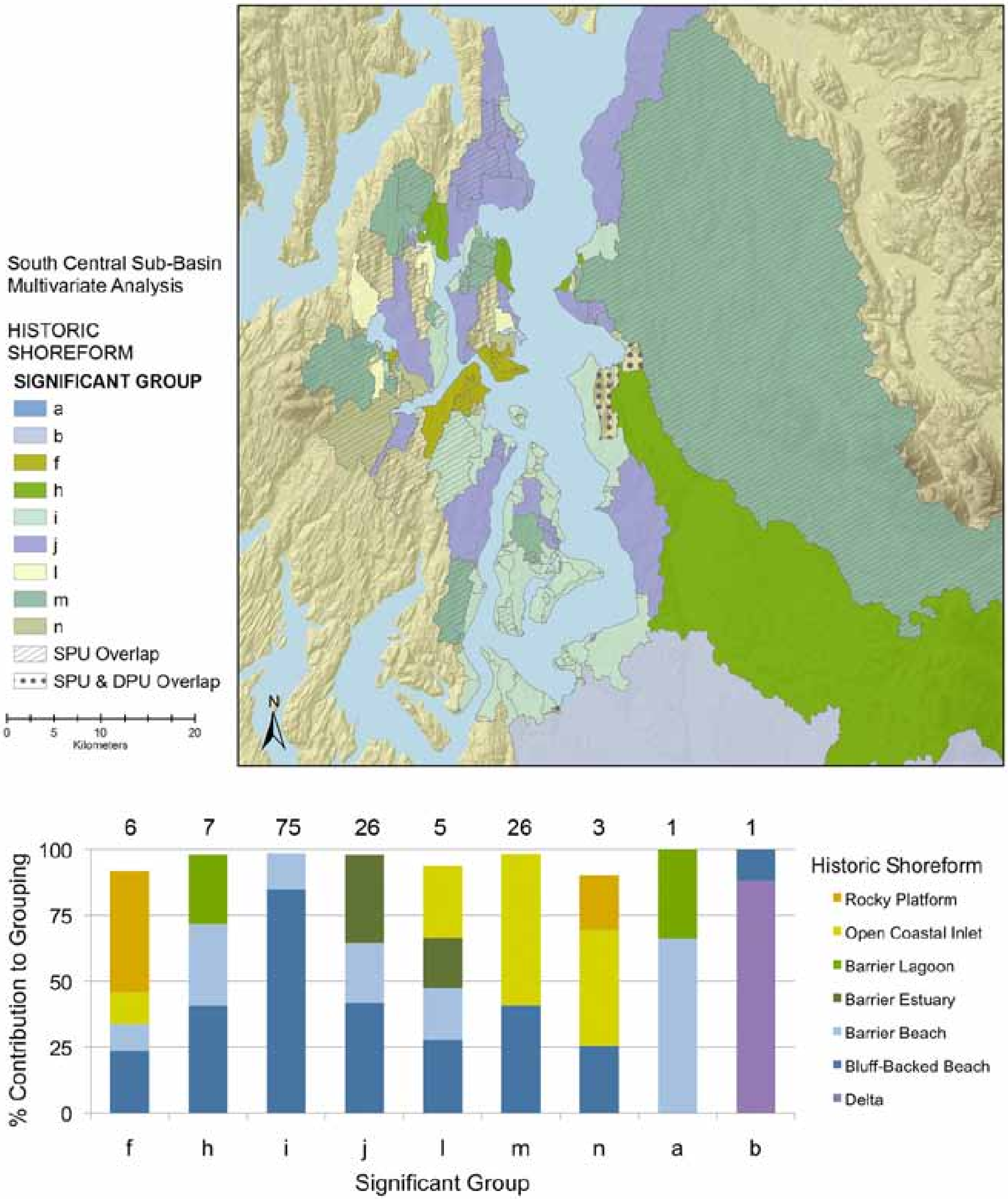


Figure 136. (Top) Distribution of process unit (PU) groups with significantly similar historical shoreform composition in South Central Sub-Basin of Puget Sound based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for historical shoreform composition in the PU. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group. Groups composed of one PU show the descriptive composition of the PU.

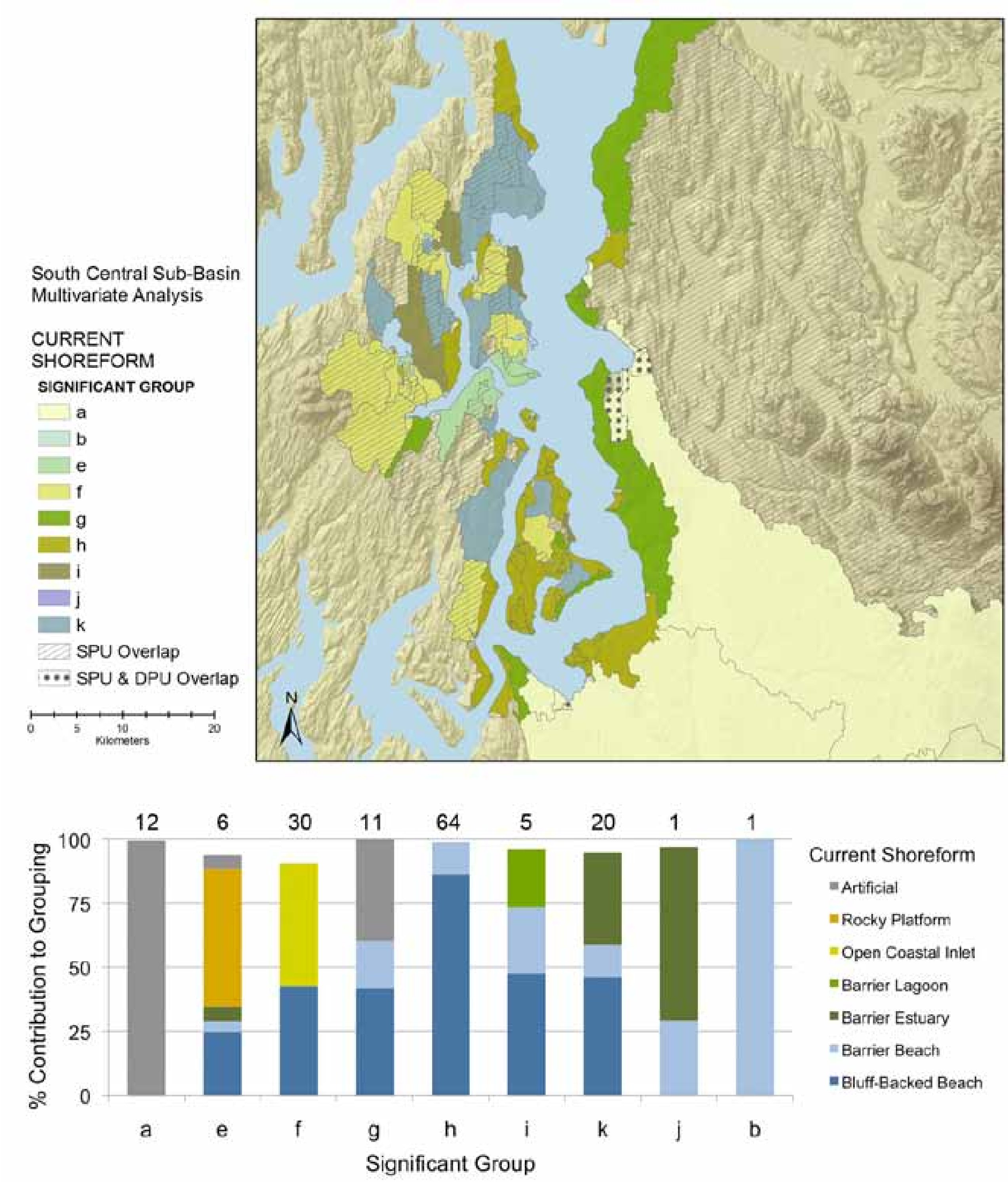


Figure 137. (Top) Distribution of process unit (PU) groups with significantly similar current shoreform composition in South Central Sub-Basin of Puget Sound based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for current shoreform composition in the PU. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group. Groups composed of one PU show the descriptive composition of the PU.

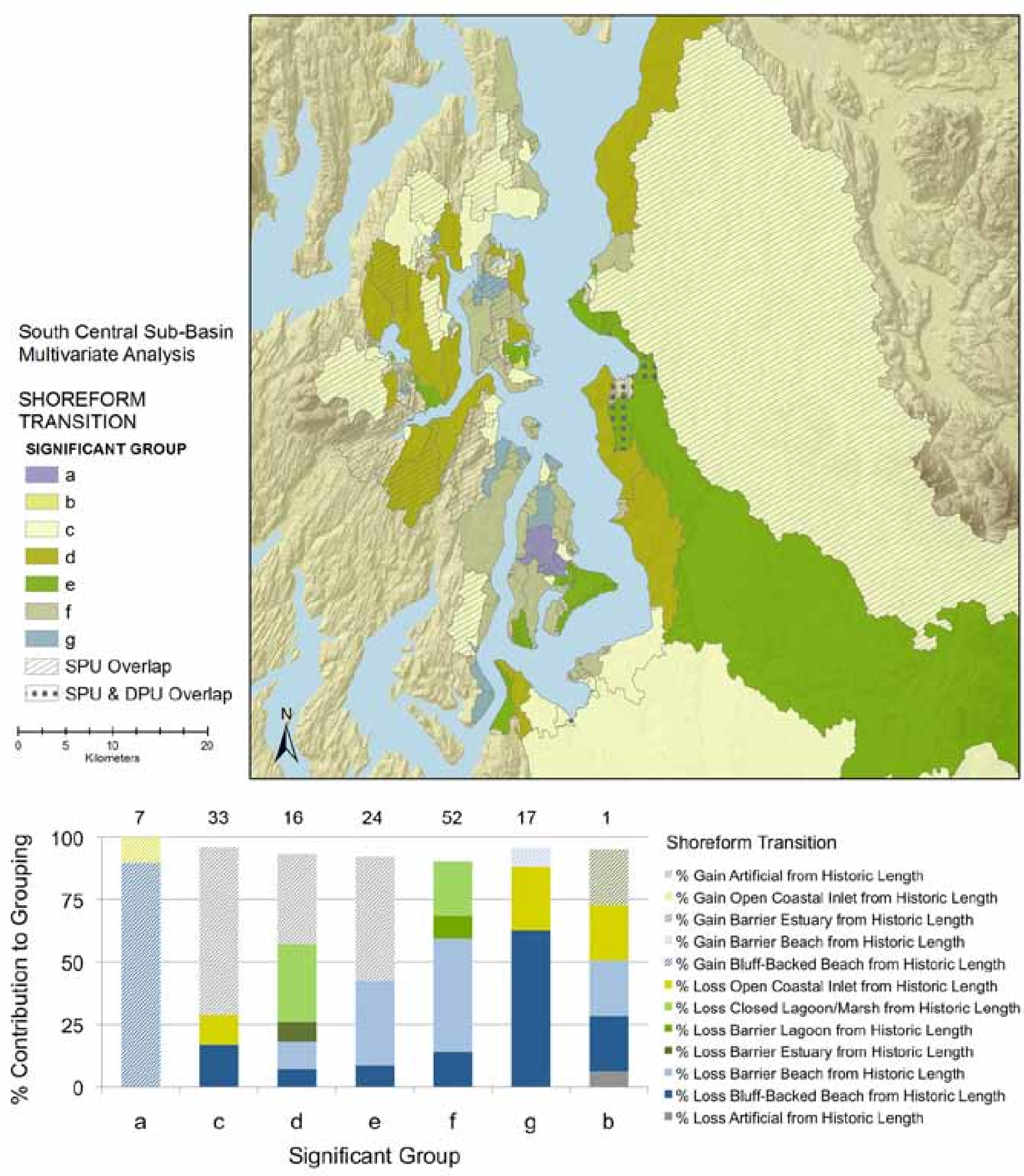


Figure 138. (Top) Distribution of process unit (PU) groups with significantly similar shoreform transitions in South Central Sub-Basin of Puget Sound based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for shoreform transitions in the PU. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group. Groups composed of one PU show the descriptive composition of the PU.

Table 17.Shoreform transitions (Tier 1) of South Central Puget Sound Sub-Basin. Highlighted numbers (diagonal line) represent the number that did not transition and are derived as the difference between the historical shoreform count and the total number of transitions.

Shoreform Transition	***Current* ------------------------>**											
Historic	Bluff-Backed Beach	Barrier Beach	Delta	Barrier Estuary	Barrier Lagoon	Closed Lagoon/ Marsh	Open Coastal Inlet	Rocky Platform	Pocket Beach	Artificial	Shoreform Absent	Total Transitions
Bluff-Backed Beach	107	3		2						58		63
Barrier Beach	2	123								35		37
Delta			0							2		2
Barrier Estuary				16	1					8	14	23
Barrier Lagoon					8	1				2	20	23
Closed Lagoon/Marsh						4					37	37
Open Coastal Inlet				4			6			21		25
Rocky Platform								21		1		1
Pocket Beach									10			0
Artificial										2		0
Shoreform Absent					1					8		9
Total Transitions	3	3	0	7	2	1	0	0	0	135	71	222

Shoreline Alterations

Descriptive

Alterations of the South Central Puget Sound Sub-Basin shoreline are omnipresent, with almost complete shoreline armoring throughout (Figs. 139-142). In the eastern component, the total shoreline length of seven contiguous PU have nearly total armoring, with associated tidal barriers and roads, nearshore fill and overwater structures, especially around the industrialized deltas (Fig. 139). Nearshore roads sporadically compound the armoring in all the sub-basin components and can reach high proportions of PU in South Kitsap and Vashon Island. Outside the eastern component, nearshore fill, overwater structures, and marinas are relatively isolated except in concentrated population areas such as around Gig Harbor (SPU 4030–4033) and Sinclair Inlet/Bremerton (SPU 4043–4046).

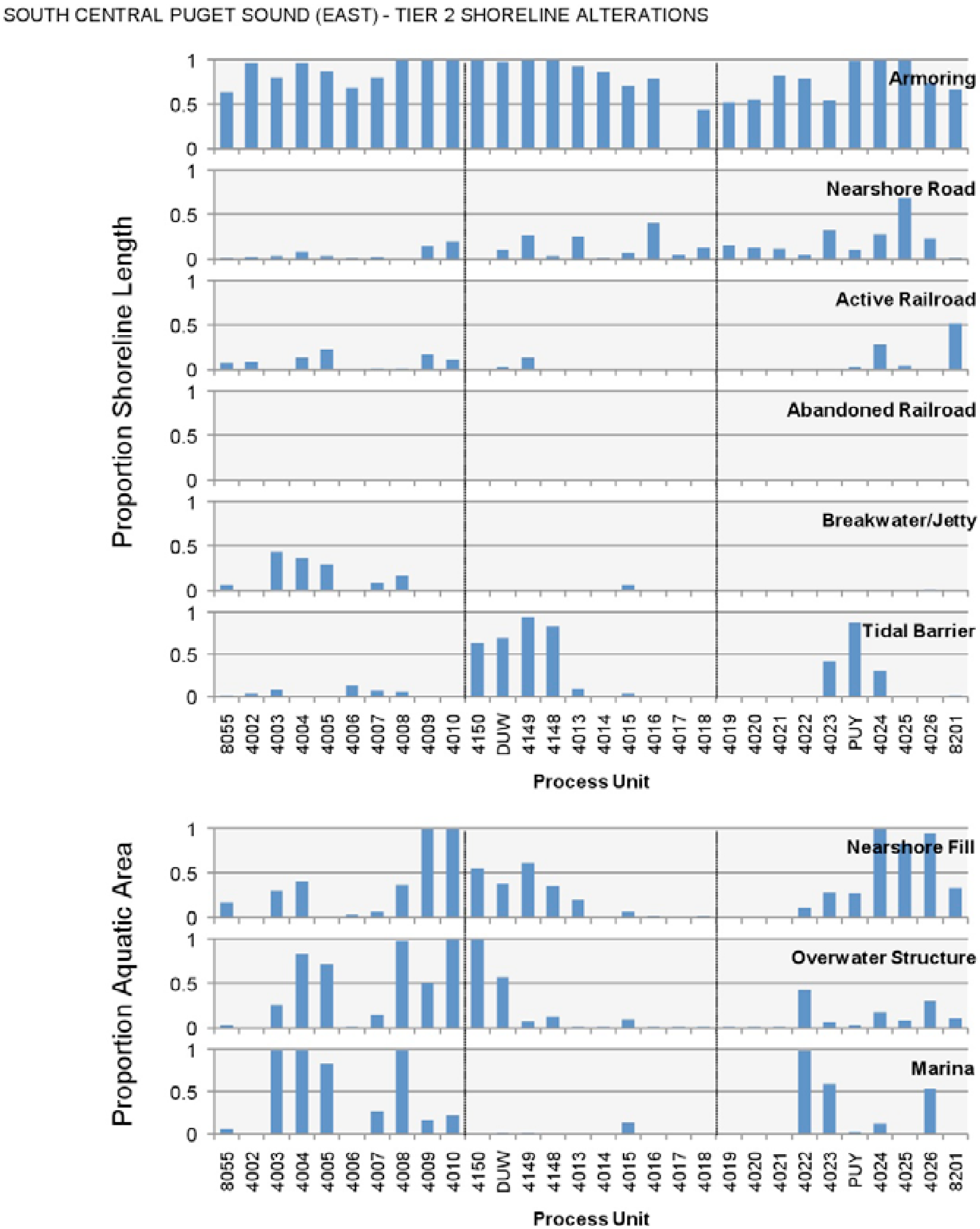


Figure 139. Shoreline alterations along sequential process units (PU) in the eastern component of the South Central Puget Sound Sub-Basin.

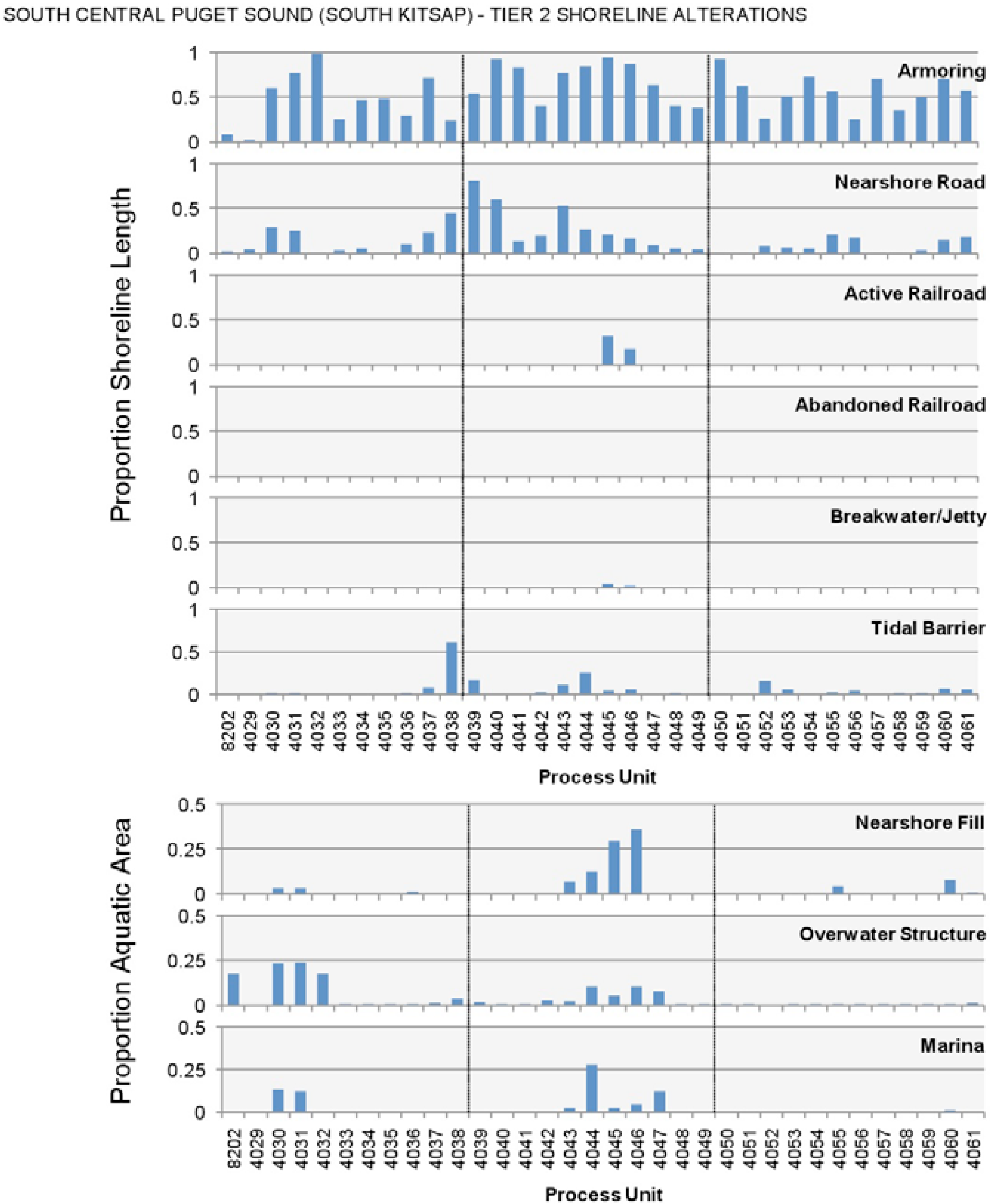


Figure 140. Shoreline alterations along sequential process units (PU) in the South Kitsap component of the South Central Puget Sound Sub-Basin.

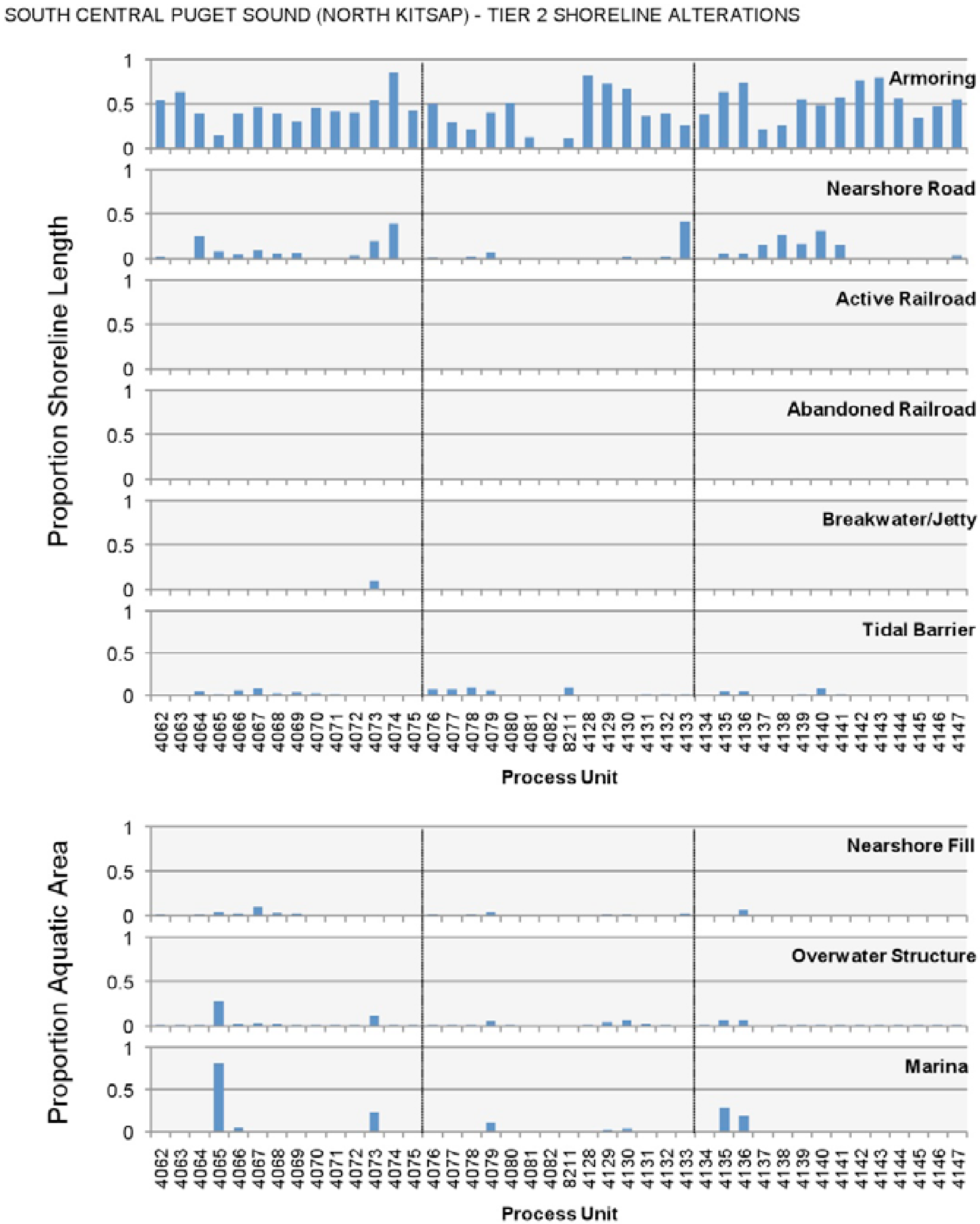


Figure 141. Shoreline alterations along sequential process units (PU) in the North Kitsap component of the South Central Puget Sound Sub-Basin.

SOUTH CENTRAL PUGET SOUND (VASHON ISLAND) - TIER 2 SHORELINE ALTERATIONS

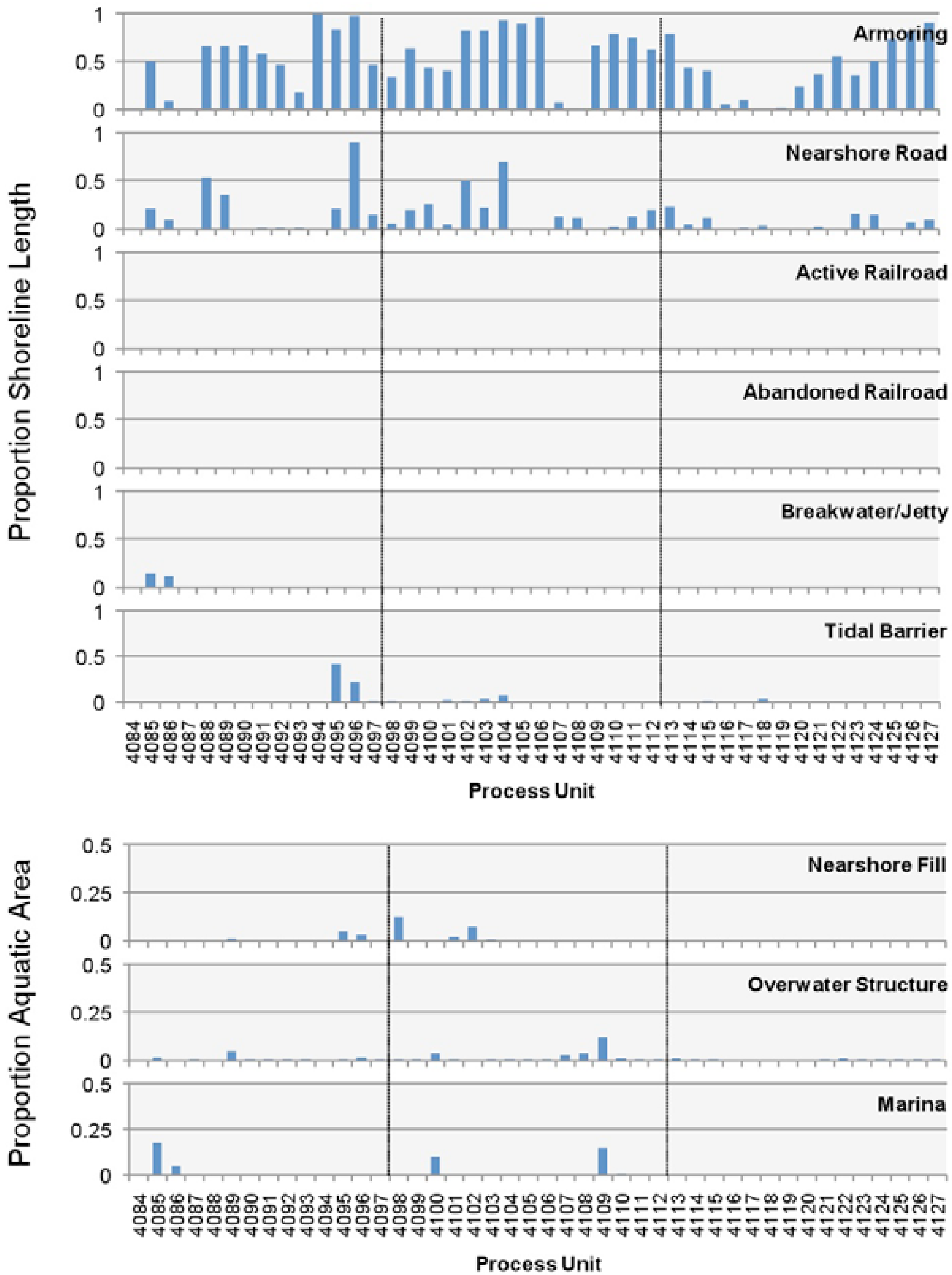


Figure 142. Shoreline alterations along sequential process units (PU) in the Vashon Island component of the South Central Puget Sound Sub-Basin.

Multivariate Analysis

The prevalent group of commonly associated alterations in the sub-region includes estuarine mixing wetland loss, armoring, and nearshore roads (group d; 86 PU) (Fig. 143). The other group that occurs sporadically in all components is characterized by gain in estuarine mixing wetlands, armoring and nearshore road (group i; 29 PU). The DPU are associated with a group (group m; 14 PU) that is distinguished by nearshore fill, overwater structures, and marinas.

Adjacent Upland and Watershed Change

Descriptive

The South Central Puget Sound Sub-Basin has pervasive development, not only on the shoreline, but also throughout both the adjacent upland as well as the watershed area in all sub-basin components (Figs. 144-147). This is particularly so in the eastern component, where both Seattle and Tacoma are located and the natural land cover has been converted to moderate to high intensity development (Fig. 144), but also clearly evident in the South Kitsap component around the cities of Gig Harbor and Bremerton (Fig. 145). The proportion of open space and low intensity development is comparatively greater in the North Kitsap and Vashon components, making up roughly one-third to one-half of the land cover, with the remaining area mostly forested (Figs. 146-147).

Multivariate Analysis

Analysis of adjacent upland change shows groups h and j to be the most numerically common within the sub-basin (64 and 47 PU, respectively) (Fig. 148). Both groups are characterized by fairly low intensity development and moderate impervious surface coverage. Groups a, e, and f all contain process units with considerable levels of high intensity development and high impervious surface coverage.

Analysis of watershed area change shows group d to be numerically common (100 PU) with process units concentrated on the western half of the sub-basin (Fig. 149). It is distinguished by moderate levels of development, while group h (33 PU) represents PU containing high-intensity developed areas. This group is present along the east shoreline around Seattle and Tacoma, and Dyes Inlet around Bremerton. Group e (6 PU, including the deltas) shows similar contributions of the high development variables, but is distinguished by the presence of dams.

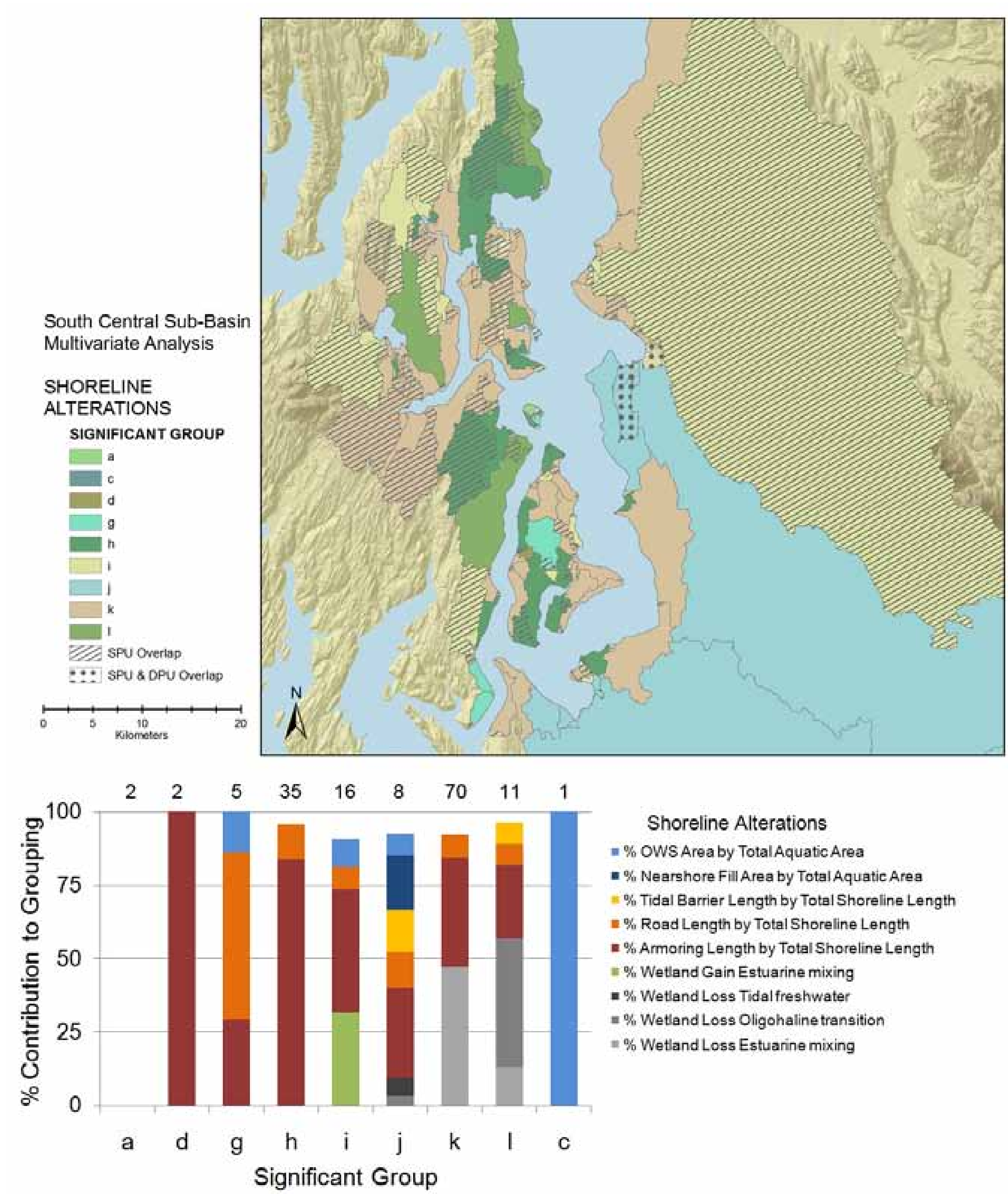


Figure 143. (Top) Process unit (PU) groups with significant similar shoreline alterations and stressors in South Central Sub-Basin based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for shoreline alterations in the PU. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group. Groups composed of one PU show the descriptive composition of the PU. Group 'a' does not contain any shoreline alterations.

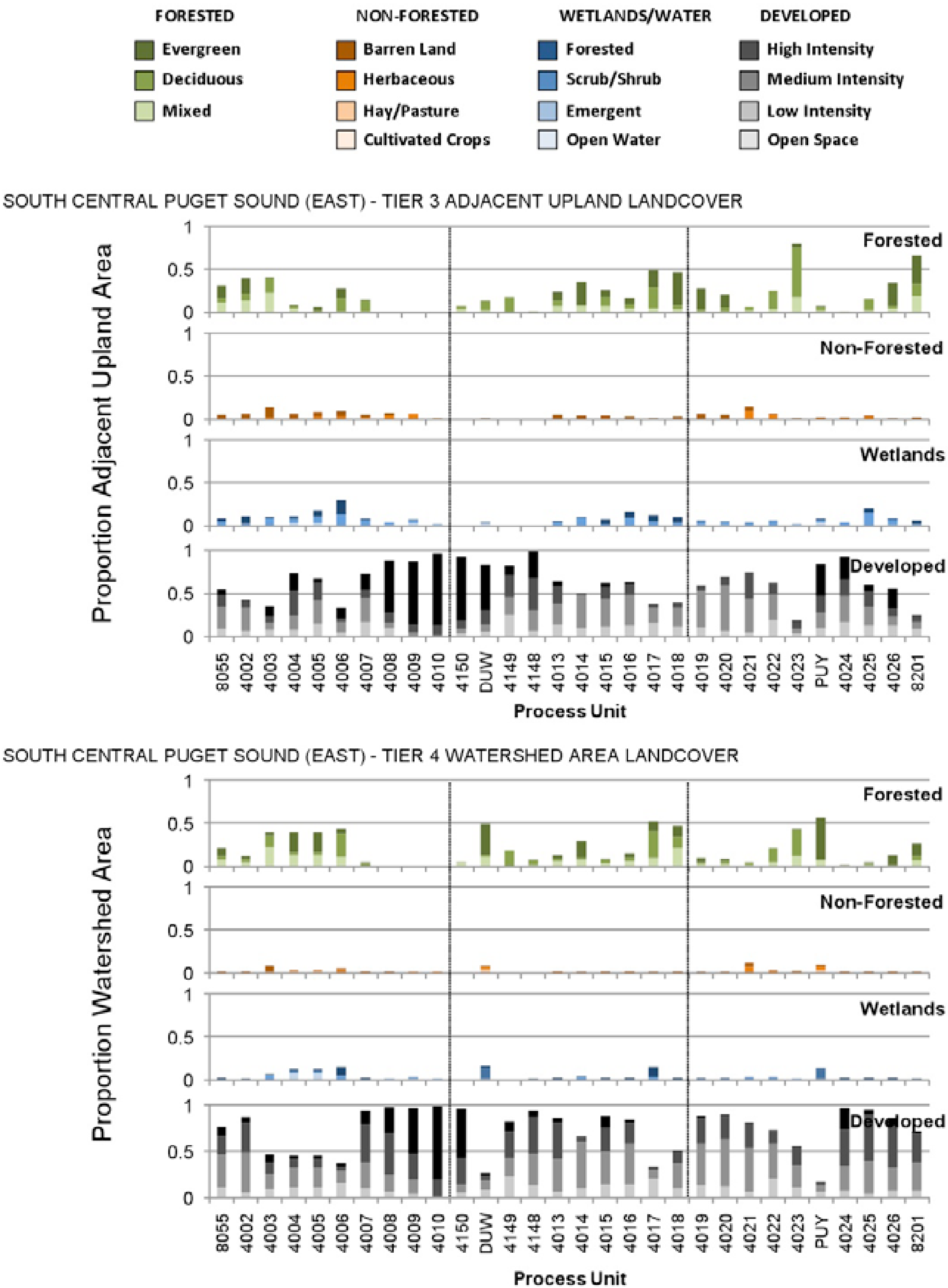


Figure 144. Land cover/land and stressors in adjacent upland (Tier 3, top) and watershed areas (Tier 4, bottom) in the eastern component of the South Central Puget Sound Sub-Basin.

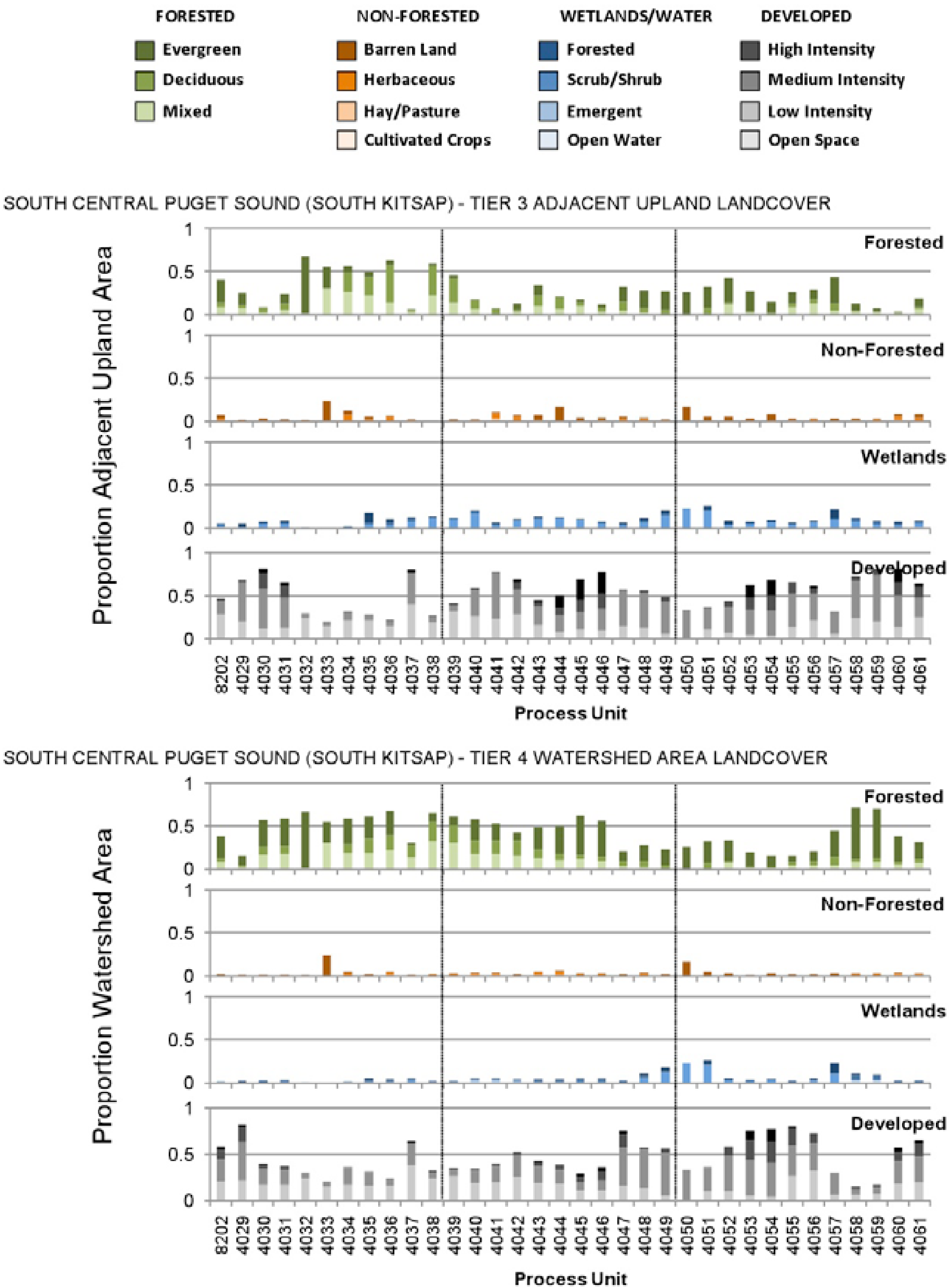


Figure 145. Land cover/land and stressors in adjacent upland (Tier 3, top) and watershed areas (Tier 4, bottom) in the South Kitsap component of the South Central Puget Sound Sub-Basin.

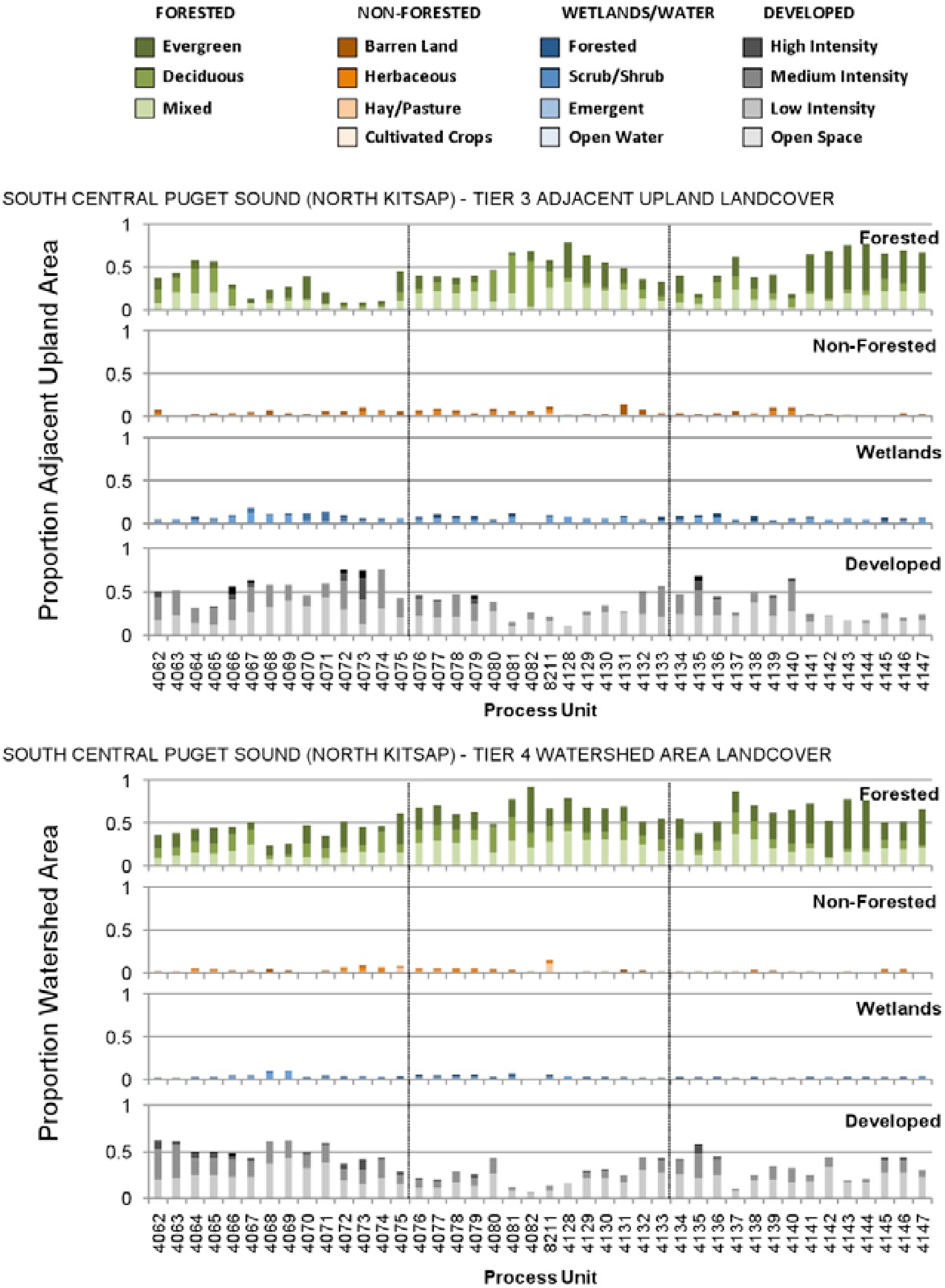


Figure 146. Land cover/land and stressors in adjacent upland (Tier 3, top) and watershed areas (Tier 4, bottom) in the North Kitsap component of the South Central Puget Sound Sub-Basin.

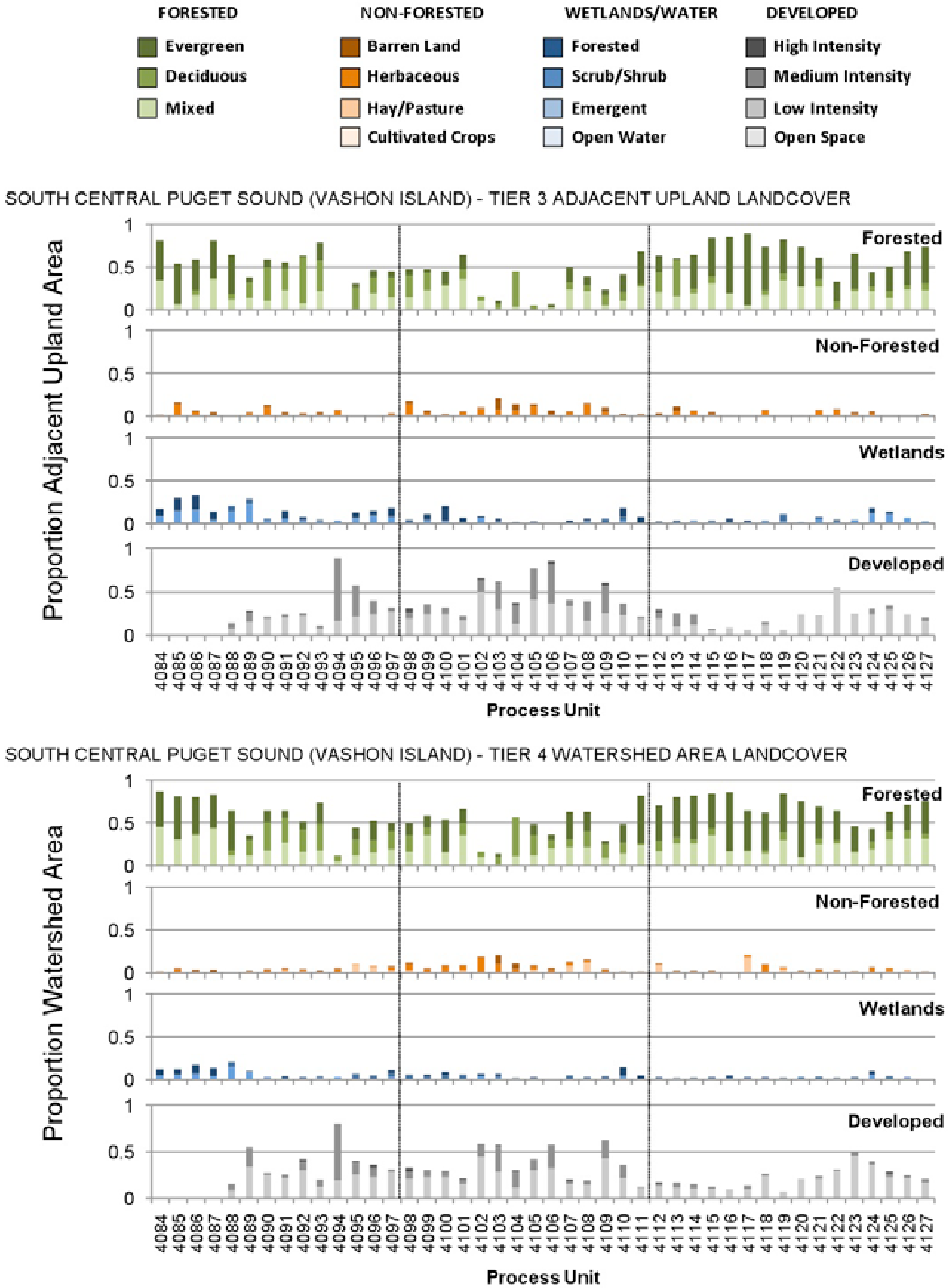
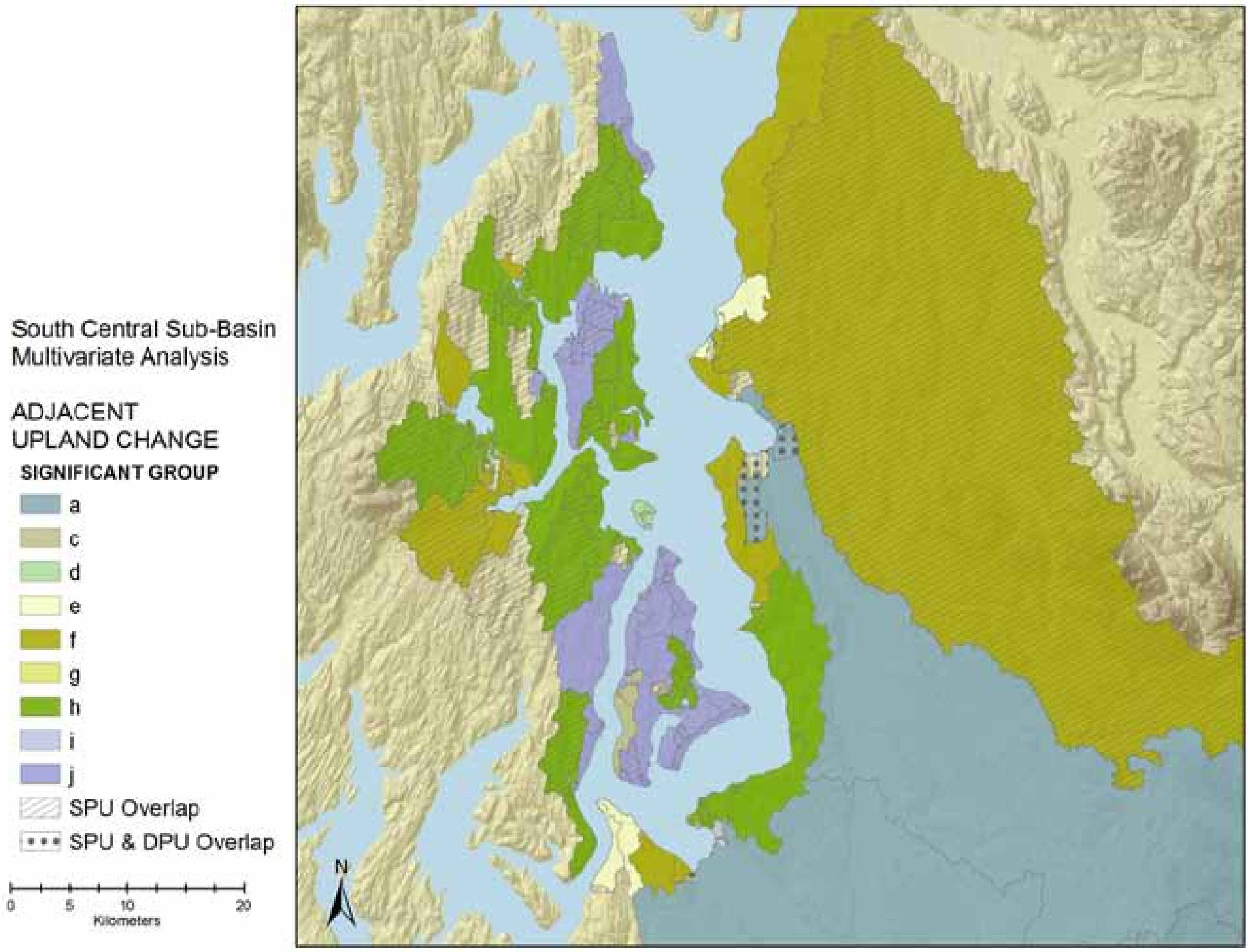


Figure 147. Land cover/land and stressors in adjacent upland (Tier 3, top) and watershed areas (Tier 4, bottom) in the Vashon Island component of the South Central Puget Sound Sub-Basin.



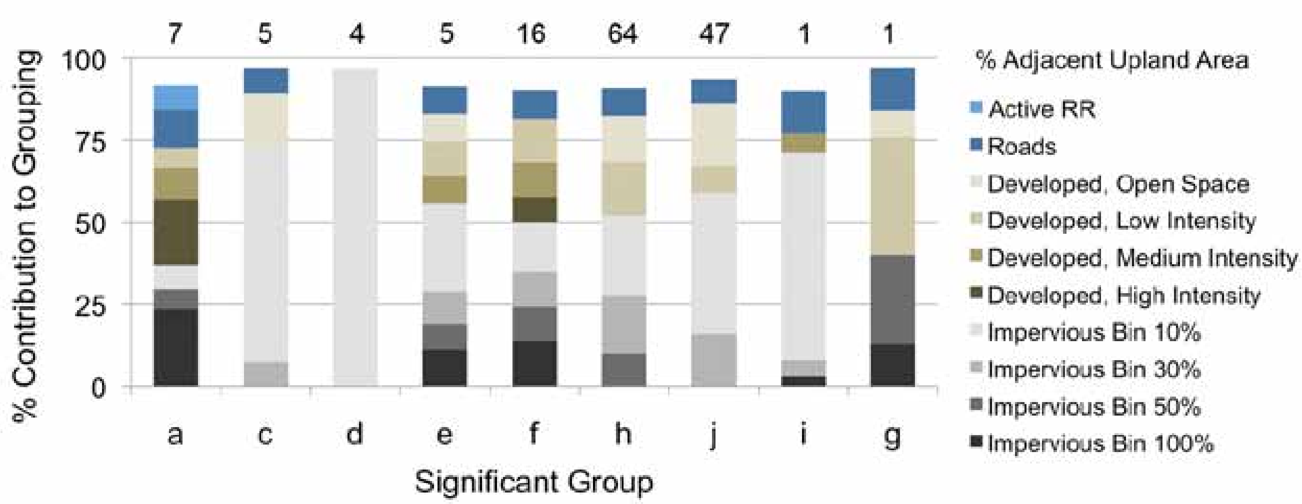


Figure 148. (Top) Distribution of process unit (PU) groups with significantly similar adjacent upland changes in South Central Sub-Basin of Puget Sound based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for adjacent upland change in the PU. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group. Groups composed of one PU show the descriptive composition of the PU.

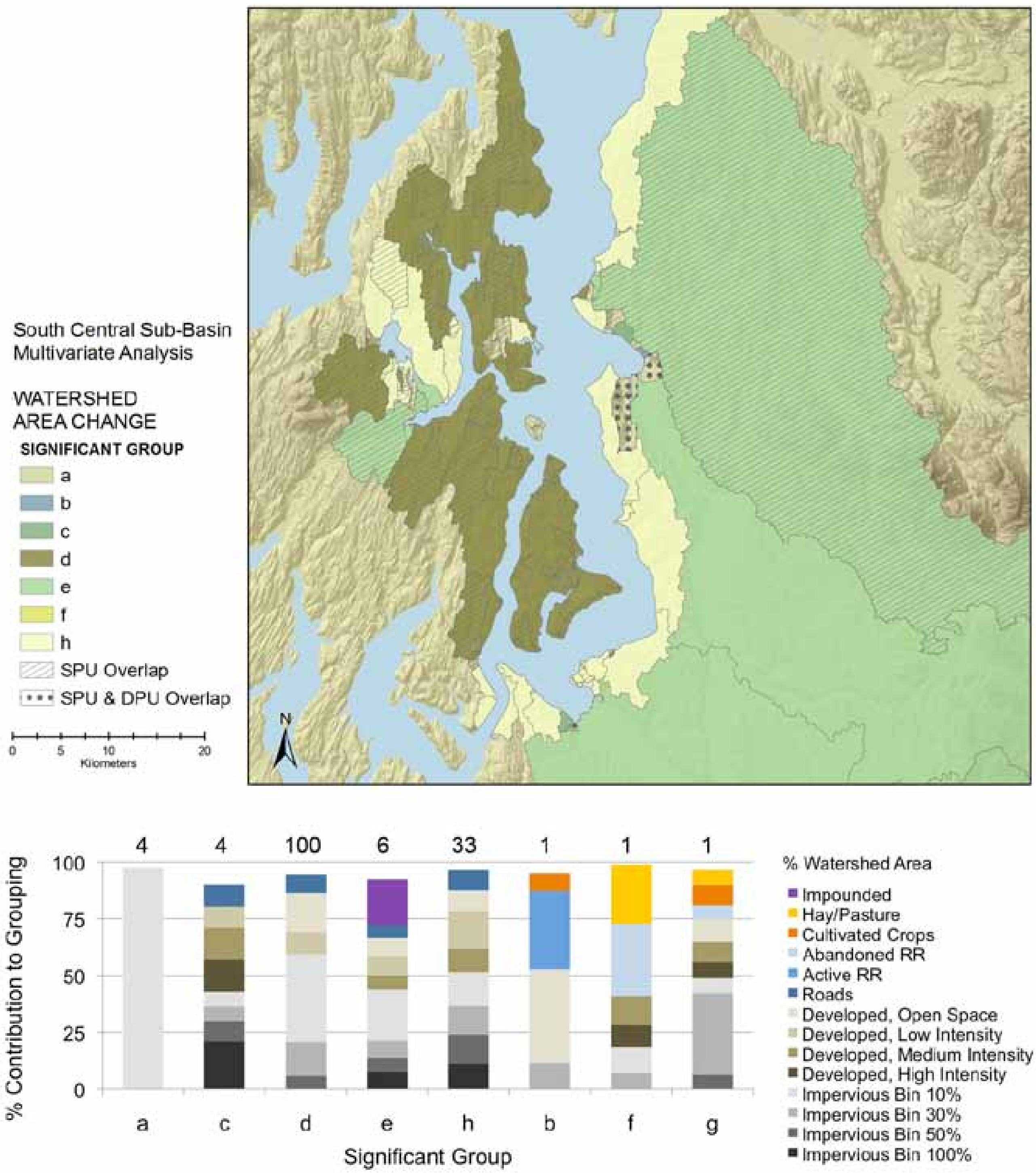


Figure 149. (Top) Distribution of process unit (PU) groups with significantly similar total watershed area changes in South Central Sub-Basin of Puget Sound based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for watershed area change in the PU. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group. Groups composed of one PU show the descriptive composition of the PU.

South Puget Sound Sub-Basin

Shoreform Change and Transition

Descriptive

The most dramatic change in the South Puget Sound Sub-Basin (Fig. 150) is the 73.6 percent decrease in the Nisqually River delta shoreline, and second is a pervasive decline in embayment complexity (Table 4; Fig. 151). However, it is important to note that since this analysis was completed, major restoration has occurred in the Nisqually River delta, reversing many of these changes. At the time of this writing, no information was available to update the PSNERP geodatabase for the delta. Barrier estuaries, barrier lagoons, closed lagoons/marshes, and open coastal inlets have current shorelines that are 30 to 75 percent less than their historical length. Numeric loss of shoreform segments is also high: 12 barrier estuaries (12 percent), 22 barrier lagoons (29 percent), and 50 closed lagoons/marshes (82 percent) have disappeared (Table 5).

Shoreform transitions in the South Puget Sound Sub-Basin substantiate the absolute loss of embayments, not all of which are substituted by artificial shoreforms (Table 18). Eighteen historical barrier estuaries, 26 barrier lagoons and 51 closed lagoons/marshes are no longer identifiable, and 8 of these are identifiable now as artificial. The most prevalent shoreforms, bluff-backed and barrier beaches, have transitioned to artificial in 22 and 10 instances, respectively.

We have partitioned the sub-basin into eight components (see Appendix D, Figs. E.16-E. 23 for PU distributions) in order to examine the contiguous shoreline for concentrations of shoreline length change (Figs. 152-159). In the Nisqually component of the South Puget Sound Sub-Basin, reductions in shoreline length are concentrated in bluff-backed beaches, barrier estuaries, and barrier lagoons north of the Nisqually delta and south of The Narrows (SPU 3001–3006); barrier estuaries are the shoreform most reduced on both shores of the peninsula on the eastern margin of Henderson Inlet (SPU 3012–3025) (Fig. 152).

In addition to the greater than 50 percent reduction in the Deschutes River delta shoreline, the Deschutes component of the South Puget Sound Sub-Basin has lost some bluff-backed beach shoreline in Budd Inlet (SPU 3043–3045), but most of the loss is concentrated in reduced open coastal inlet shorelines around Eld Inlet (SPU 3048–3050, 3054–3055, 3058–3059, 3063) (Fig. 153). Similarly, although some scattered degradation in bluff-backed and barrier beach shoreline lengths is found in the West Inlets component, the most concentrated loss is in open coastal inlet shorelines in southern Totten Inlet (SPU 3082–3085) and Oakland Bay (SPU 3090–3095) (Fig. 154).

The Case Inlet component of the South Puget Sound Sub-Basin has dramatically reduced barrier estuary and open coastal inlet shorelines in three regions, in Pickering Passage (SPU 3112–3120), inner Case Inlet and the western shore of Key Peninsula (SPU 3124–3144), and Pitt Passage (3146–3151) (Fig. 155).

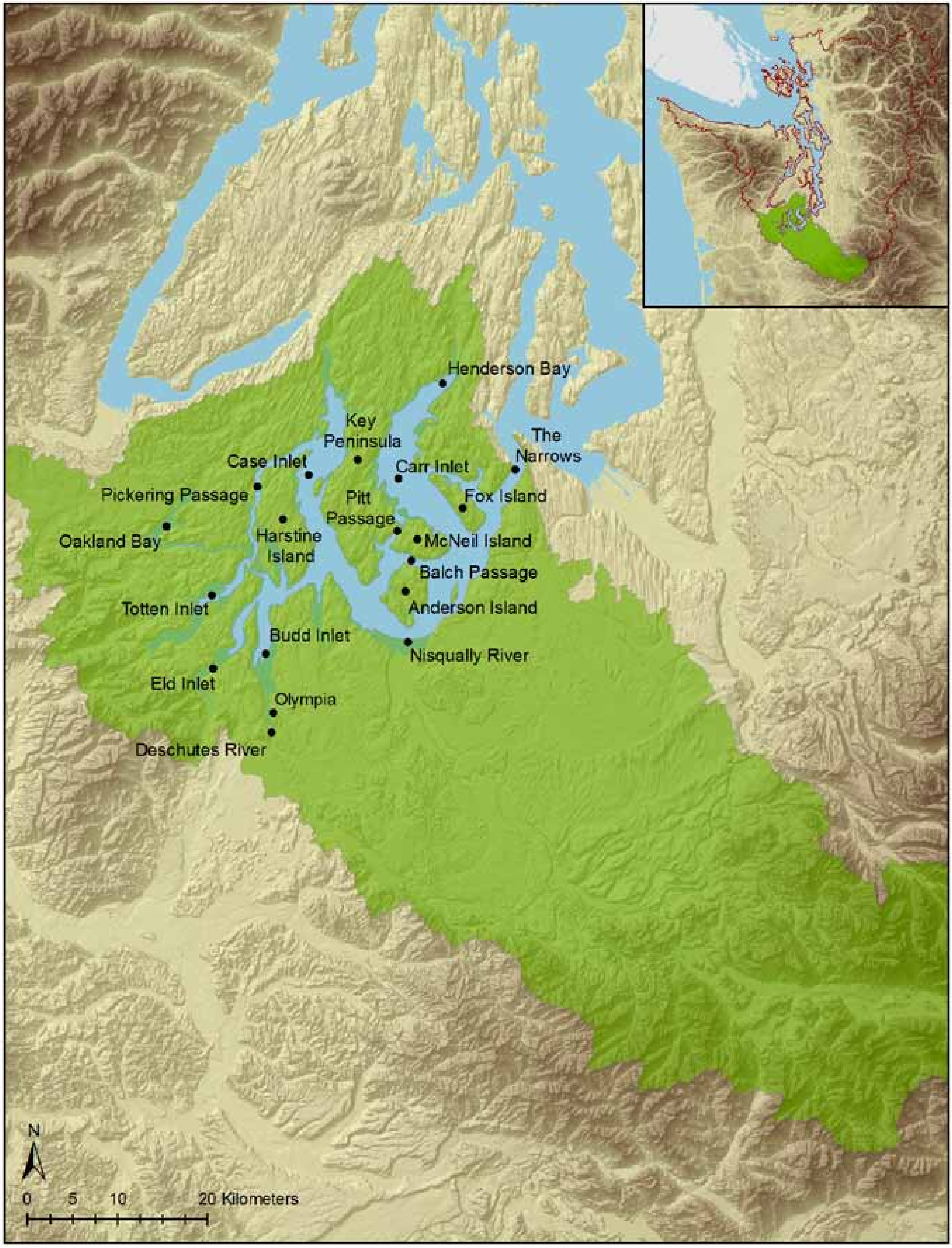


Figure 150. South Puget Sound Sub-Basin.

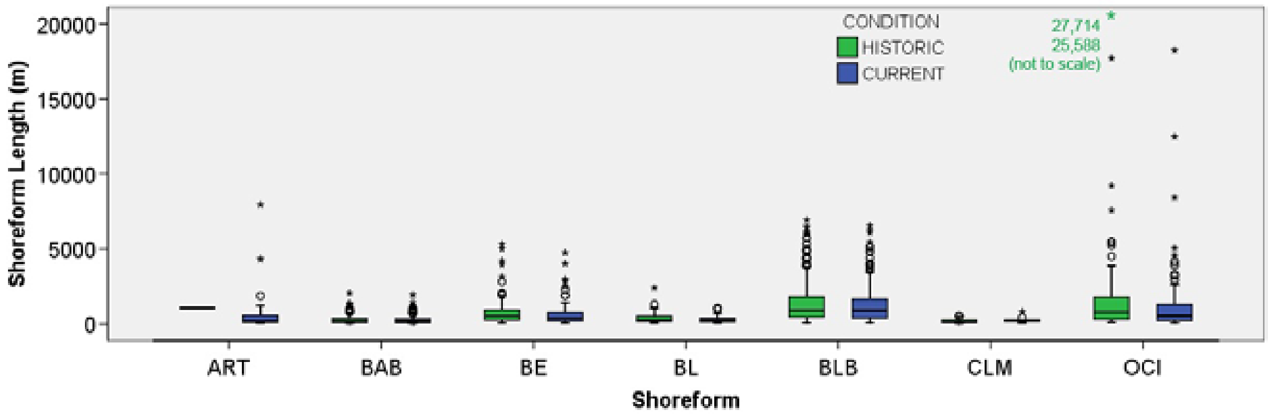


Figure 151. Historical and current contiguous shoreline length of South Puget Sound shoreforms in PU (excludes delta shoreform); see Fig. 20 for shoreform codes. Each box represents the median and upper and lower quartile of the shoreform length data. The 'whiskers' (lines that extend out of the top and bottom of box) represent the highest and lowest values that are not outliers or extreme values. Outliers (values between 1.5 and 3 times the interquartile range) are marked with a circle and extreme cases (values more than 3 times the interquartile range) with an asterisk. Extreme cases not shown to scale are indicated with the shoreform length (m) measurement.

Degradation of shoreline complexity in the Henderson Bay component is uniquely concentrated on open coastal inlet shoreforms on both the western and eastern shorelines of central Carr Inlet (SPU 3160–3165, 3170–3177) (Fig. 156). Harstine Island is the focal point of several concentrations of barrier beach, barrier estuary and open coastal inlet shoreline reductions in the Harstine component (Fig. 157). The southern end of the Island (SPU 3204–3205) and eastern margin (SPU 3217–3221) are particularly reduced.

In the Balch Passage component, the southern shore of Anderson Island (SPU 3258–3260) has notable reduction in barrier lagoon shoreline, and the western and northern shores of McNeil Island (SPU 3232–3237, 3244–3249) have moderately reduced barrier estuary and barrier beach shoreforms (Fig. 158). Most SPU in the Fox Island component are comparable to their historical shoreline length, except for several along the northern portion (SPU 3079–3081) (Fig. 159).

Multivariate Analysis

Reflecting the complexity of the South Puget Sound Sub-Basin, diverse groups of PU had varying historical shoreform composition, although all the dominant (seven) groups, including 391 PU, are variants on bluff-backed and barrier beaches with varying representations of the four types of embayment shoreforms (Fig. 160). Under current conditions, however, these are consolidated into four dominant groups (273 PU) of bluff-backed and barrier beach alone (group f) and mixed with barrier estuary (group e) or open coastal inlet (group h) (Fig. 161). The nine transitions groups represent very complex combinations of changes and a large group (d) is characterized by the loss of beaches and embayments and gain of artificial shoreforms (Fig. 162).

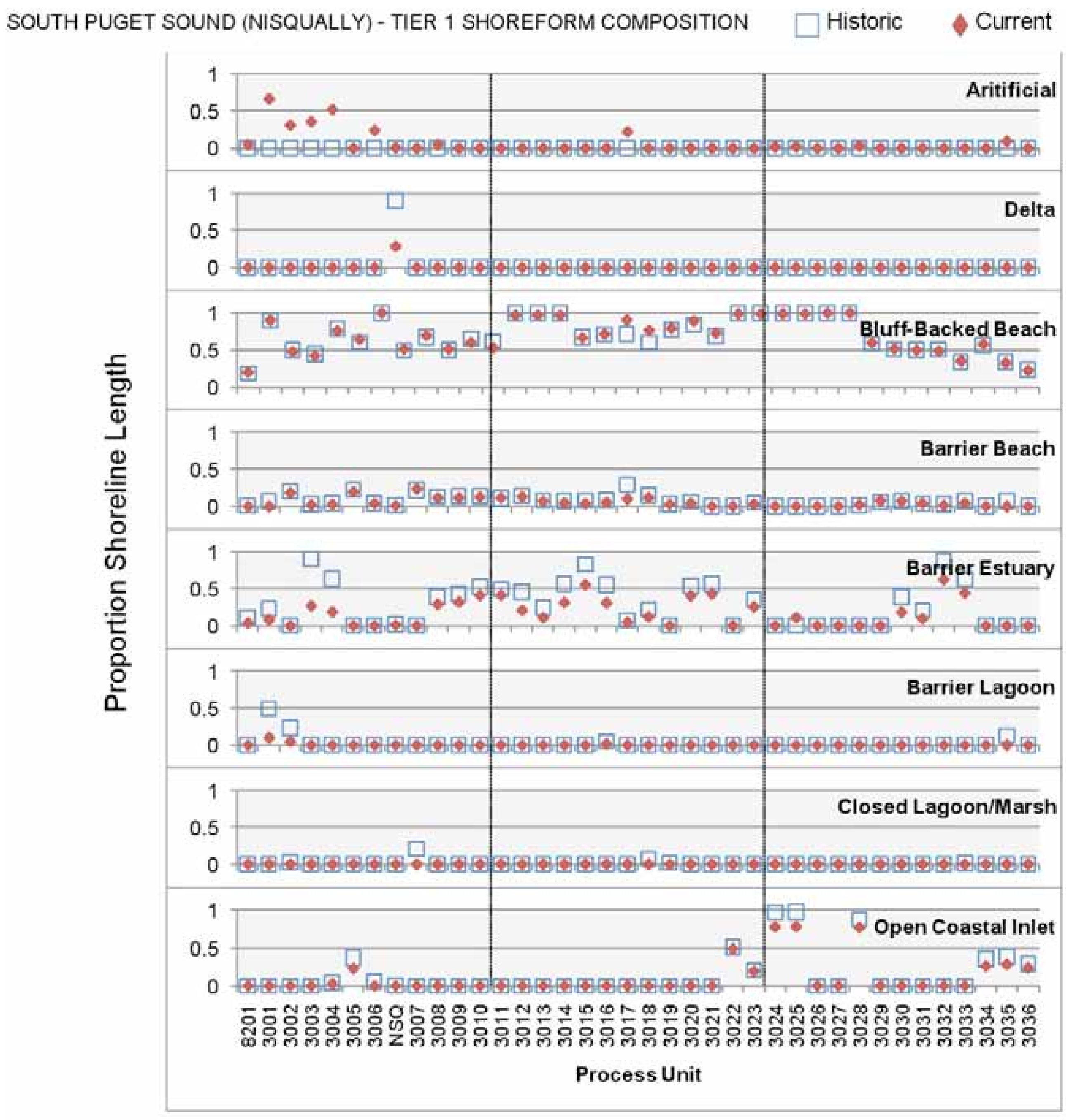


Figure 152. Proportional lengths of historical and current shoreforms along sequential process units (PU) of the Nisqually component of the South Puget Sound Sub-Basin.

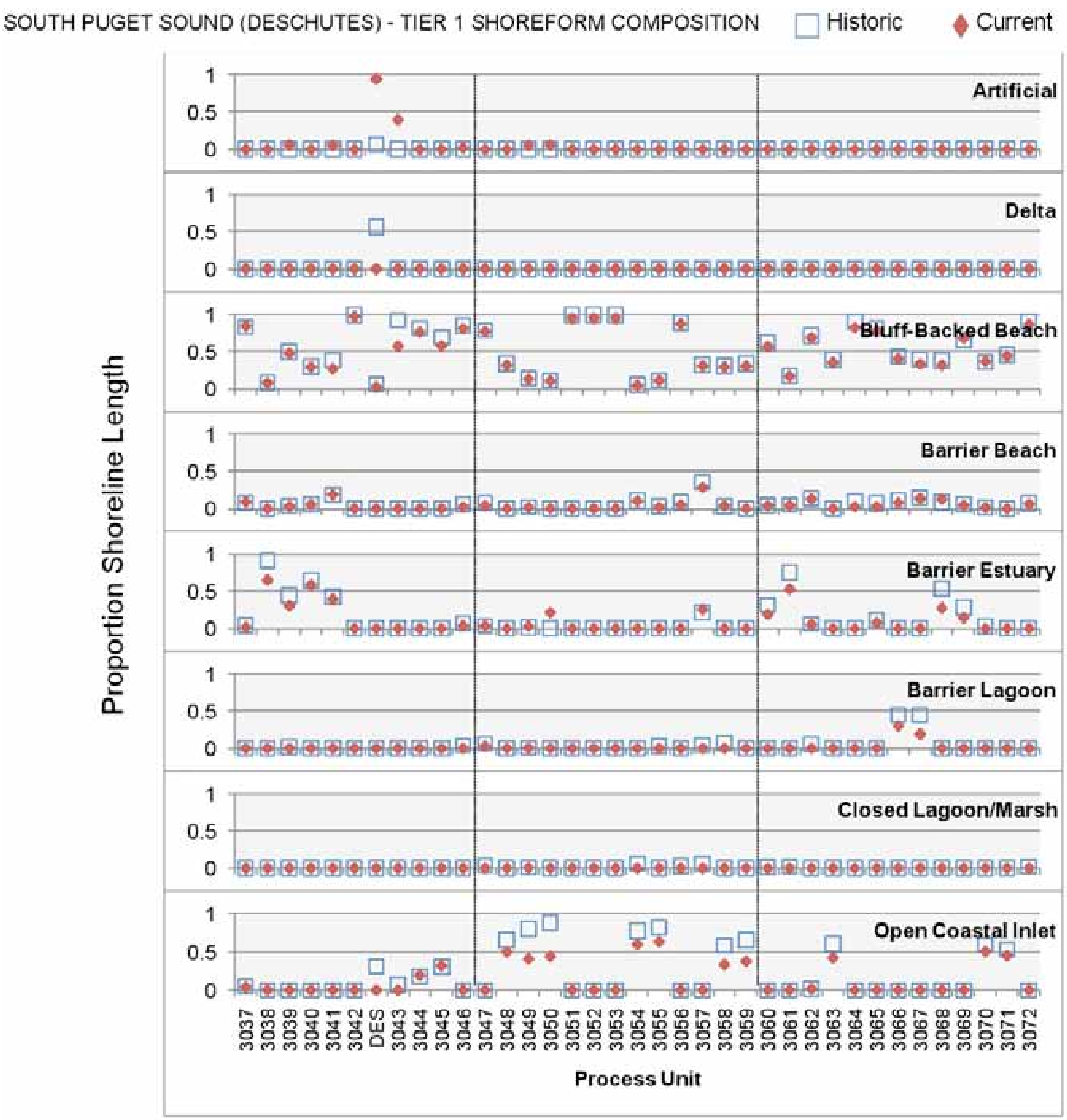


Figure 153. Proportional lengths of historical and current shoreforms along sequential process units (PU) of the Deschutes component of the South Puget Sound Sub-Basin.

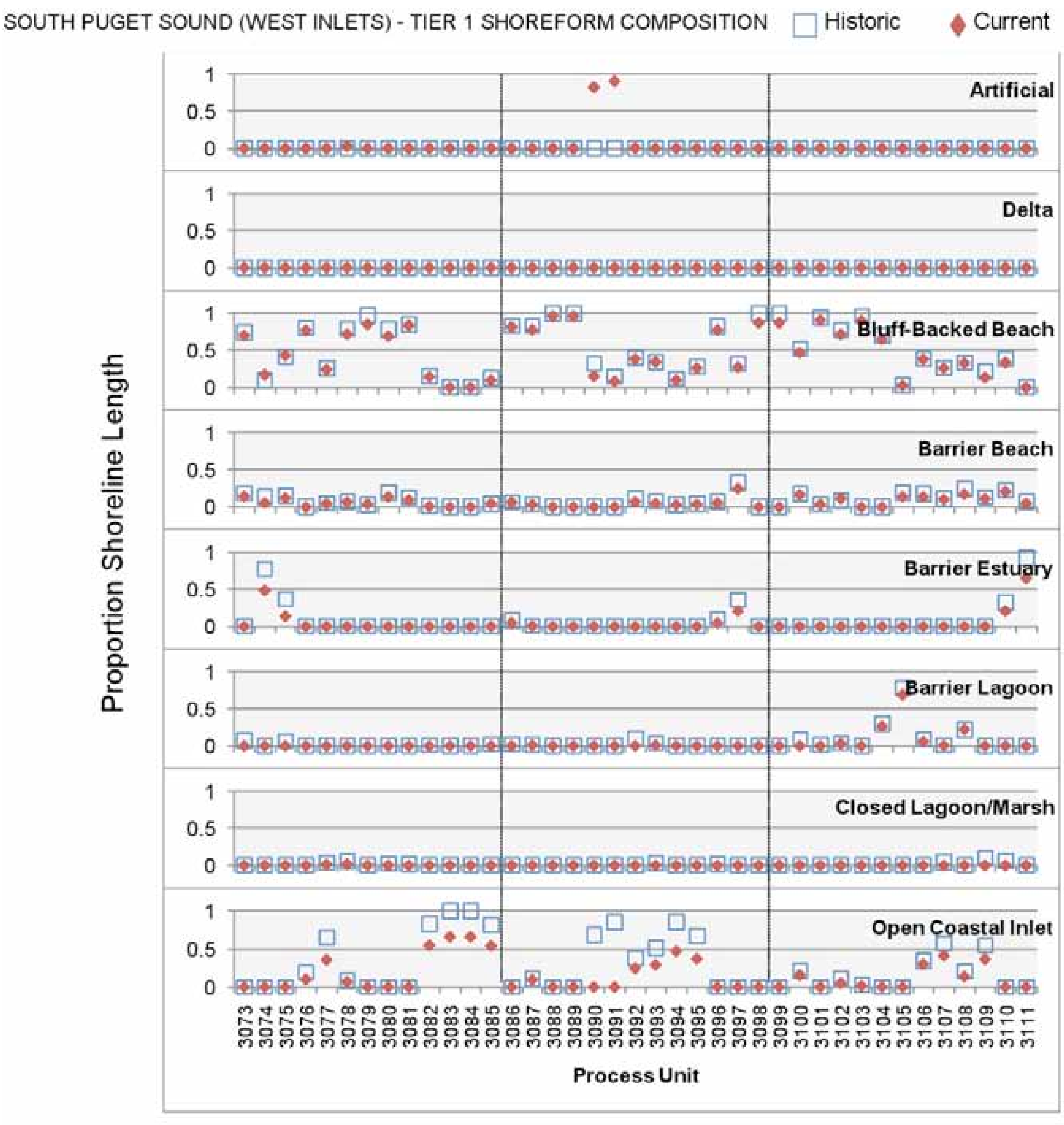


Figure 154. Proportional lengths of historical and current shoreforms along sequential process units (PU) of West Inlets component of the South Puget Sound Sub-Basin.

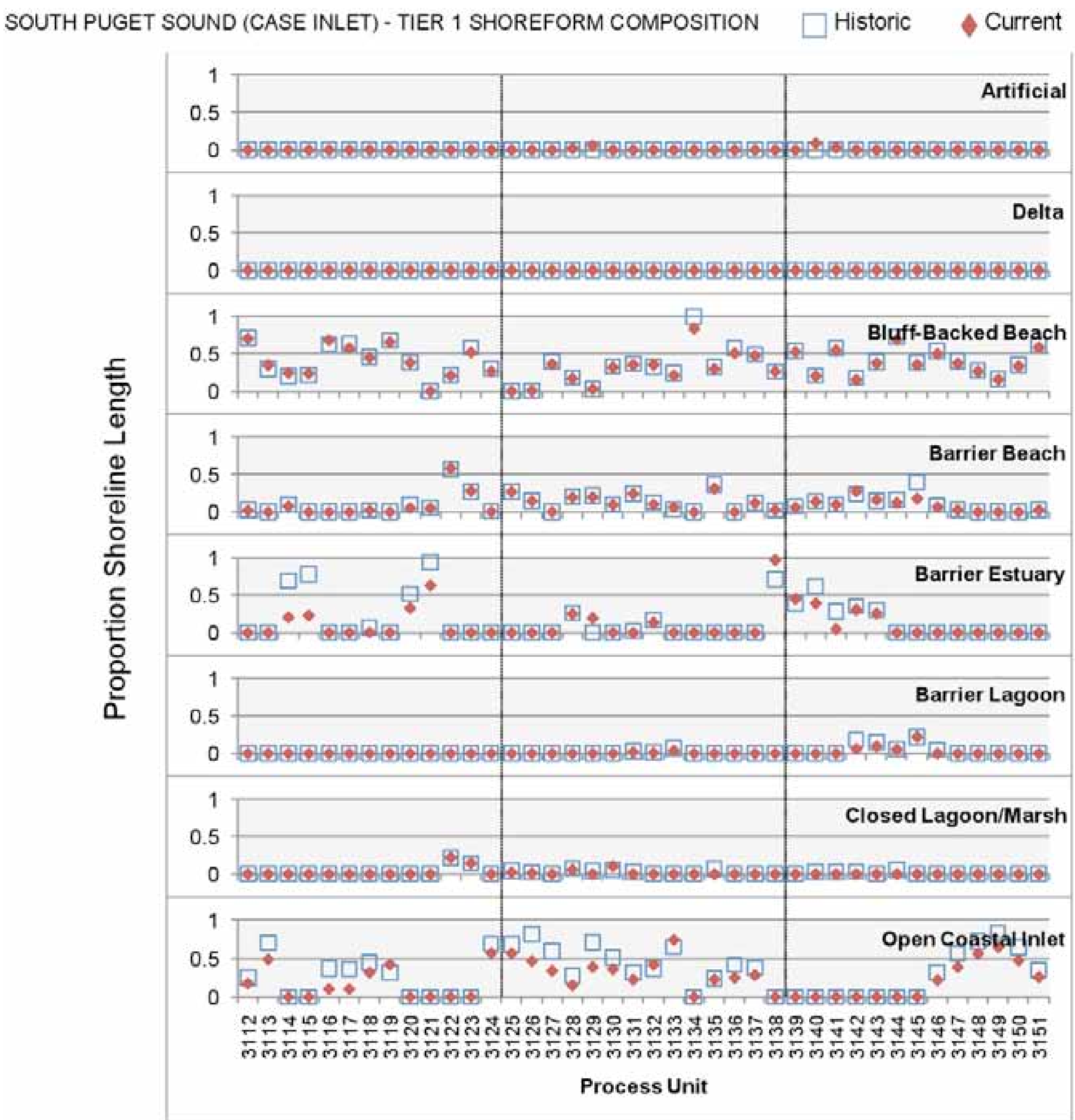


Figure 155. Proportional lengths of historical and current shoreforms along sequential process units (PU) of the Case Inlet component of the South Puget Sound Sub-Basin.

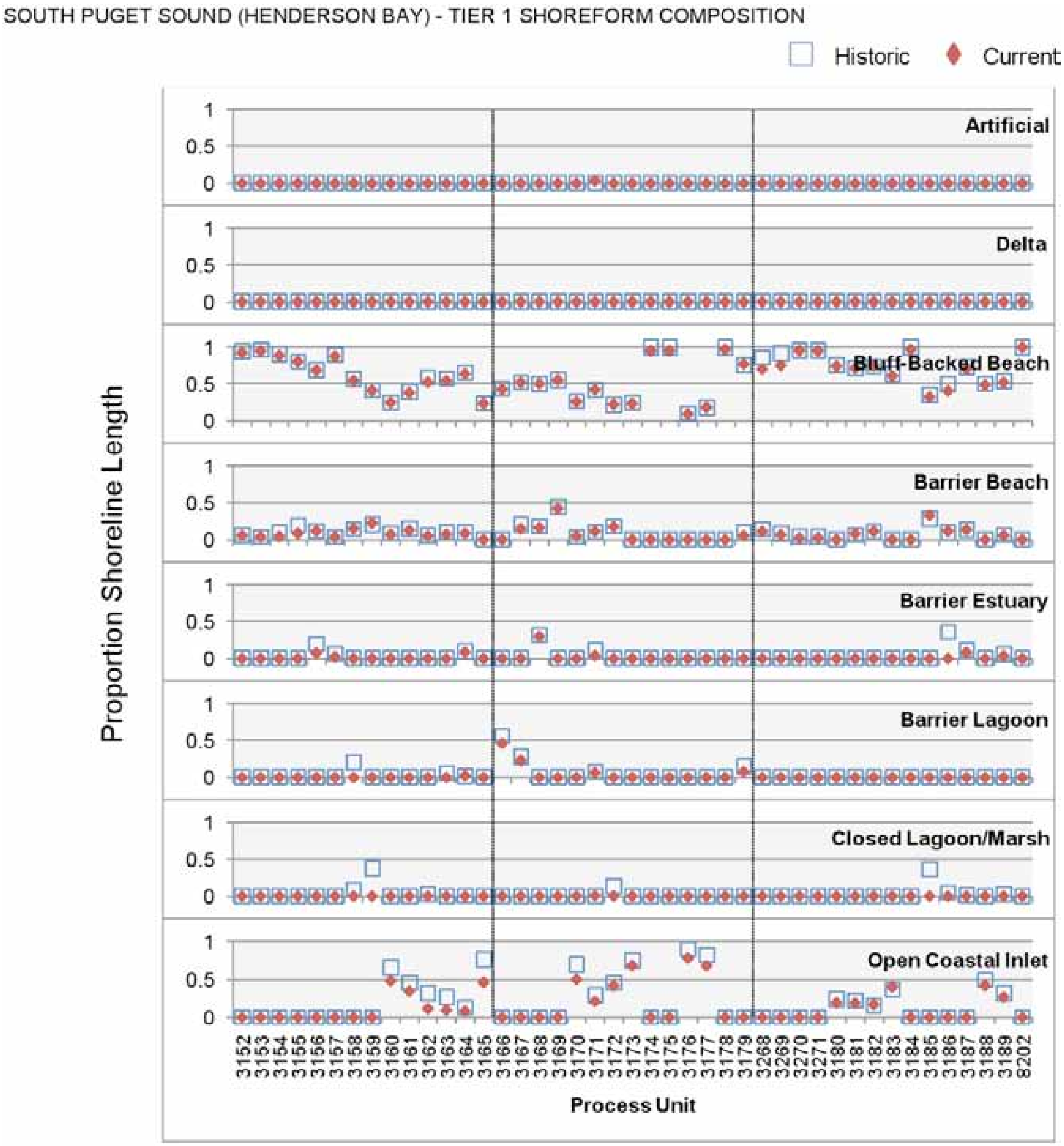


Figure 156. Proportional lengths of historical and current shoreforms along sequential process units (PU) of the Henderson Bay component of the South Puget Sound Sub-Basin.

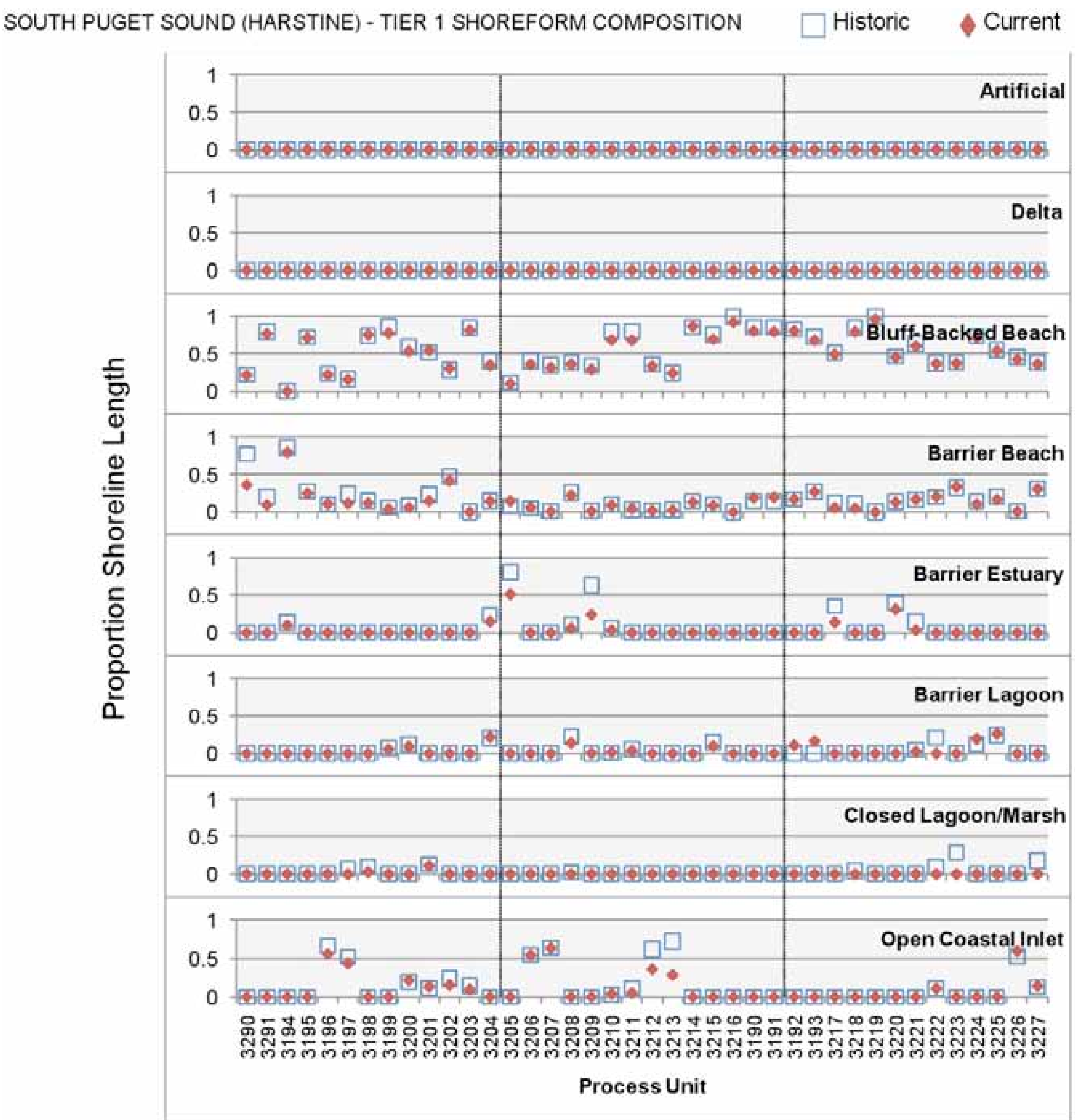


Figure 157. Proportional lengths of historical and current shoreforms along sequential process units (PU) of the Harstine component of the South Puget Sound Sub-Basin.

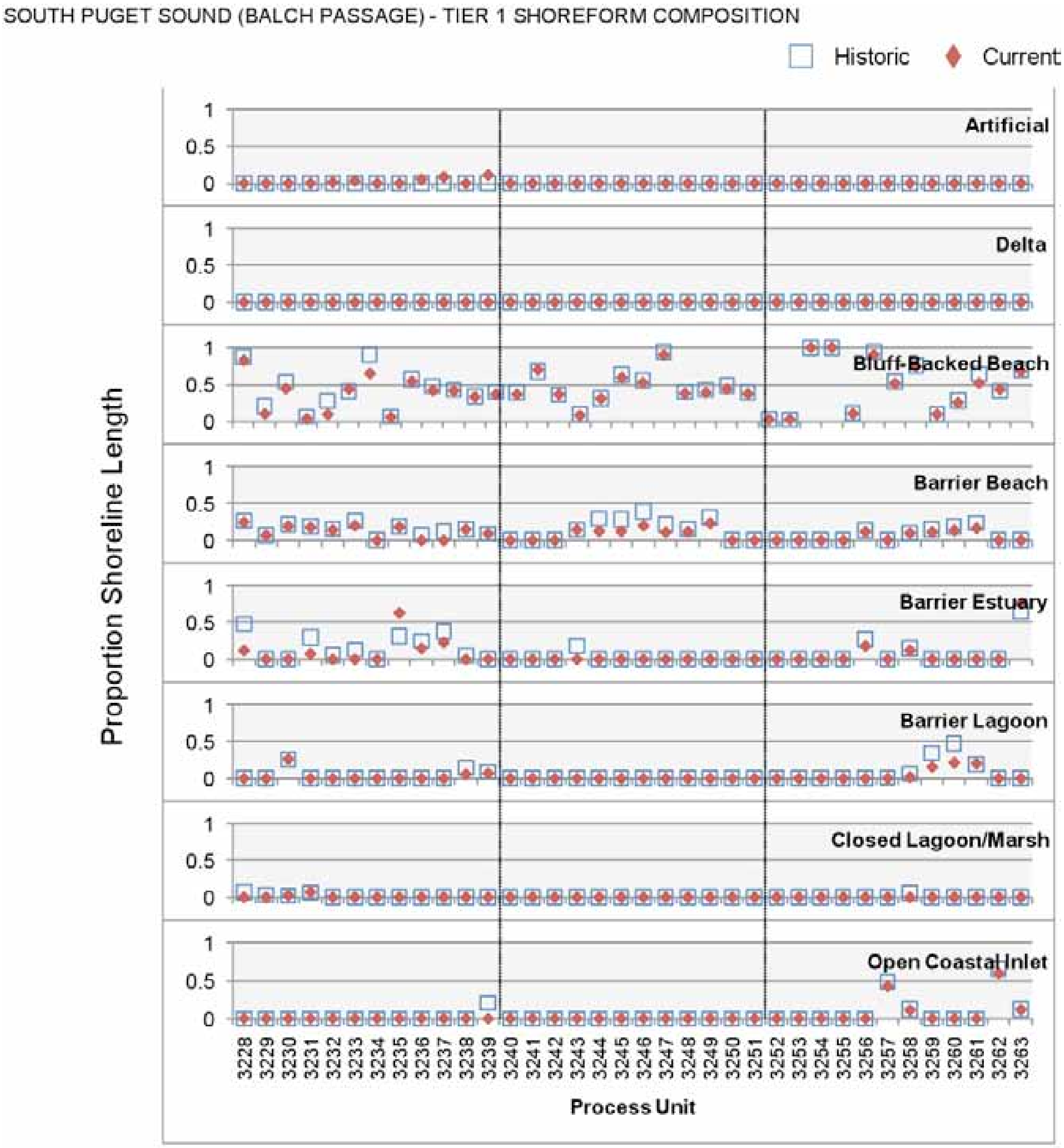


Figure 158. Proportional lengths of historical and current shoreforms along sequential process units (PU) of the Balch Passage component of the South Puget Sound Sub-Basin.

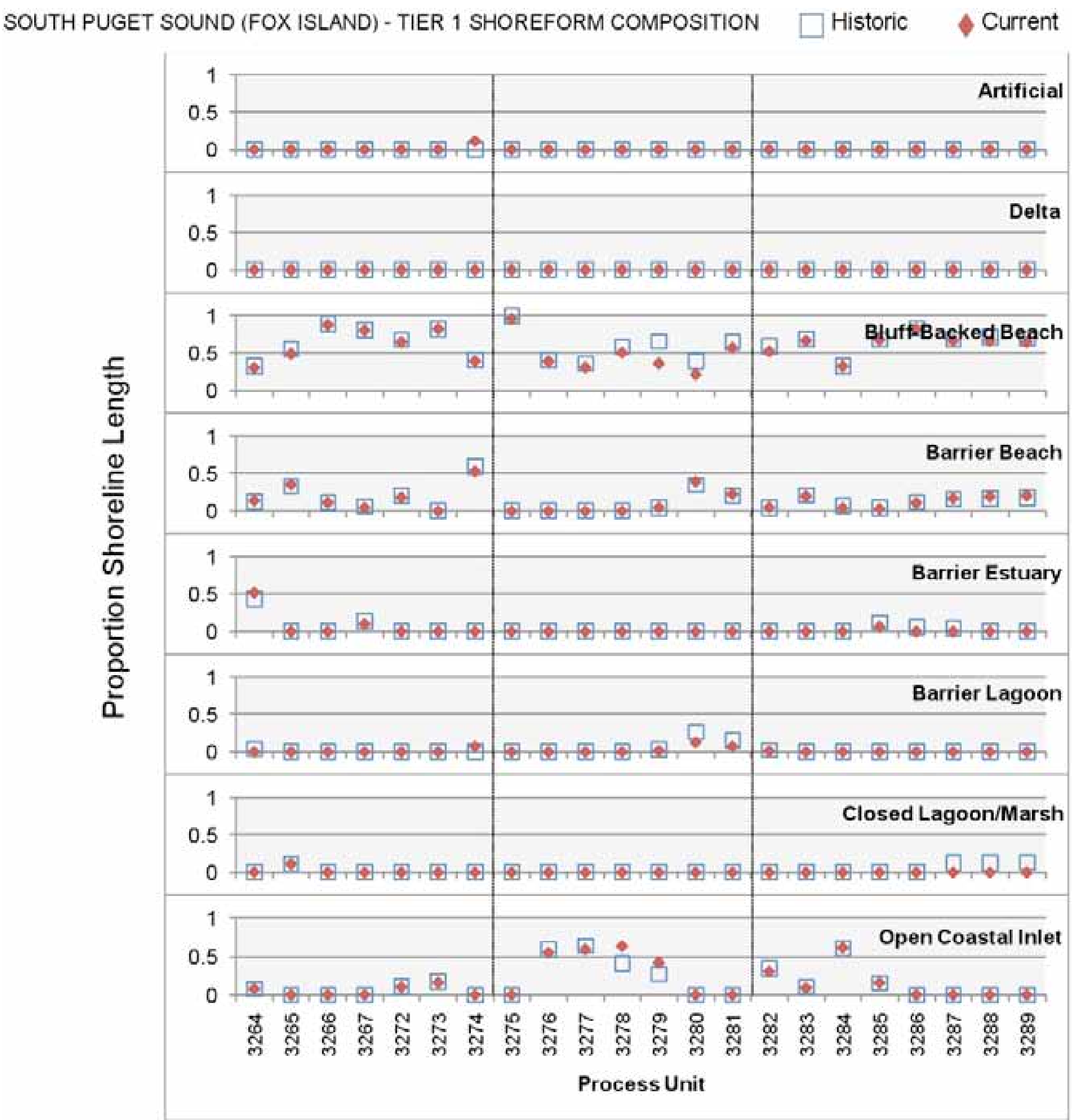


Figure 159. Proportional lengths of historical and current shoreforms along sequential process units (PU) of the Fox Island component of the South Puget Sound Sub-Basin.

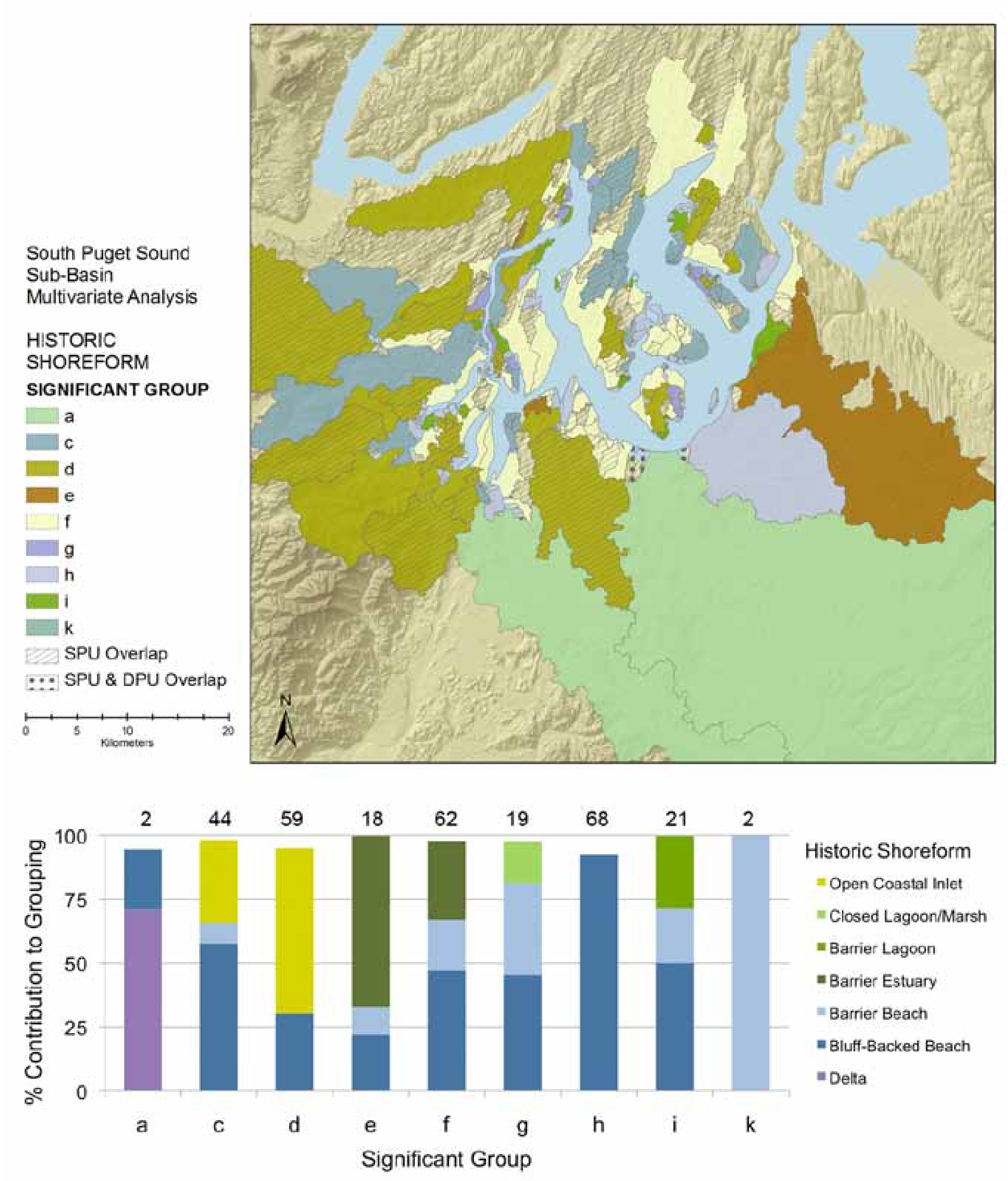


Figure 160. (Top) Distribution of process unit (PU) groups with significantly similar historical shoreform composition in South Puget Sound Sub-Basin of Puget Sound based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for historical shoreform composition in the PU. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group.

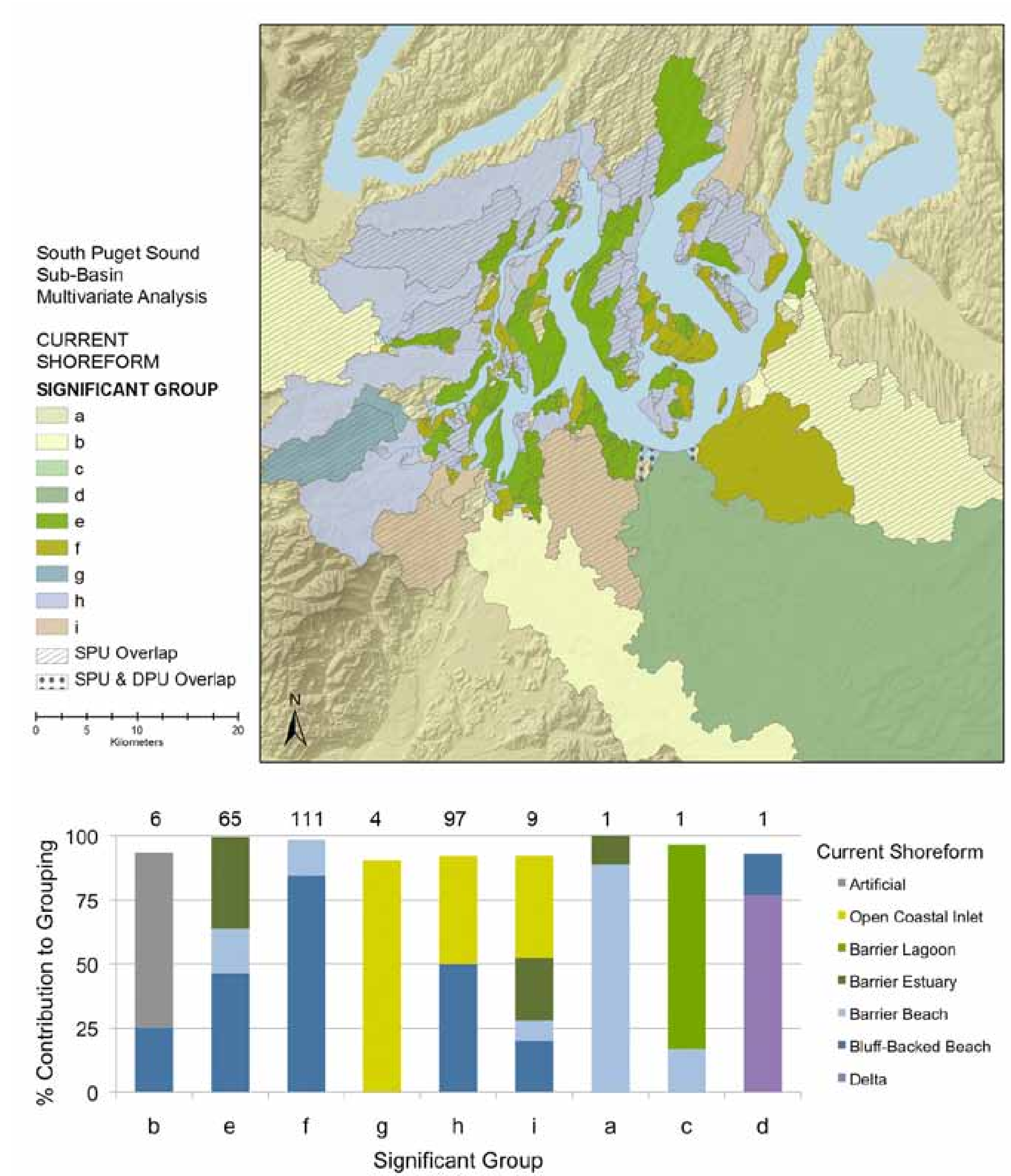


Figure 161. (Top) Distribution of process unit (PU) groups with significantly similar current shoreform composition in South Puget Sound Sub-Basin based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for current shoreform composition in the PU. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group. Groups composed of one PU show the descriptive composition of the PU.

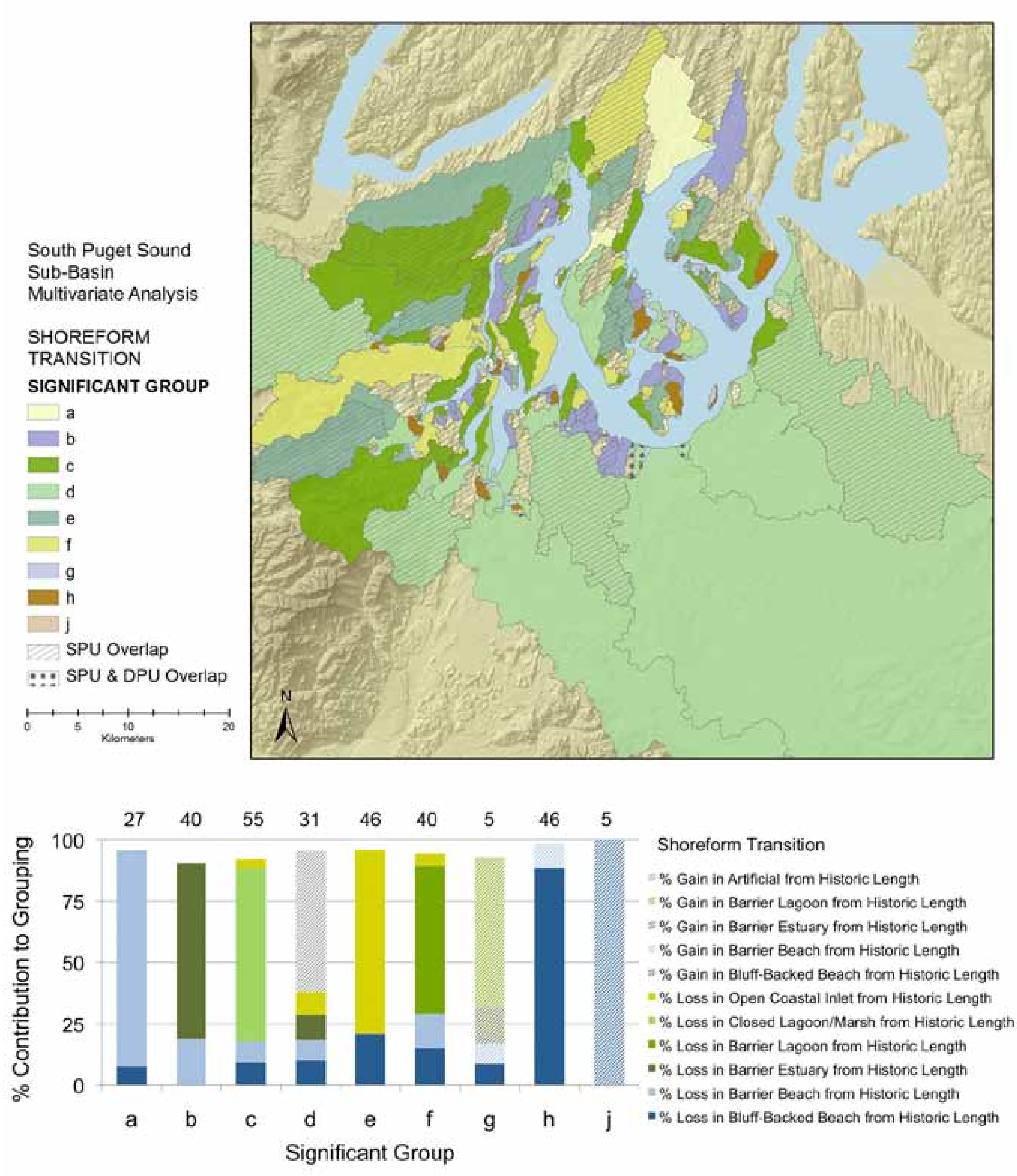


Figure 162. (Top) Distribution of process unit (PU) groups with significantly similar shoreform transitions in South Puget Sound Sub-Basin based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for shoreform transitions in the PU. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group.

Table 18.Shoreform transitions (Tier 1) of South Puget Sound Sub-Basin. Highlighted numbers (diagonal line) represent the number that did not transition and are derived as the difference between the historical shoreform count and the total number of transitions.

Shoreform Transition / *Historic*	*Current* ------------------------> Bluff-Backed Beach	Barrier Beach	Delta	Barrier Estuary	Barrier Lagoon	Closed Lagoon/ Marsh	Open Coastal Inlet	Artificial	Shoreform Absent	Total Transitions
Bluff-Backed Beach	302							22		22
Barrier Beach		296						10		10
Delta			1					1		1
Barrier Estuary				77				5	18	23
Barrier Lagoon					45			3	26	30
Closed Lagoon/Marsh						10			51	51
Open Coastal Inlet				4			70	16		20
Artificial								1		0
Shoreform Absent					3			3		6
Total Transitions	3	0	0	4	3	1	0	60	95	166

Shoreline Alterations

Descriptive

Shorelines in all components of the South Puget Sound Sub-Basin are almost contiguously armored, often extensively (75–100 percent of PU length), except for the Harstine Island and Balch Passage regions (Fig. 163-170). Other alterations are more intermittent along the shoreline except for the active railroad and nearshore fill (approximately 50 percent of PU shoreline length) in the reach north of the Nisqually River delta (Fig. 163).

Multivariate Analysis

Three groups represent the common associations of shoreline alterations in the South Puget Sound Sub-Basin, all associated with variations on armoring and nearshore roads: group af (107 PU) distinguished by additional loss of estuarine mixing wetlands; group ad (68 PU) with just armoring and nearshore roads; and group ac (62 PU) distinguished by additional gain of estuarine mixing wetlands (Fig. 171). Group ae (15 PU) occurs in the most densely developed shoreline and is distinguished by nearshore fill, overwater structures, and marinas.

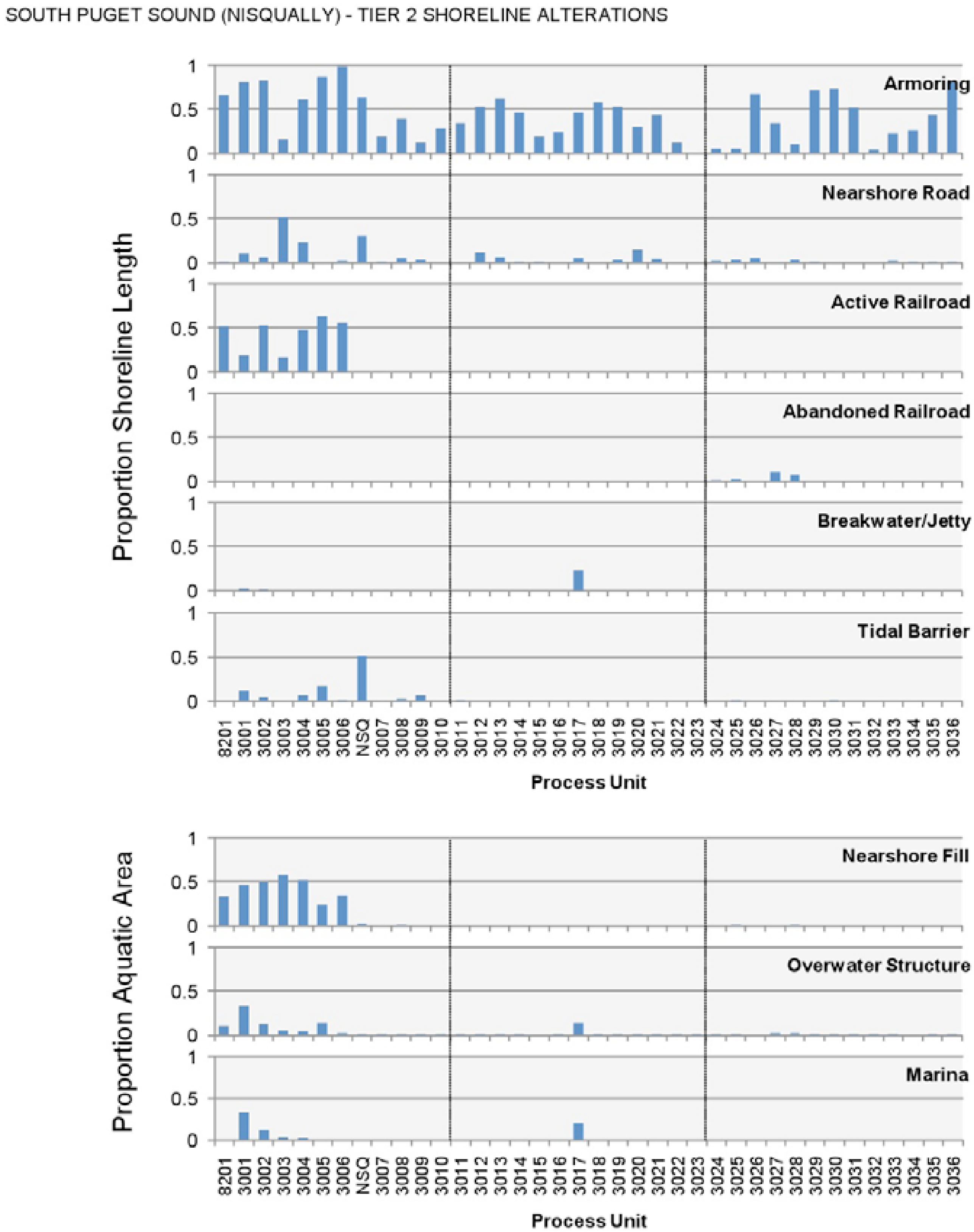


Figure 163. Shoreline alterations along sequential process units (PU) in the Nisqually component of the South Puget Sound Sub-Basin.

SOUTH PUGET SOUND (DESCHUTES) - TIER 2 SHORELINE ALTERATIONS

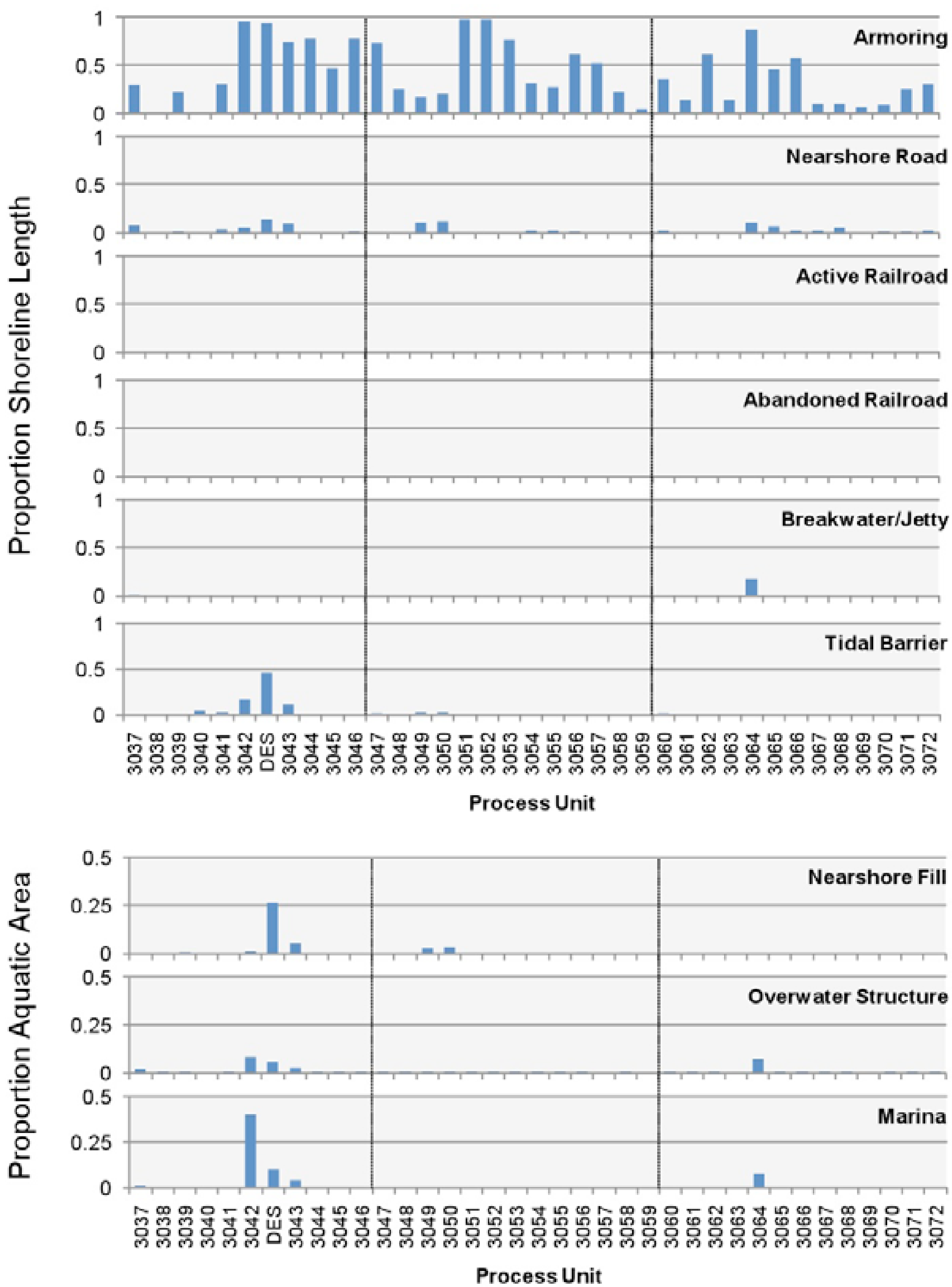


Figure 164. Shoreline alterations along sequential process units (PU) in the Deschutes component of the South Puget Sound Sub-Basin.

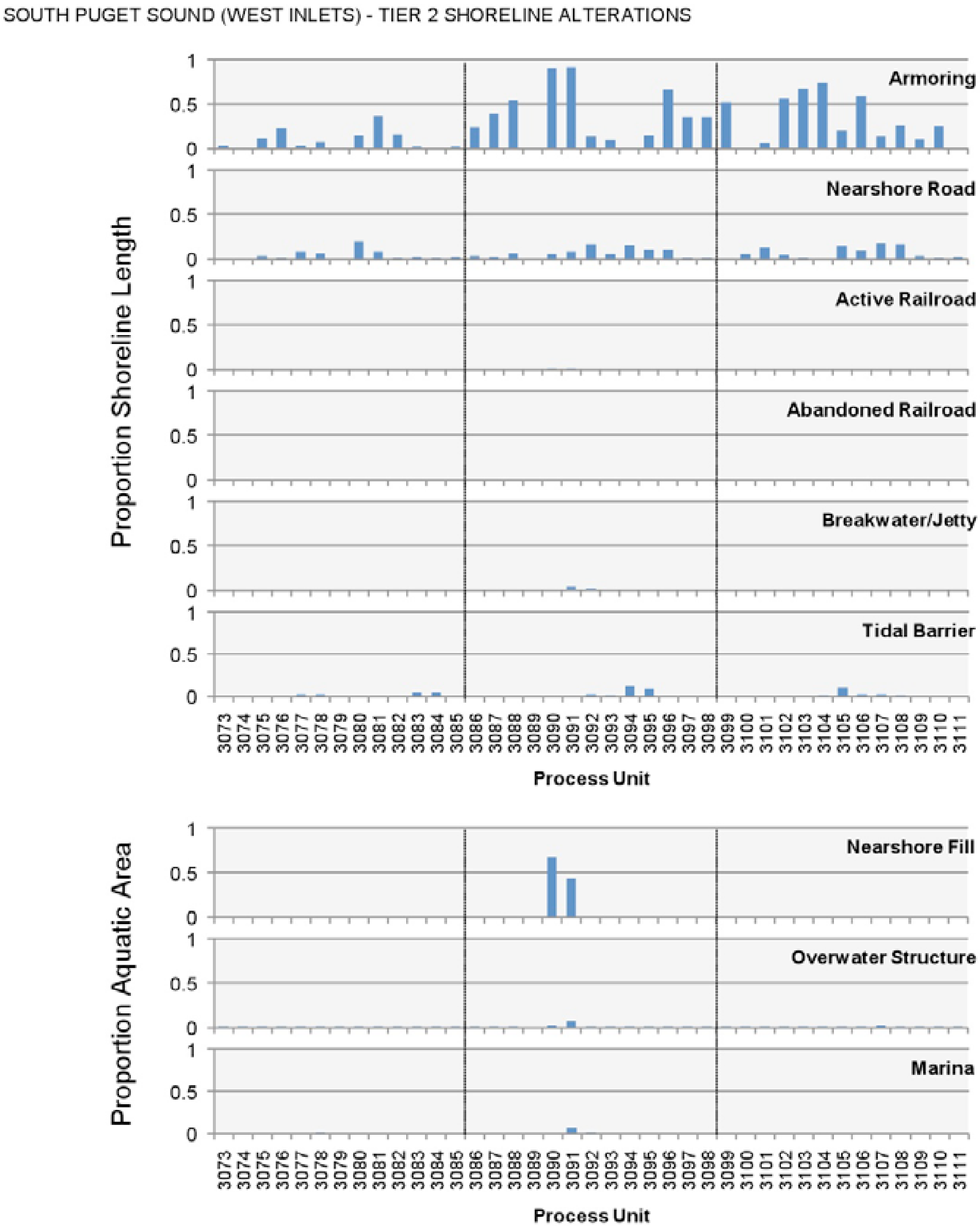


Figure 165. Shoreline alterations along sequential process units (PU) in the West Inlets component of the South Puget Sound Sub-Basin.

SOUTH PUGET SOUND (CASE INLET) - TIER 2 SHORELINE ALTERATIONS

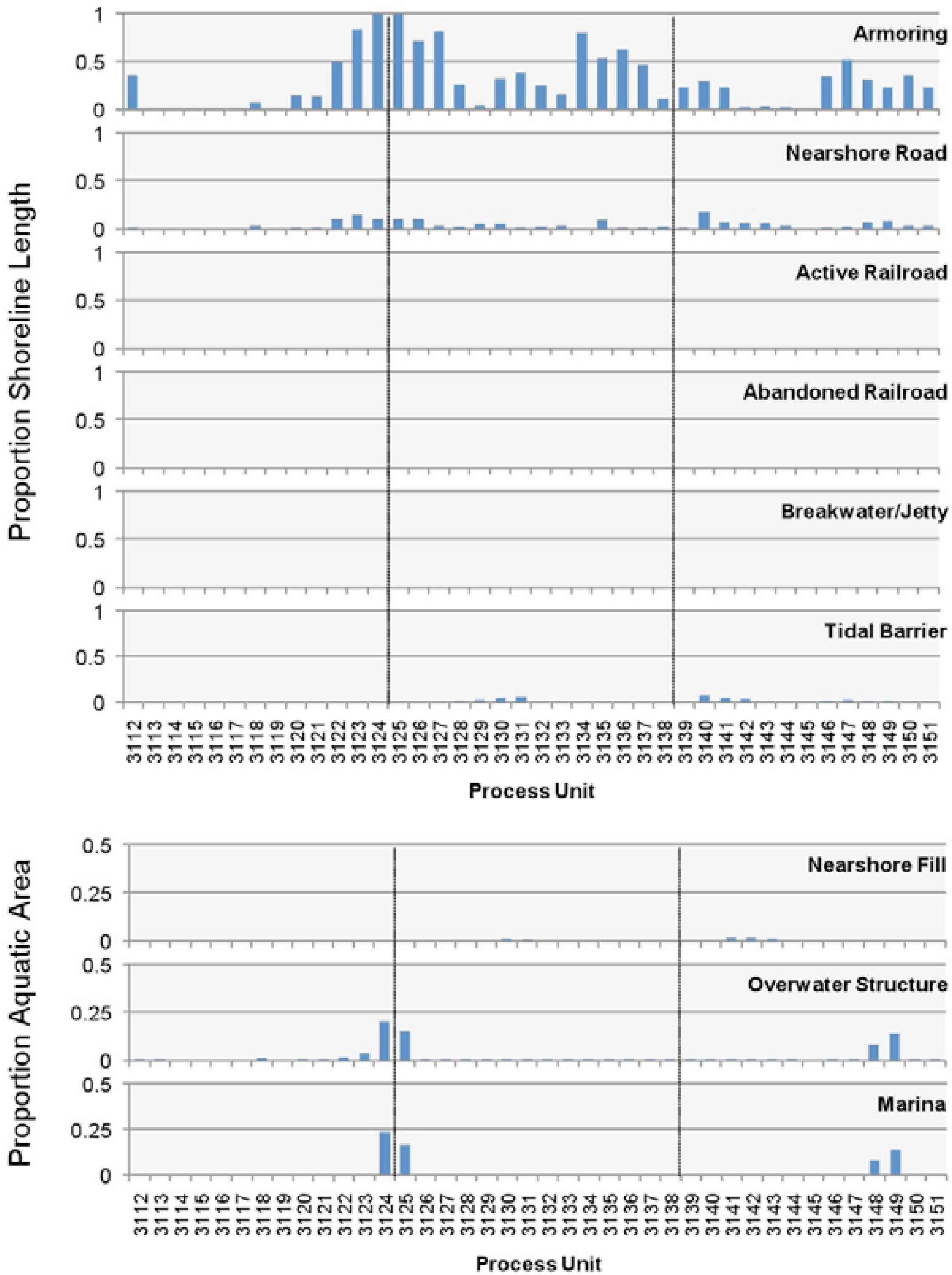


Figure 166. Shoreline alterations along sequential process units (PU) in the Case Inlet component of the South Puget Sound Sub-Basin.

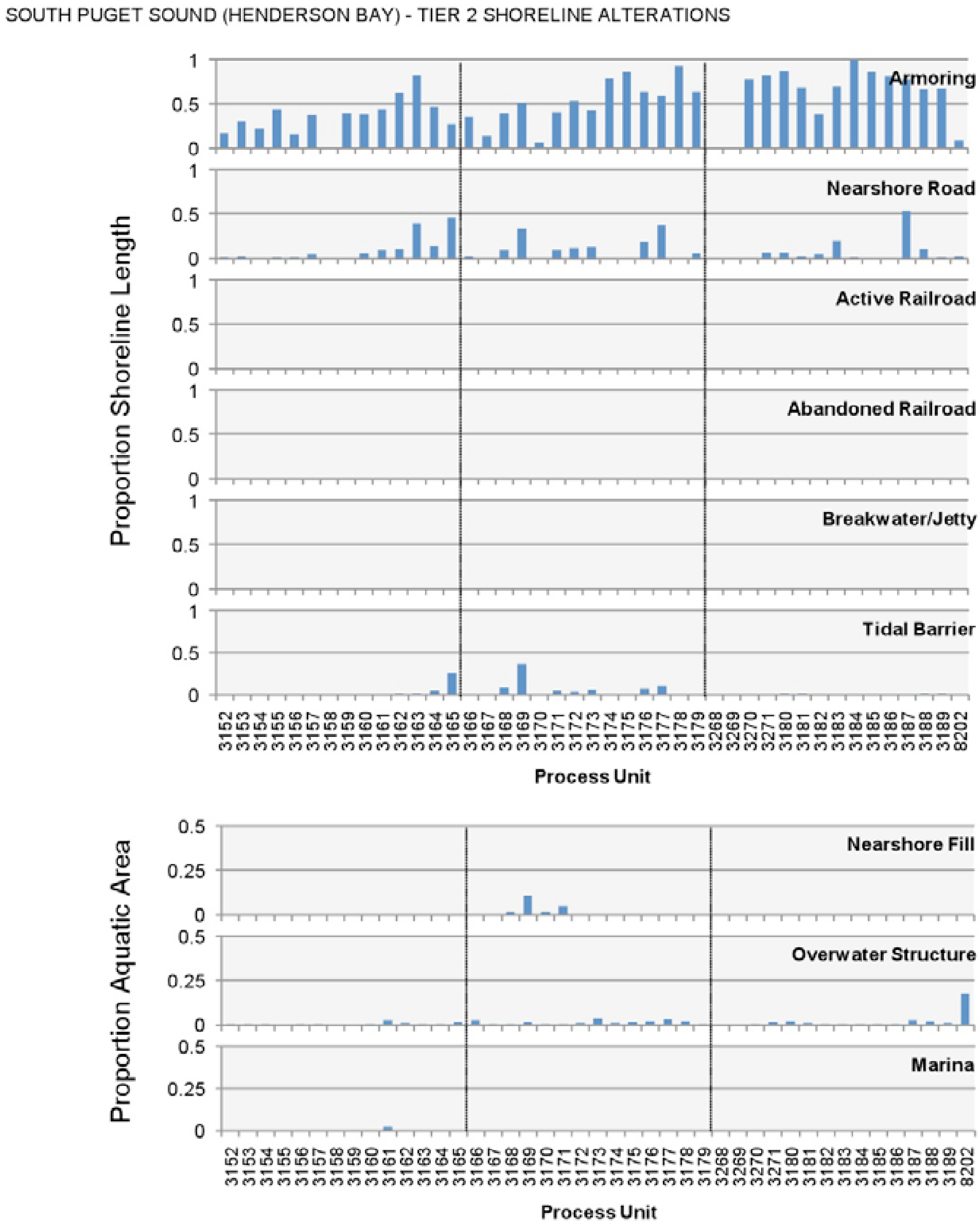


Figure 167. Shoreline alterations along sequential process units (PU) in the Henderson Bay component of the South Puget Sound Sub-Basin.

SOUTH PUGET SOUND (HARSTINE) - TIER 2 SHORELINE ALTERATIONS

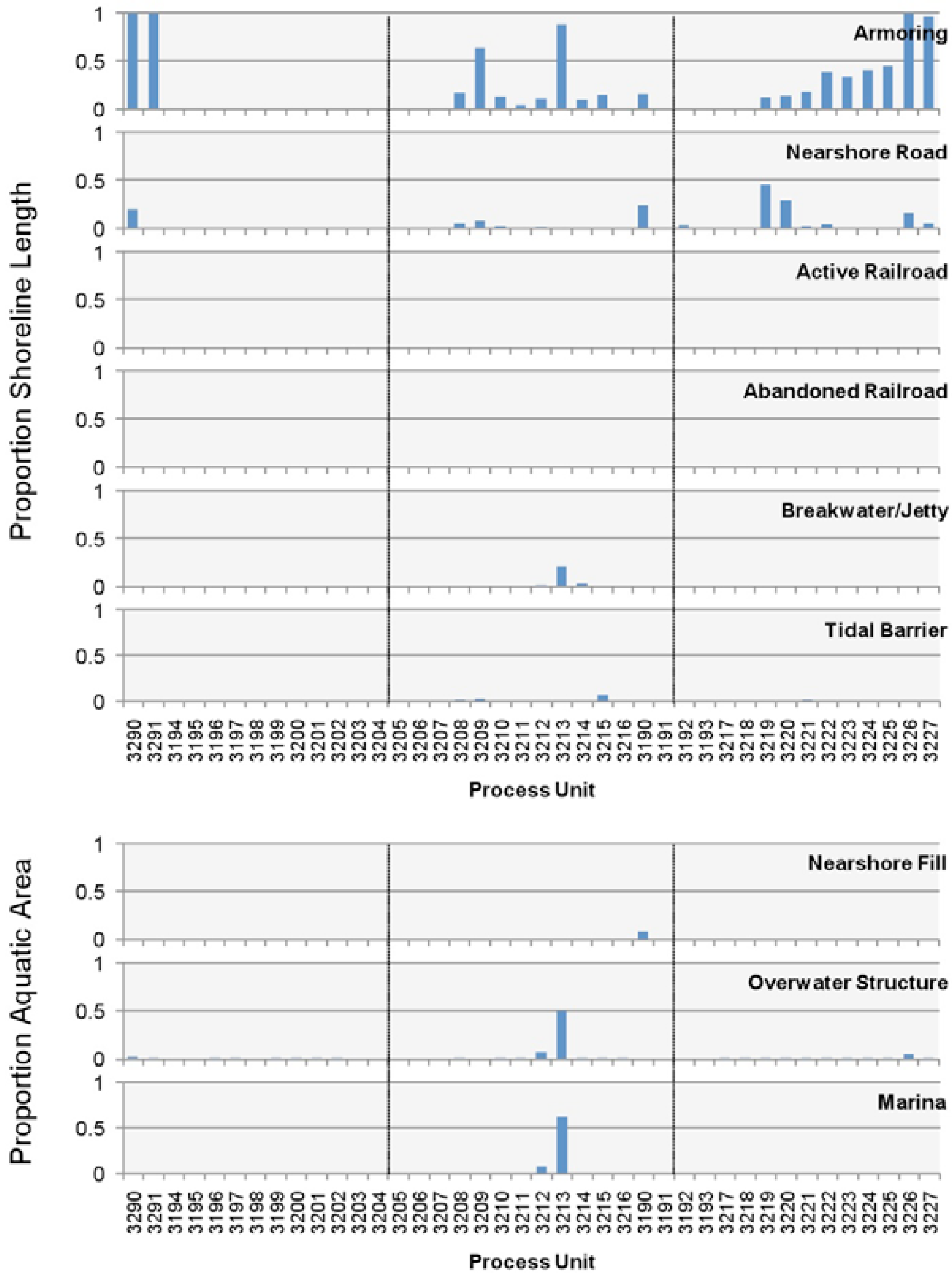


Figure 168. Shoreline alterations along sequential process units (PU) in the Harstine component of the South Puget Sound Sub-Basin.

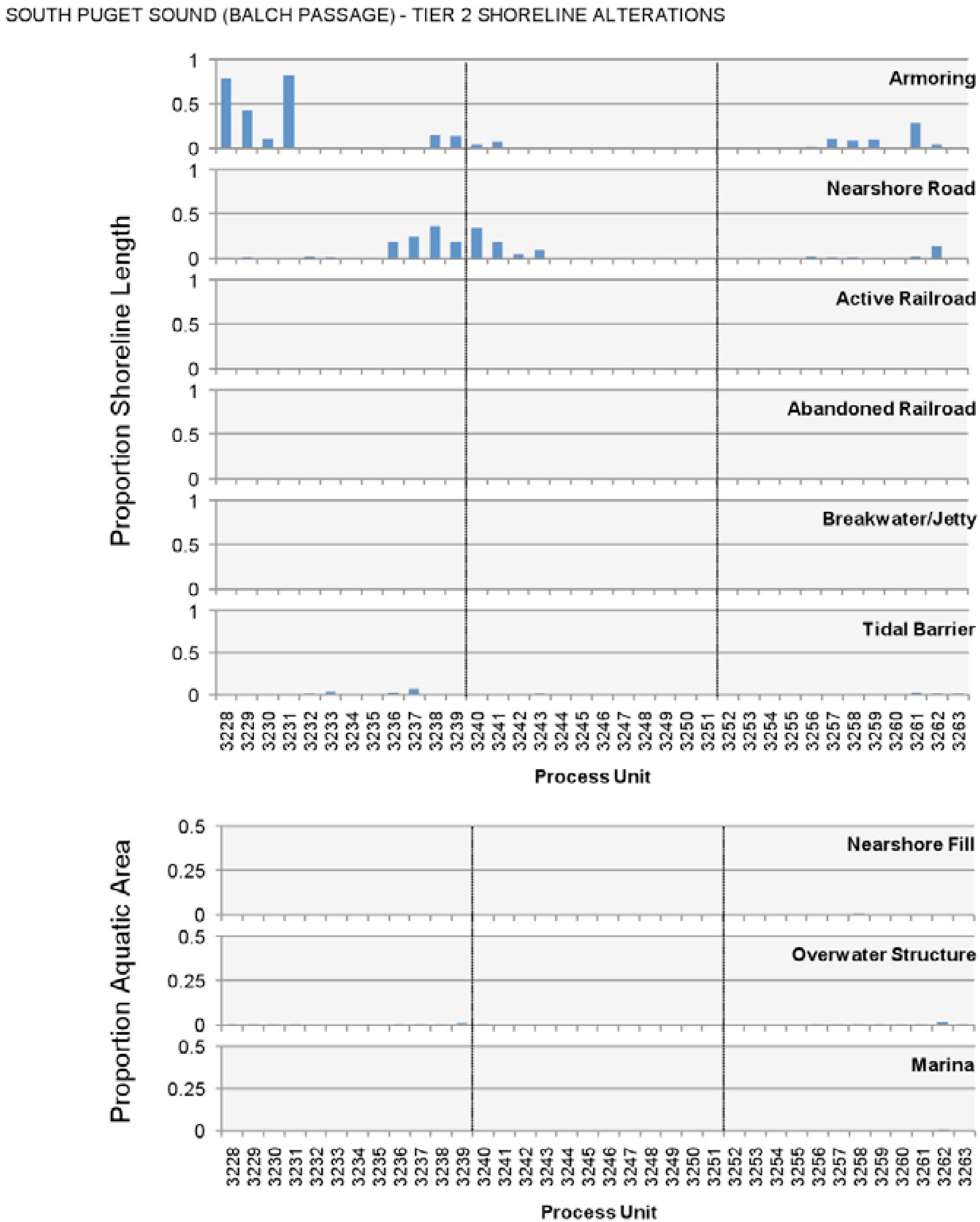
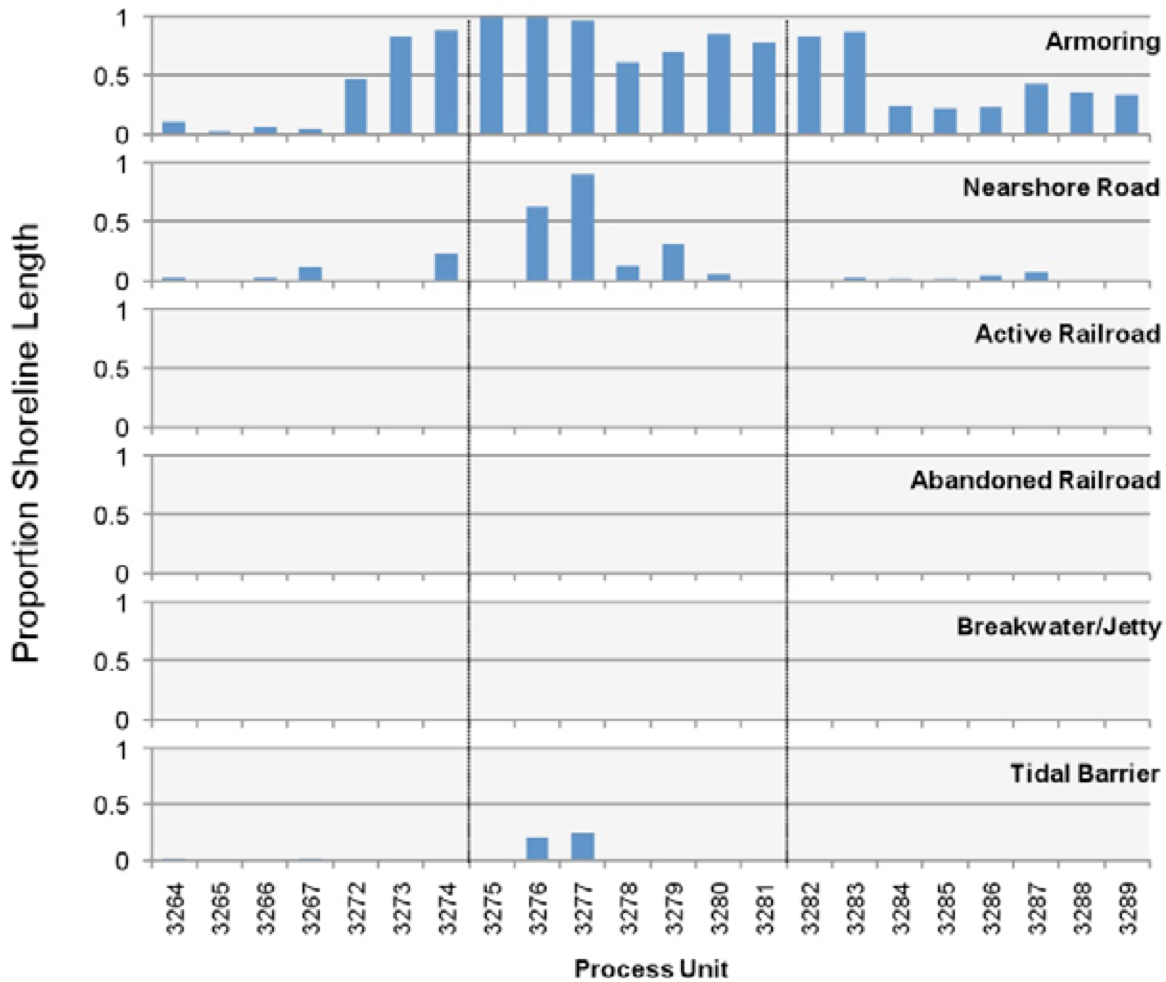


Figure 169. Shoreline alterations along sequential process units (PU) in the Balch Passage component of the South Puget Sound Sub-Basin.

SOUTH PUGET SOUND (FOX ISLAND) - TIER 2 SHORELINE ALTERATIONS



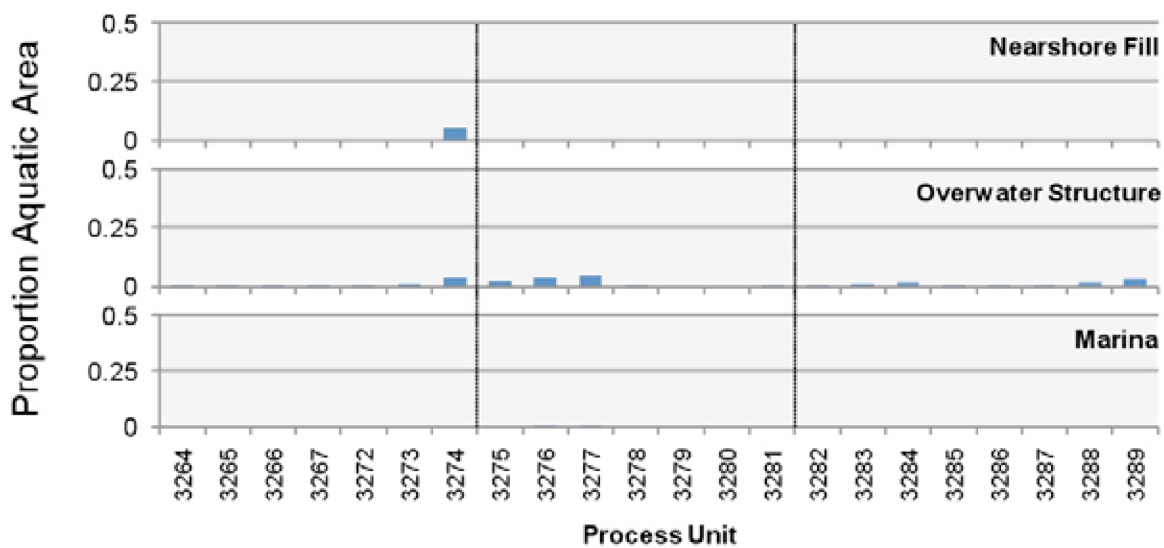


Figure 170. Shoreline alterations along sequential process units (PU) in the Fox Island component of the South Puget Sound Sub-Basin.

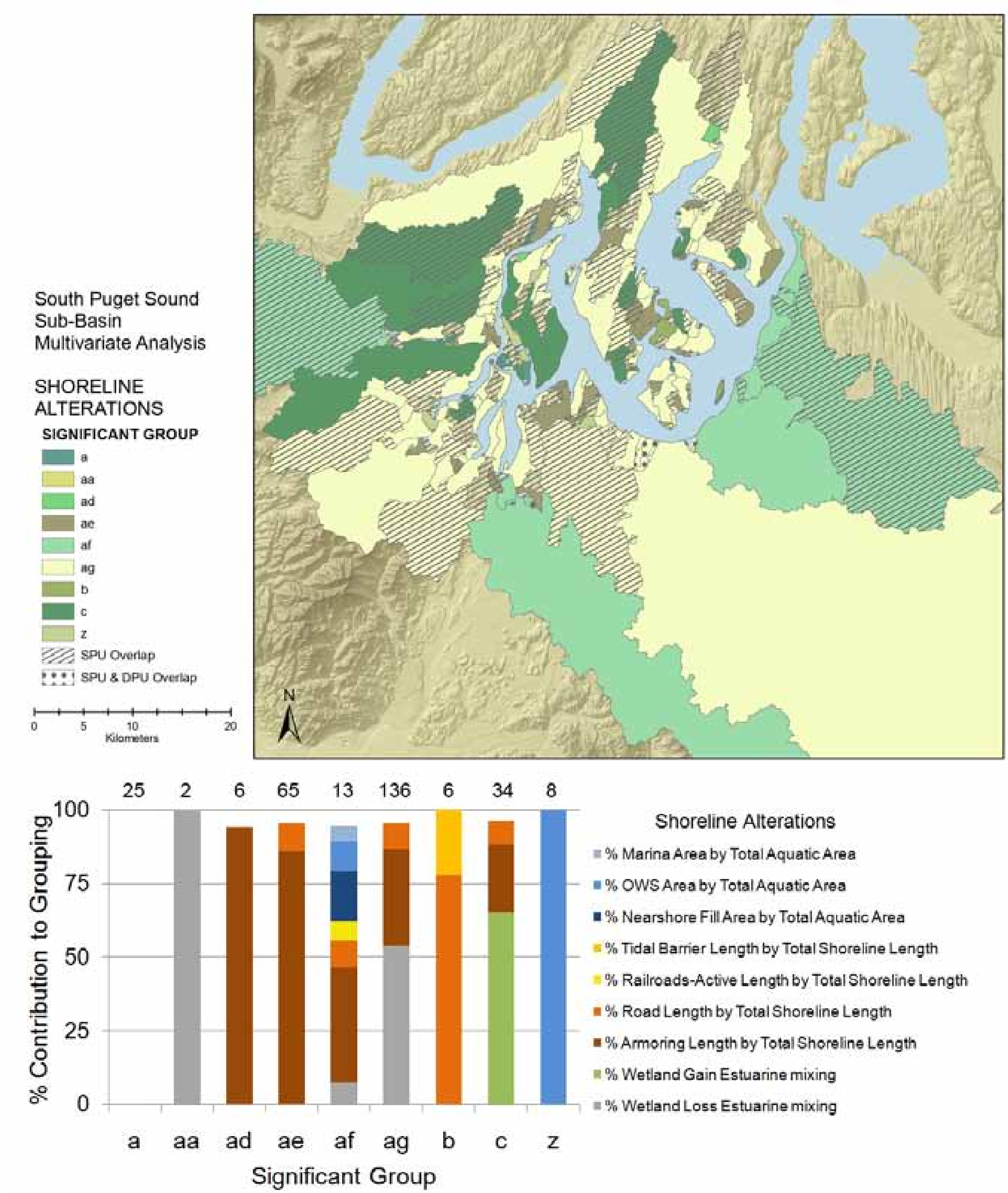


Figure 171. (Top) Process unit (PU) groups with significant similar shoreline alterations and stressors in South Puget Sound Sub-Basin based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for shoreline alterations in the PU. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group. Groups composed of one PU show the descriptive composition of the PU. Group a does not contain any shoreline alterations.

Adjacent Upland and Watershed Change

Descriptive

Although the shoreline of the South Puget Sound Sub-Basin is heavily modified, the adjacent upland is approximately 75 percent natural land cover, most of this as evergreen and mixed forest, along with forested and emergent wetlands (Table 11; Figs. 172–179). Development is fairly consistent throughout the sub-basin components; however, concentrations occur between Tacoma and the Nisqually delta in the Nisqually component (Fig. 172), and around the Deschutes River delta in the Deschutes component (Fig. 173).

Multivariate Analysis

Group j (116 PU) is typical of adjacent upland change in the sub-basin, distinguished by low to moderate levels of impervious surface and development and roads (Fig. 180). Group h (101 PU) is also widely distributed throughout the sub-basin and is characterized mainly by low levels of impervious surface along with the presence of roads. Group a (50 PU) has seen little change in the adjacent upland, distinguished only by zero to minimal impervious surface, and is mainly located on minimally impacted islands, such as Squaxin Island off of Arcadia and the northern tip of McNeil Island. Groups d and e represent areas of greatest development.

Group h (134 PU) is the most common and widespread watershed area change group, characterized by low levels of impervious surface and development. Group g is also typical of the region (95 PU), distinguished from the former by slightly higher levels of impervious surface (Fig. 181).

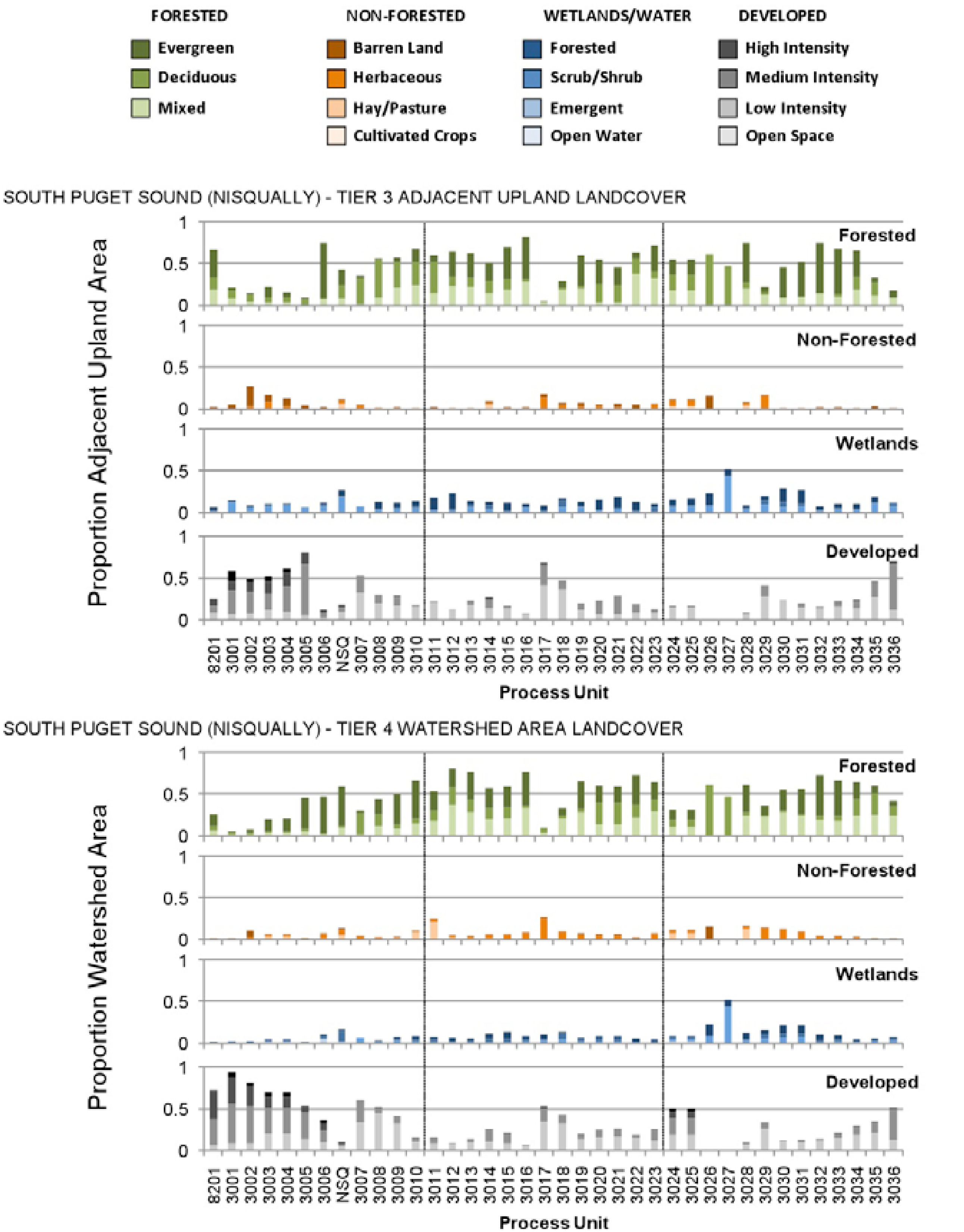


Figure 172. Land cover/land and stressors in adjacent upland (Tier 3, top) and watershed areas (Tier 4, bottom) in the Nisqually component of the South Puget Sound Sub-Basin.

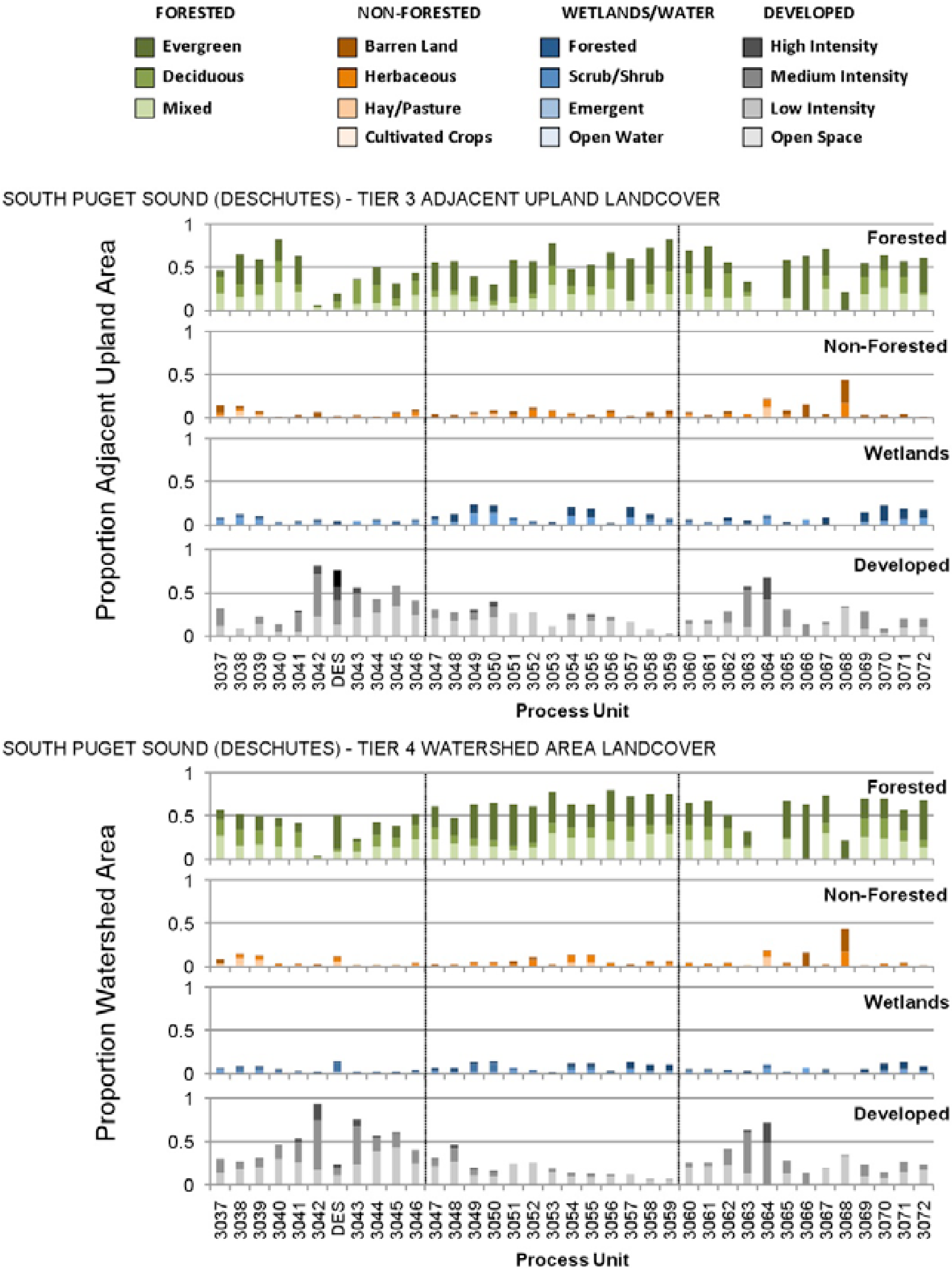


Figure 173. Land cover/land and stressors in adjacent upland (Tier 3, top) and watershed areas (Tier 4, bottom) in the Deschutes component of the South Puget Sound Sub-Basin.

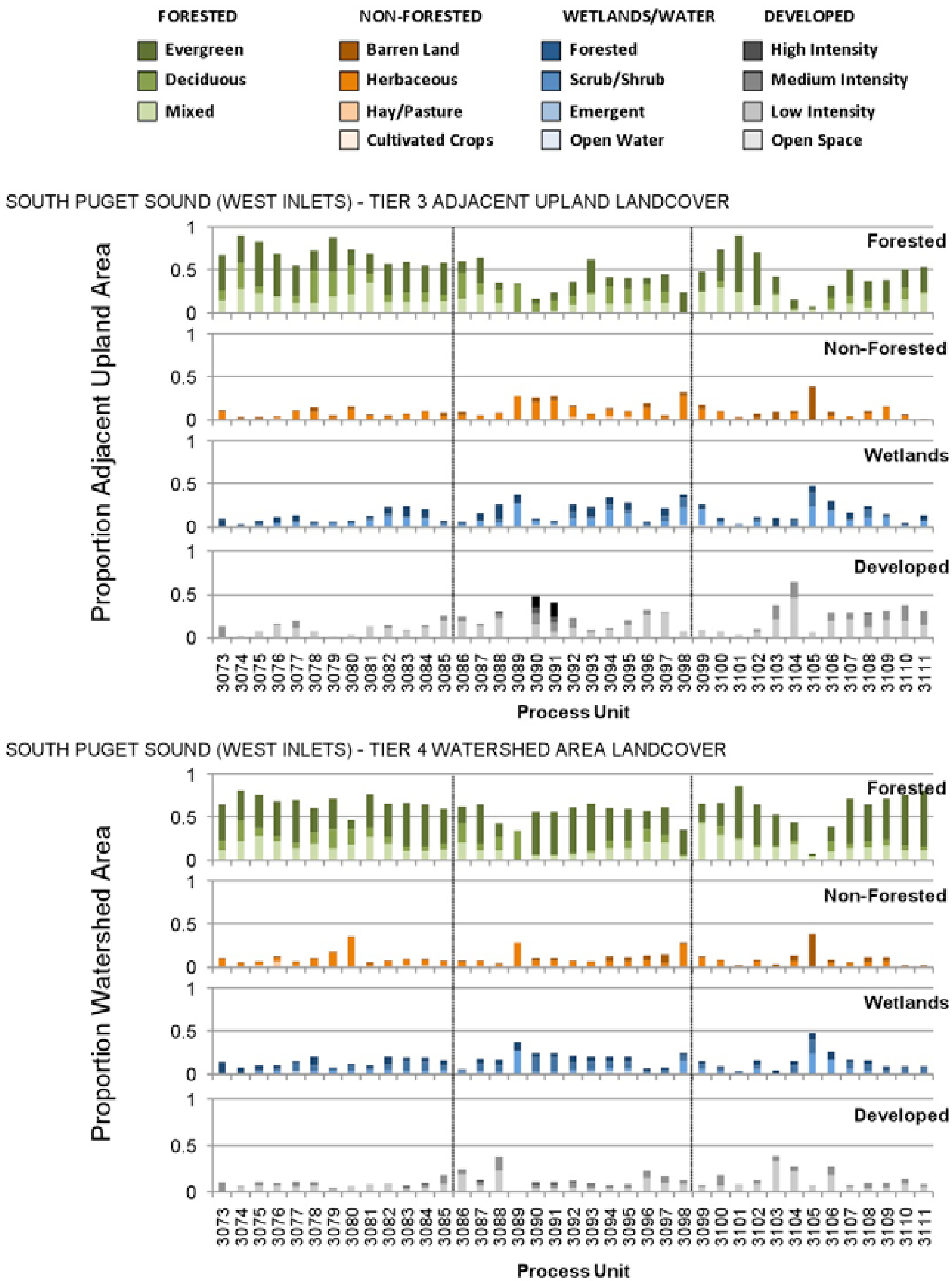


Figure 174. Land cover/land and stressors in adjacent upland (Tier 3, top) and watershed areas (Tier 4, bottom) in the West Inlets component of the South Puget Sound Sub-Basin.

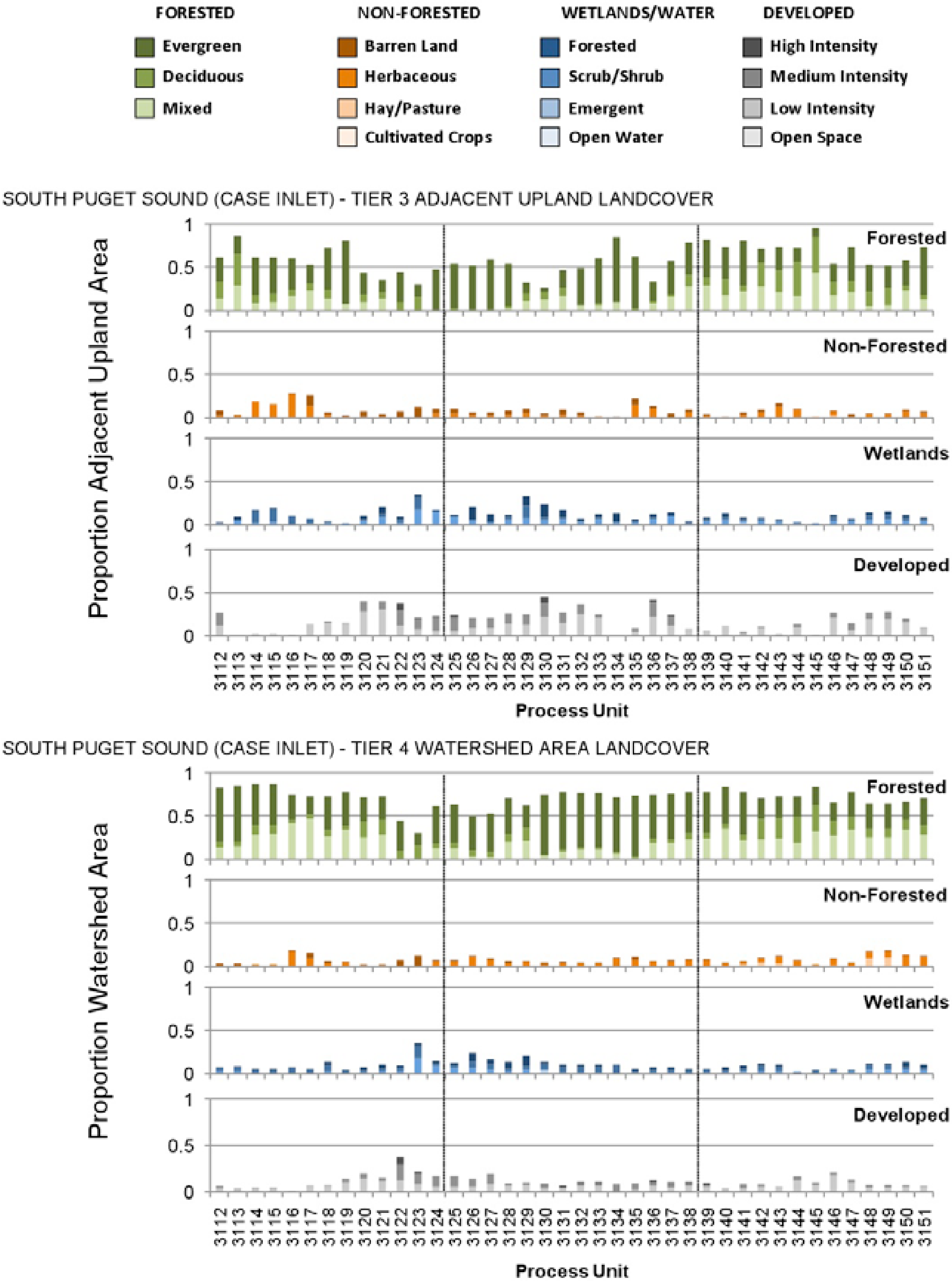


Figure 175. Land cover/land and stressors in adjacent upland (Tier 3, top) and watershed areas (Tier 4, bottom) in the Case Inlet component of the South Puget Sound Sub-Basin.

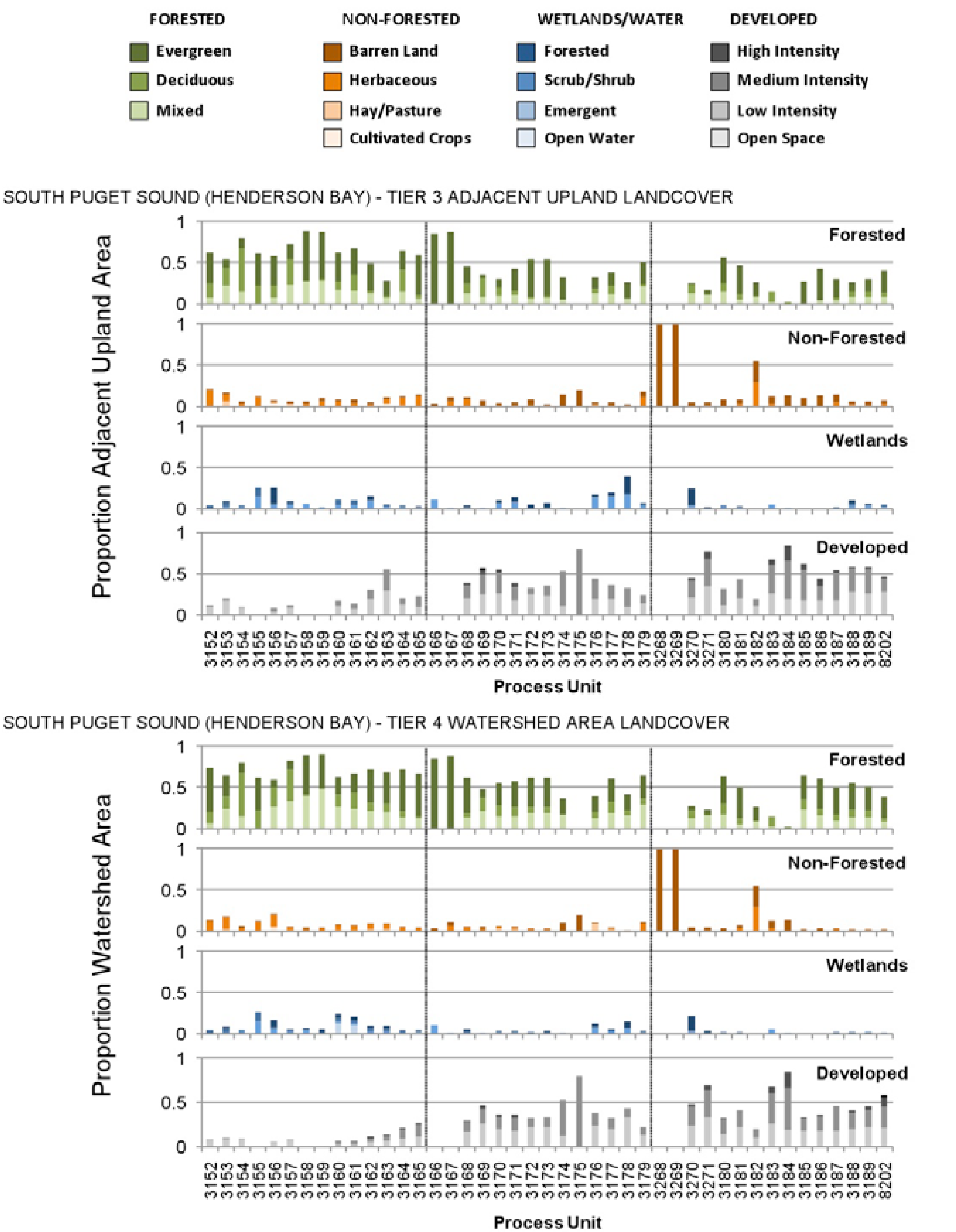


Figure 176. Land cover/land and stressors in adjacent upland (Tier 3, top) and watershed areas (Tier 4, bottom) in the Henderson Bay component of the South Puget Sound Sub-Basin.

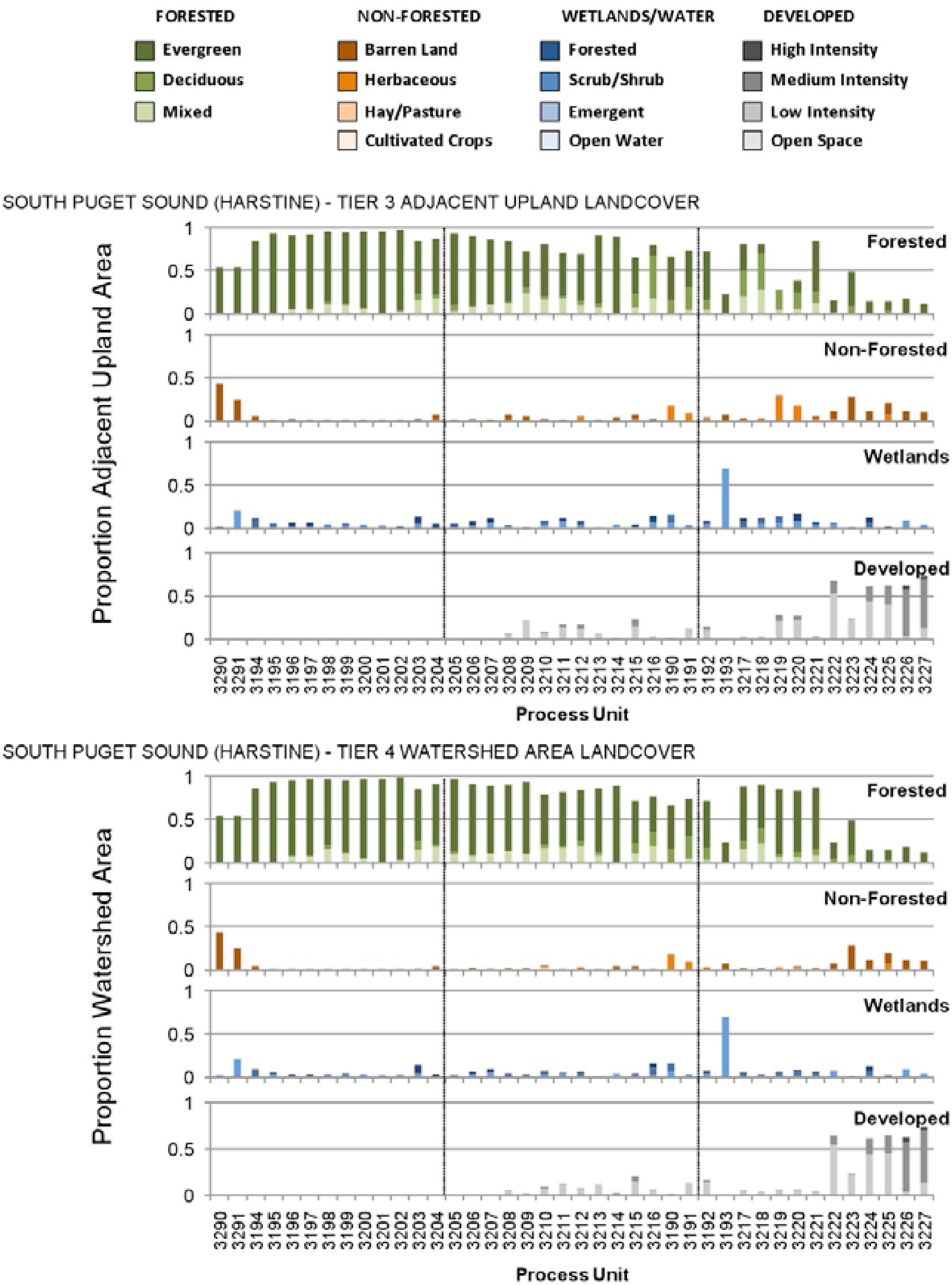


Figure 177. Land cover/land and stressors in adjacent upland (Tier 3, top) and watershed areas (Tier 4, bottom) in the Harstine component of the South Puget Sound Sub-Basin.

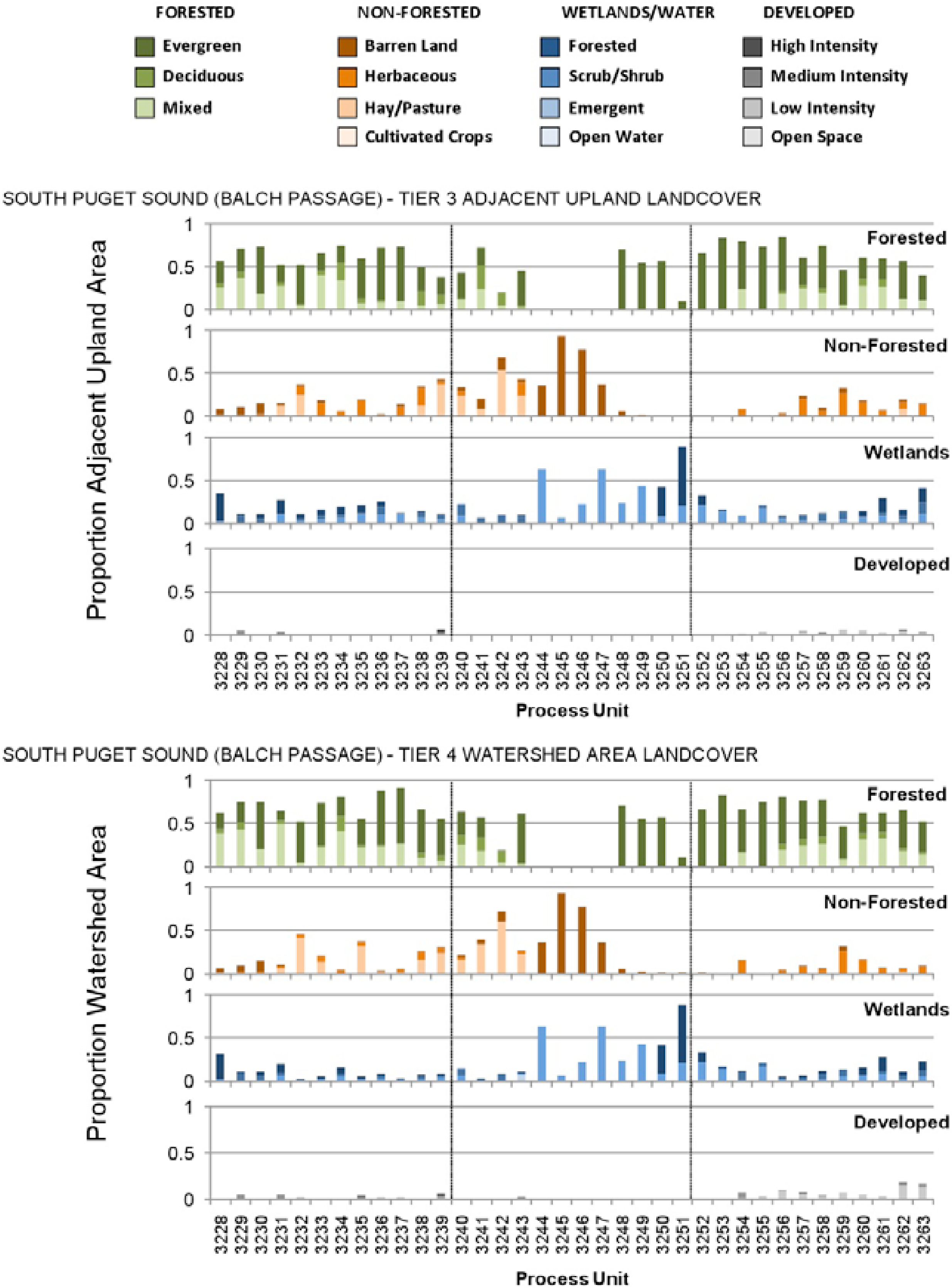


Figure 178. Land cover/land and stressors in adjacent upland (Tier 3, top) and watershed areas (Tier 4, bottom) in the Balch Passage component of the South Puget Sound Sub-Basin.

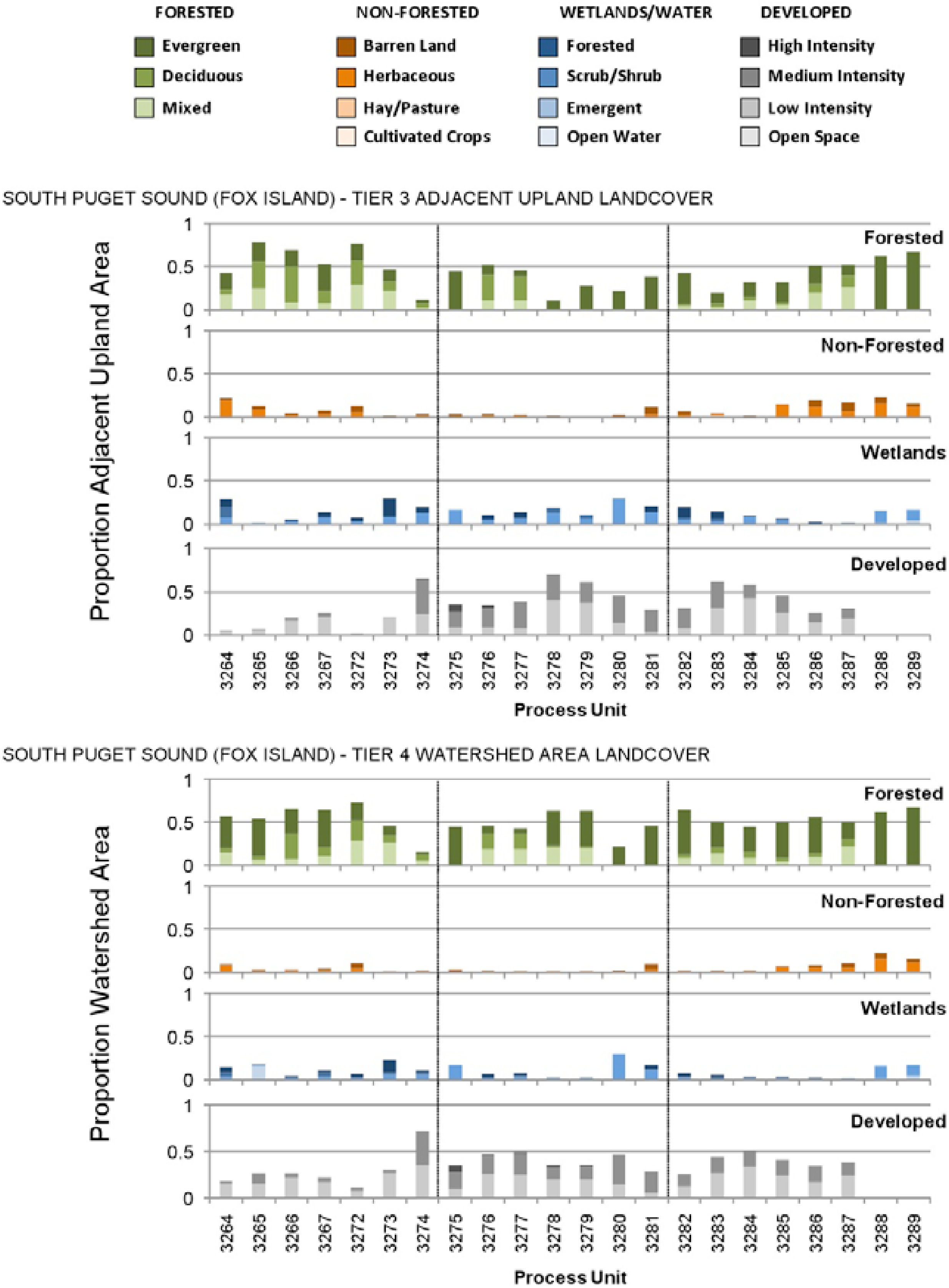


Figure 179. Land cover/land and stressors in adjacent upland (Tier 3, top) and watershed areas (Tier 4, bottom) in the Fox Island component of the South Puget Sound Sub-Basin.

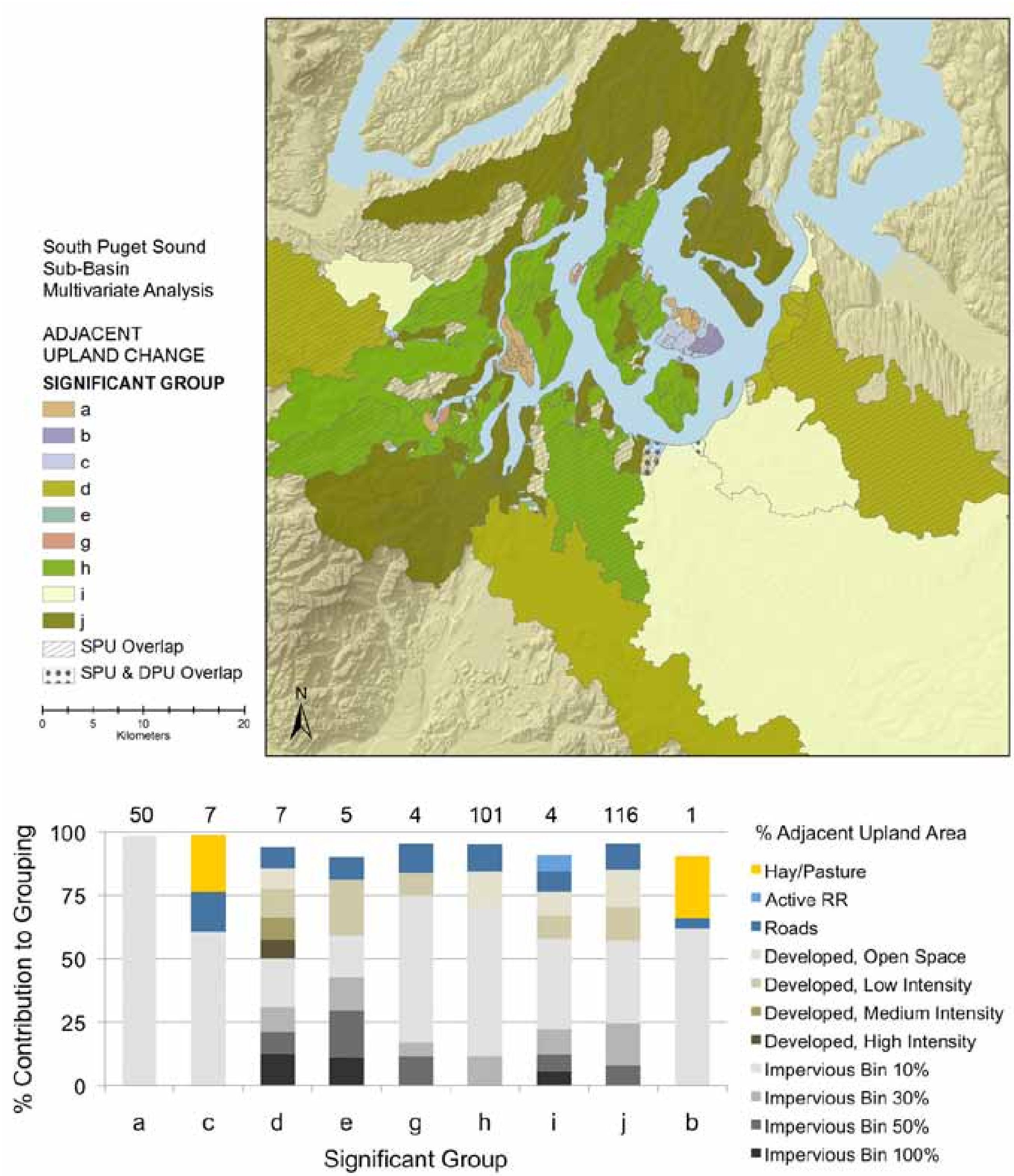


Figure 180. (Top) Distribution of process unit (PU) groups with significantly similar adjacent upland changes in South Puget Sound Sub-Basin of Puget Sound based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for adjacent upland change in the PU. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group. Groups composed of one PU show the descriptive composition of the PU.

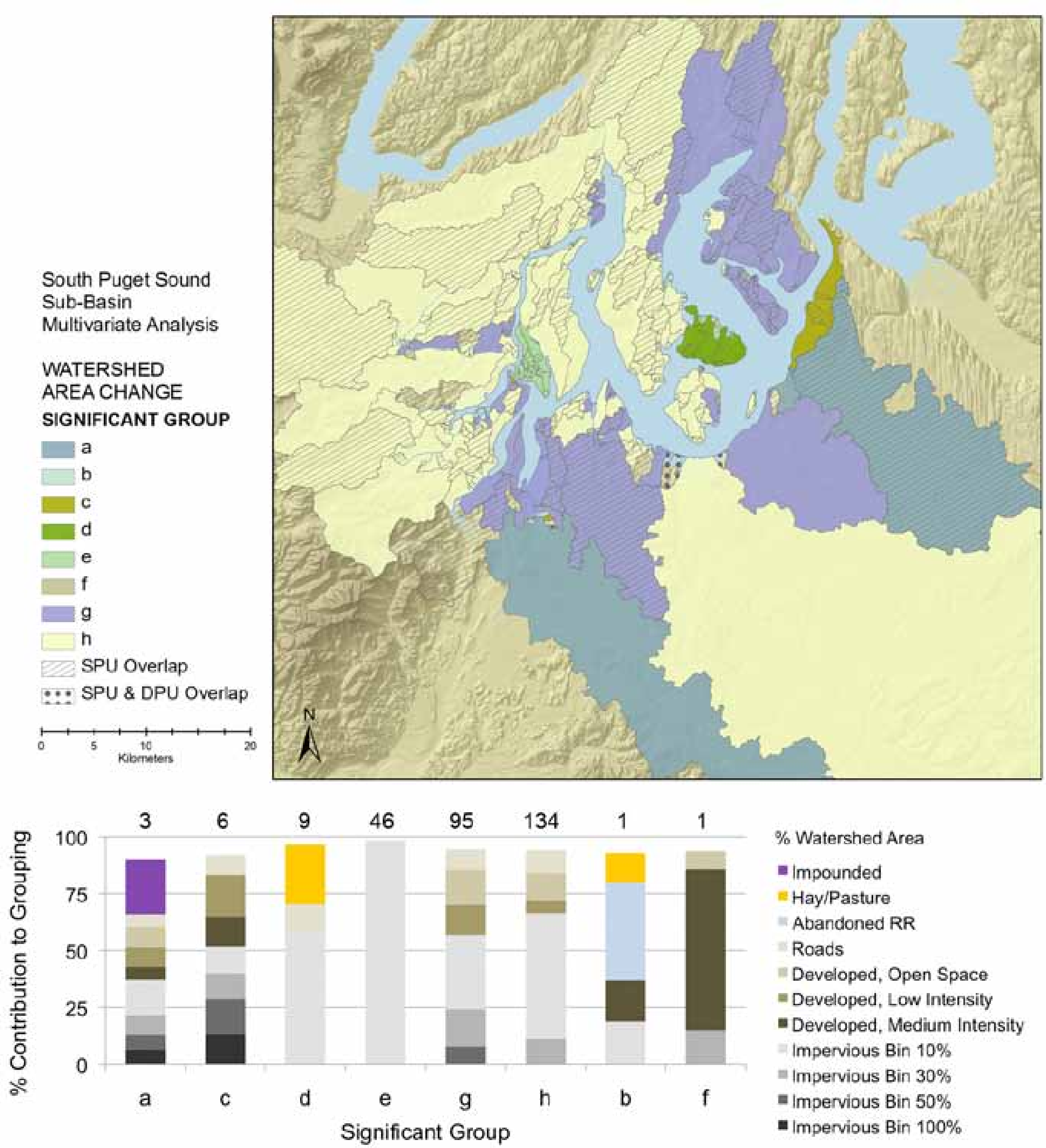


Figure 181. (Top) Distribution of process unit (PU) groups with significantly similar total watershed area changes in South Puget Sound Sub-Basin of Puget Sound based on multivariate analysis. Areas left blank represent the overlap of two PU that do not belong to the same group. (Bottom) SIMPER multivariate analysis results for watershed area change in the PU. Only higher-contributing variables are shown, with a cumulative cut-off of 90%. Number above stacked histograms indicates the number of PU in each group. Groups composed of one PU show the descriptive composition of the PU.

Co-Occurrence of Alterations and Stressors

To this point, we have presented multiple shoreline alterations and other stressors as coincident within the scale of a PU, but not necessarily spatially overlapping. Spatial co-occurrence may produce cumulative or synergistic effects resulting from multiple stressors on one location. To enable comparative analysis between all features, all shoreline alterations were first converted to a length measurement along the shoreline.

Shoreforms and Shoreline Alterations

As might be expected, the highest coincidences between shoreline alterations with shoreforms in the Puget Sound basin are associated with the artificial shoreform (Table 19). In particular, 74 percent of the artificial shoreform length is armored and 62 percent is associated with nearshore fill. Among the natural shoreforms, the highest co-occurrences are armoring with bluff-backed beach (33 percent of the bluff-backed beach shoreform length is armored), barrier beaches (27 percent), open coastal inlets (22 percent), deltas (17 percent), nearshore roads (those occurring within 25 m of the shoreline) with deltas (23 percent of the delta shoreform length has a road), barrier estuaries (22 percent), and open coastal inlets (17 percent). Tidal barriers are highly correlated with deltas (62 percent of the delta shoreform length has a tidal barrier), as are barrier estuaries (21 percent) and open coastal inlets (16 percent), to a lesser extent.

Relationships between shoreforms and shoreline alterations are presented for each of the seven Puget Sound Sub-Basins (Table 20-26).

Co-occurrence of Shoreline Alterations

In the Puget Sound basin overall, the co-occurrence of shoreline alterations is most evident with armoring (Table 27). The extent of co-occurrence ranges from 72 percent of the active railroad length as armored to 22 percent of the tidal barrier length as armored. Nearshore fill is highly coincident with marinas (62 percent of the total length of marinas occurs with nearshore fill), breakwaters and jetties (45 percent), and overwater structures (43 percent). Other co-occurrences of interest are nearshore roads with tidal barriers (33 percent of the tidal barrier length occurs with a road), abandoned railroads (31 percent), and breakwaters and jetties (24 percent).

Some variation in the magnitude of these relationships occurs among the sub-basins, but overall the patterns remain relatively similar (Tables 28-34).

Table 19. Occurrence of shoreline alterations (Tier 2 stressors) by different shoreforms in Puget Sound.

Stressors	Current Shoreforms									
	BLB	BAB	D	BE	BL	OCI	PL	RP	PB	ART
Armoring	33%	27%	17%	7%	15%	22%	1%	4%	8%	74%
BW/J	0%	0%	2%	1%	1%	2%	0%	0%	0%	16%
Marinas	0%	0%	0%	1%	0%	1%	0%	0%	1%	14%
Nearshore Fill	3%	10%	6%	3%	9%	4%	0%	0%	0%	62%
OWS	2%	2%	2%	5%	7%	5%	1%	1%	3%	30%
Roads	7%	10%	23%	22%	13%	17%	0%	2%	4%	23%
RR, Abandoned	1%	1%	0%	2%	3%	3%	0%	0%	0%	1%
RR, Active	1%	0%	1%	3%	1%	1%	0%	1%	0%	6%
Tidal Barriers	0%	0%	69%	21%	12%	16%	0%	0%	0%	0%

Table 20. Occurrence of shoreline alterations (tier 2 stressors) by different shoreforms in Strait of Juan de Fuca Sub-Basin.

Stressors	Current Shoreforms									
	BLB	BAB	D	BE	BL	OCI	PL	RP	PB	ART
Armoring	14%	24%	4%	0%	22%	4%	0%	4%	18%	85%
BW/J	0%	0%	0%	0%	0%	0%	0%	0%	0%	51%
Marinas	1%	0%	0%	0%	0%	0%	0%	0%	0%	13%
Nearshore Fill	2%	9%	0%	0%	22%	0%	0%	0%	0%	48%
OWS	1%	1%	6%	15%	22%	1%	0%	0%	1%	27%
Roads	4%	11%	12%	18%	21%	11%	0%	4%	8%	13%
RR, Abandoned	6%	5%	0%	4%	24%	46%	0%	0%	0%	10%
RR, Active	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Tidal Barriers	0%	0%	24%	13%	22%	41%	0%	0%	0%	0%

Table 21. Occurrence of shoreline alterations (tier 2 stressors) by different shoreforms in San Juan Islands–Strait of Georgia Sub-Basin.

Stressors	Current Shoreforms									
	BLB	BAB	D	BE	BL	OCI	PL	RP	PB	ART
Armoring	14%	20%	47%	34%	21%	37%	0%	2%	6%	60%
BW/J	0%	0%	5%	40%	4%	7%	0%	0%	0%	32%
Marinas	0%	0%	0%	0%	0%	0%	0%	0%	1%	23%
Nearshore Fill	2%	10%	0%	12%	2%	10%	0%	0%	0%	57%
OWS	1%	1%	3%	12%	10%	2%	1%	1%	3%	25%
Roads	11%	12%	11%	3%	26%	34%	0%	1%	4%	17%
RR, Abandoned	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%
RR, Active	2%	0%	7%	50%	4%	5%	0%	1%	0%	10%
Tidal Barriers	0%	0%	49%	82%	19%	41%	0%	0%	0%	0%

Table 22. Occurrence of shoreline alterations (tier 2 stressors) by different shoreforms in Hood Canal Sub-Basin.

Stressors	Current Shoreforms									
	BLB	BAB	D	BE	BL	OCI	PL	RP	PB	ART
Armoring	27%	27%	3%	1%	15%	5%	4%	6%	24%	39%
BW/J	0%	0%	5%	0%	0%	2%	0%	0%	0%	0%
Marinas	0%	0%	0%	2%	0%	0%	0%	0%	0%	6%
Nearshore Fill	0%	3%	13%	2%	4%	15%	0%	0%	0%	53%
OWS	3%	4%	2%	4%	6%	1%	1%	2%	1%	20%
Roads	13%	8%	19%	24%	3%	16%	8%	6%	0%	16%
RR, Abandoned	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
RR, Active	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Tidal Barriers	0%	0%	66%	17%	7%	19%	0%	0%	0%	0%

Table 23. Occurrence of shoreline alterations (tier 2 stressors) by different shoreforms in North Central Puget Sound Sub-Basin.

Stressors	Current Shoreforms									
	BLB	BAB	D	BE	BL	OCI	PL	RP	PB	ART
Armoring	7%	9%	--	0%	0%	9%	0%	4%	12%	36%
BW/J	0%	0%	--	0%	0%	0%	0%	0%	0%	14%
Marinas	0%	0%	--	0%	0%	3%	0%	1%	7%	11%
Nearshore Fill	1%	8%	--	0%	0%	1%	0%	0%	6%	59%
OWS	0%	1%	--	1%	0%	10%	0%	4%	7%	31%
Roads	1%	4%	--	3%	3%	9%	0%	1%	2%	9%
RR, Abandoned	0%	0%	--	0%	0%	0%	0%	0%	0%	0%
RR, Active	0%	0%	--	0%	0%	0%	0%	0%	0%	0%
Tidal Barriers	0%	0%	--	22%	0%	18%	0%	0%	0%	0%

Table 24. Occurrence of shoreline alterations (tier 2 stressors) by different shoreforms in Whidbey Sub-Basin.

Stressors	Current Shoreforms									
	BLB	BAB	D	BE	BL	OCI	PL	RP	PB	ART
Armoring	29%	29%	8%	10%	12%	0%	0%	2%	11%	53%
BW/J	0%	0%	1%	1%	0%	0%	0%	0%	0%	17%
Marinas	0%	0%	0%	2%	0%	0%	0%	0%	0%	17%
Nearshore Fill	9%	27%	5%	7%	30%	0%	0%	0%	2%	78%
OWS	1%	2%	2%	3%	0%	0%	2%	1%	0%	24%
Roads	5%	7%	26%	24%	15%	0%	1%	1%	3%	5%
RR, Abandoned	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
RR, Active	1%	0%	1%	0%	0%	0%	0%	0%	0%	3%
Tidal Barriers	0%	0%	78%	17%	14%	0%	0%	0%	0%	0%

Table 25. Occurrence of shoreline alterations (tier 2 stressors) by different shoreforms in South Central Puget Sound Sub-Basin.

Stressors	Current Shoreforms									
	BLB	BAB	D	BE	BL	OCI	PL	RP	PB	ART
Armoring	58%	48%	--	21%	19%	49%	--	49%	53%	86%
BW/J	0%	0%	--	0%	0%	0%	--	0%	0%	7%
Marinas	1%	0%	--	0%	0%	3%	--	0%	0%	11%
Nearshore Fill	8%	14%	--	8%	0%	4%	--	0%	0%	66%
OWS	3%	4%	--	5%	10%	7%	--	2%	4%	33%
Roads	8%	11%	--	36%	2%	8%	--	29%	7%	32%
RR, Abandoned	0%	0%	--	0%	0%	0%	--	0%	0%	0%
RR, Active	2%	0%	--	1%	0%	0%	--	0%	0%	6%
Tidal Barriers	0%	0%	--	45%	3%	3%	--	0%	0%	0%

Table 26. Occurrence of shoreline alterations (tier 2 stressors) by different shoreforms in South Puget Sound Sub-Basin.

Stressors	Current Shoreforms									
	BLB	BAB	D	BE	BL	OCI	PL	RP	PB	ART
Armoring	41%	32%	66%	3%	12%	12%	--	--	--	82%
BW/J	0%	0%	0%	0%	0%	0%	--	--	--	1%
Marinas	0%	0%	0%	0%	2%	0%	--	--	--	11%
Nearshore Fill	4%	7%	20%	2%	3%	1%	--	--	--	84%
OWS	2%	2%	1%	2%	4%	7%	--	--	--	27%
Roads	5%	9%	35%	19%	1%	12%	--	--	--	16%
RR, Abandoned	0%	0%	0%	3%	0%	4%	--	--	--	2%
RR, Active	3%	1%	0%	4%	1%	0%	--	--	--	19%
Tidal Barriers	0%	0%	67%	10%	4%	5%	--	--	--	0%

Table 27. Co-occurrence of shoreline alterations (Tier 2 stressors) in Puget Sound.

Stressors	Stressors								
	Armoring	BW/J	Marinas	Nearshore Fill	OWS	Roads	RR, Abandoned	RR, Active	Tidal Barriers
Armoring	100%	63%	71%	68%	64%	46%	40%	72%	22%
BW/J	5%	100%	33%	9%	10%	4%	2%	12%	4%
Marinas	4%	28%	100%	11%	27%	2%	2%	1%	0%
Nearshore Fill	23%	45%	62%	100%	43%	13%	14%	59%	9%
OWS	12%	27%	80%	23%	100%	10%	31%	10%	3%
Roads	18%	24%	16%	14%	20%	100%	31%	22%	33%
RR, Abandoned	1%	1%	1%	1%	4%	2%	100%	2%	3%
RR, Active	4%	10%	1%	10%	3%	3%	5%	100%	2%
Tidal Barriers	6%	14%	1%	7%	5%	23%	30%	9%	100%

Table 28. Co-occurrence of shoreline alterations (Tier 2 stressors) in Strait of Juan de Fuca Sub-Basin.

Stressors	Stressors								
	Armoring	BW/J	Marinas	Nearshore Fill	OWS	Roads	RR, Abandoned	RR, Active	Tidal Barriers
Armoring	100%	94%	99%	88%	62%	43%	55%	--	18%
BW/J	17%	100%	78%	13%	23%	7%	4%	--	0%
Marinas	6%	25%	100%	10%	21%	5%	4%	--	0%
Nearshore Fill	31%	26%	60%	100%	37%	17%	21%	--	16%
OWS	15%	31%	87%	26%	100%	19%	25%	--	37%
Roads	21%	19%	40%	23%	37%	100%	32%	--	31%
RR, Abandoned	16%	6%	19%	17%	30%	20%	100%	--	39%
RR, Active	0%	0%	0%	0%	0%	0%	0%	--	0%
Tidal Barriers	3%	0%	0%	9%	28%	12%	25%	--	100%

Table 29. Co-occurrence of shoreline alterations (tier 2 stressors) in San Juan Islands–Strait of Georgia Sub-Basin.

Stressors	Stressors								
	Armoring	BW/J	Marinas	Nearshore Fill	OWS	Roads	RR, Abandoned	RR, Active	Tidal Barriers
Armoring	100%	57%	53%	48%	37%	47%	100%	57%	66%
BW/J	13%	100%	37%	22%	10%	17%	0%	26%	12%
Marinas	8%	23%	100%	23%	43%	3%	0%	0%	0%
Nearshore Fill	21%	41%	67%	100%	37%	12%	0%	32%	10%
OWS	9%	11%	70%	21%	100%	7%	15%	10%	3%
Roads	24%	38%	11%	14%	15%	100%	23%	28%	18%
RR, Abandoned	1%	0%	0%	0%	0%	0%	100%	5%	0%
RR, Active	9%	18%	1%	12%	7%	9%	100%	100%	6%
Tidal Barriers	22%	17%	0%	8%	5%	12%	0%	13%	100%

Table 30. Co-occurrence of shoreline alterations (tier 2 stressors) in Hood Canal Sub-Basin.

Stressors	Stressors								
	Armoring	BW/J	Marinas	Nearshore Fill	OWS	Roads	RR, Abandoned	RR, Active	Tidal Barriers
Armoring	100%	1%	19%	27%	45%	34%	--	--	1%
BW/J	0%	100%	0%	0%	0%	1%	--	--	5%
Marinas	0%	0%	100%	1%	9%	0%	--	--	0%
Nearshore Fill	5%	0%	10%	100%	11%	4%	--	--	14%
OWS	8%	0%	84%	10%	100%	4%	--	--	3%
Roads	21%	21%	4%	13%	17%	100%	--	--	40%
RR, Abandoned	0%	0%	0%	0%	0%	0%	--	--	0%
RR, Active	0%	0%	0%	0%	0%	0%	--	--	0%
Tidal Barriers	0%	76%	0%	23%	5%	19%	--	--	100%

Table 31. Co-occurrence of shoreline alterations (tier 2 stressors) in North Central Puget Sound Sub-Basin.

Stressors	Stressors								
	Armoring	BW/J	Marinas	Nearshore Fill	OWS	Roads	RR, Abandoned	RR, Active	Tidal Barriers
Armoring	100%	99%	62%	37%	26%	28%	--	100%	3%
BW/J	15%	100%	62%	15%	20%	3%	--	0%	0%
Marinas	9%	57%	100%	10%	25%	6%	--	0%	0%
Nearshore Fill	31%	85%	63%	100%	52%	21%	--	0%	0%
OWS	12%	58%	80%	27%	100%	8%	--	100%	0%
Roads	8%	6%	12%	7%	5%	100%	--	0%	13%
RR, Abandoned	0%	0%	0%	0%	0%	0%	--	0%	0%
RR, Active	0%	0%	0%	0%	0%	0%	--	100%	0%
Tidal Barriers	0%	0%	0%	0%	0%	7%	--	0%	100%

Table 32. Co-occurrence of shoreline alterations (tier 2 stressors) in Whidbey Sub-Basin.

Stressors	Stressors								
	Armoring	BW/J	Marinas	Nearshore Fill	OWS	Roads	RR, Abandoned	RR, Active	Tidal Barriers
Armoring	100%	32%	64%	52%	56%	14%	--	68%	9%
BW/J	3%	100%	17%	8%	15%	0%	--	0%	2%
Marinas	5%	15%	100%	10%	47%	1%	--	0%	0%
Nearshore Fill	38%	58%	88%	100%	73%	10%	--	44%	7%
OWS	8%	23%	88%	15%	100%	3%	--	9%	2%
Roads	8%	1%	7%	8%	12%	100%	--	20%	32%
RR, Abandoned	0%	0%	0%	0%	0%	0%	--	0%	0%
RR, Active	3%	0%	0%	2%	2%	1%	--	100%	1%
Tidal Barriers	11%	19%	6%	12%	13%	67%	--	25%	100%

Table 33. Co-occurrence of shoreline alterations (tier 2 stressors) in South Central Puget Sound Sub-Basin.

Stressors	Stressors								
	Armoring	BW/J	Marinas	Nearshore Fill	OWS	Roads	RR, Abandoned	RR, Active	Tidal Barriers
Armoring	100%	84%	87%	82%	89%	82%	--	94%	15%
BW/J	3%	100%	30%	6%	12%	1%	--	2%	0%
Marinas	5%	52%	100%	9%	26%	4%	--	1%	0%
Nearshore Fill	32%	71%	57%	100%	56%	19%	--	69%	16%
OWS	17%	70%	86%	28%	100%	18%	--	9%	2%
Roads	22%	7%	20%	13%	25%	100%	--	22%	67%
RR, Abandoned	0%	0%	0%	0%	0%	0%	--	0%	0%
RR, Active	4%	3%	1%	8%	2%	4%	--	100%	3%
Tidal Barriers	0%	0%	0%	1%	0%	8%	--	2%	100%

Table 34. Co-occurrence of shoreline alterations (tier 2 stressors) in South Puget Sound Sub-Basin.

Stressors	Stressors								
	Armoring	BW/J	Marinas	Nearshore Fill	OWS	Roads	RR, Abandoned	RR, Active	Tidal Barriers
Armoring	100%	94%	93%	87%	61%	36%	0%	81%	34%
BW/J	0%	100%	16%	0%	3%	0%	0%	0%	0%
Marinas	2%	86%	100%	6%	15%	0%	0%	3%	0%
Nearshore Fill	18%	25%	67%	100%	26%	12%	2%	91%	7%
OWS	7%	89%	95%	14%	100%	6%	47%	7%	2%
Roads	9%	4%	6%	14%	13%	100%	30%	6%	50%
RR, Abandoned	0%	0%	0%	0%	12%	4%	100%	0%	15%
RR, Active	7%	0%	13%	38%	6%	2%	0%	100%	4%
Tidal Barriers	3%	0%	0%	3%	2%	18%	46%	4%	100%

Nearshore Ecosystem Impairment

The preceding sections have enumerated the types and degrees of changes to shoreforms, shoreline attributes, and watershed characteristics. We then used Ecosystem Functions Goods and Services (EFG&S) in an exercise to compare the changes at all these levels, creating a qualitative "impairment score" that summarizes the possible effects of these changes on services of "value" to humans. As described in the Methods section, the PSNERP NST approach was not to select or weight any specific ecosystem function, good, or service, but to examine the total suite of EFG&S that could be altered by the documented changes.

Using this ranking process, nearshore ecosystem impairment at the Sound-wide scale is extremely variable, both among and within sub-regions (Figs. 182–185). As might be anticipated from the level of change described in preceding sections, the more developed sub-regions (e.g., South Central, South Puget Sound, and Whidbey) and areas of the Sound demonstrate some of the highest relative impairment, most evidently for shoreform transitions and shoreline alterations (Figs. 182–183). Conversely, the Strait of Juan de Fuca, San Juan Islands–Strait of Georgia, Hood Canal, and often components of South Puget Sound illustrate moderate or low relative impairment, especially from the standpoint of changes in the adjacent upland and total watershed area.

We have calculated and illustrated impairment scores at both the Sound-wide and the individual sub-basin scales (Figs. 186–199).

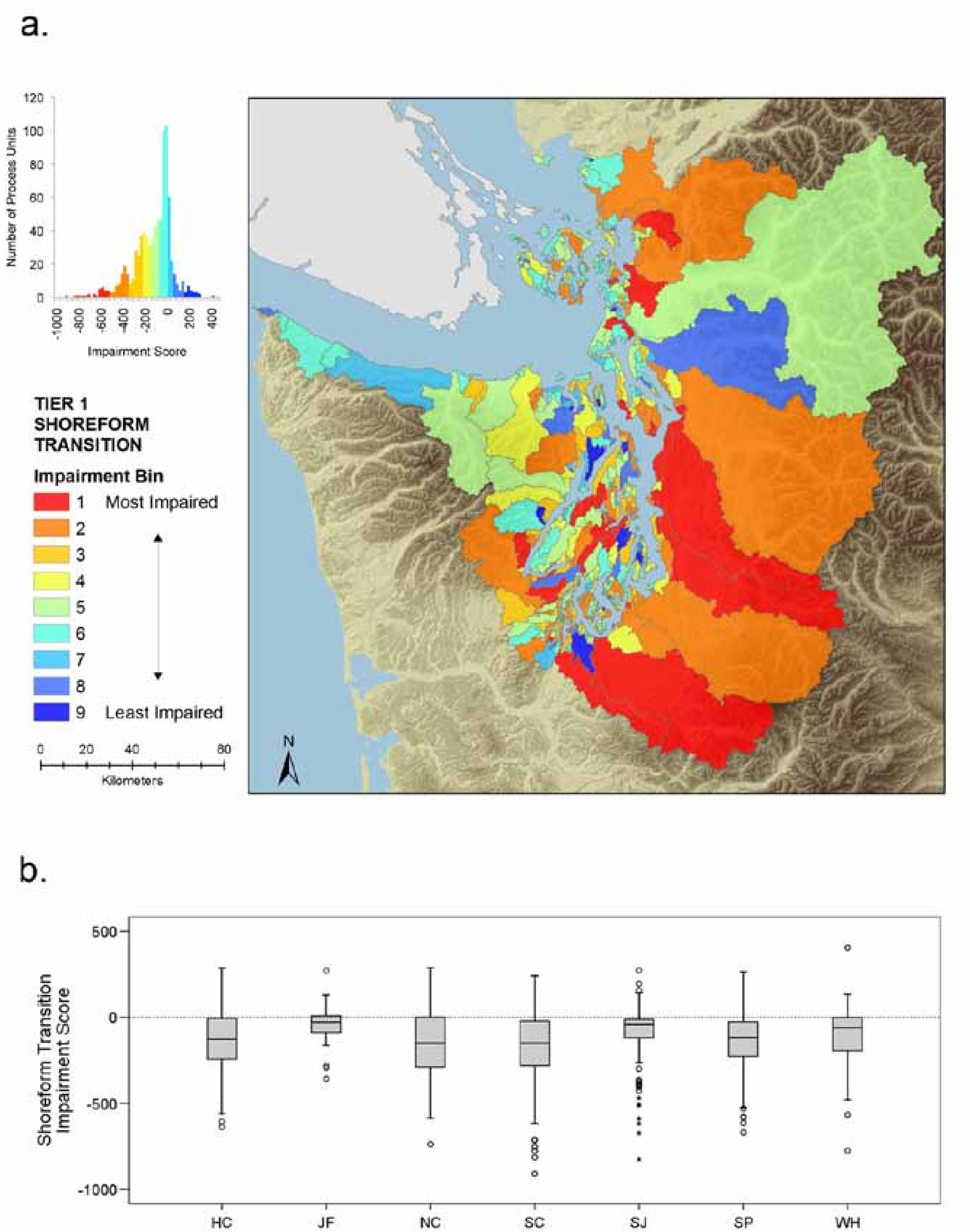


Figure 182. a) right: Potential nearshore ecosystem impairment due to shoreform transitions (Tier 1) among Sound-wide process units (PU) symbolized by Impairment Bin. a) left: Frequency distribution of Impairment Scores. b) Range of Impairment Scores by sub-basin. Boxplot shows the median, interquartile range (box length), outliers (cases with values between 1.5 and 3 box lengths from the upper or lower edge of the box), and extreme cases of individual variables (cases with values more than 3 box lengths from the upper or lower edge of the box).

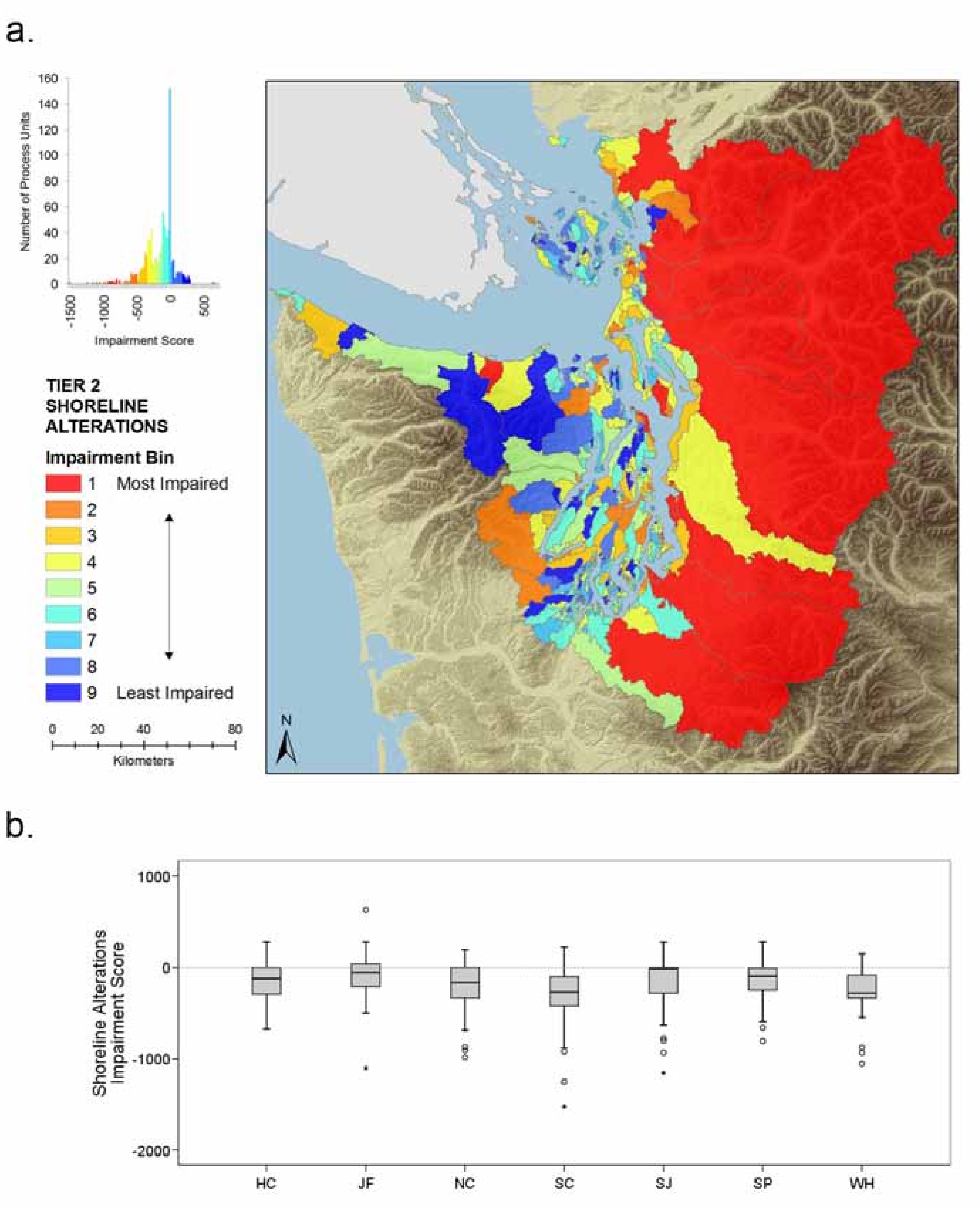


Figure 183. a) right: Potential nearshore ecosystem impairment due to shoreline alterations (Tier 2) among Sound-wide process units (PU) symbolized by Impairment Bin. a) left: Frequency distribution of Impairment Scores. b) Range of Impairment Scores by sub-basin. Boxplot shows the median, interquartile range (box length), outliers (cases with values between 1.5 and 3 box lengths from the upper or lower edge of the box), and extreme cases of individual variables (cases with values more than 3 box lengths from the upper or lower edge of the box).

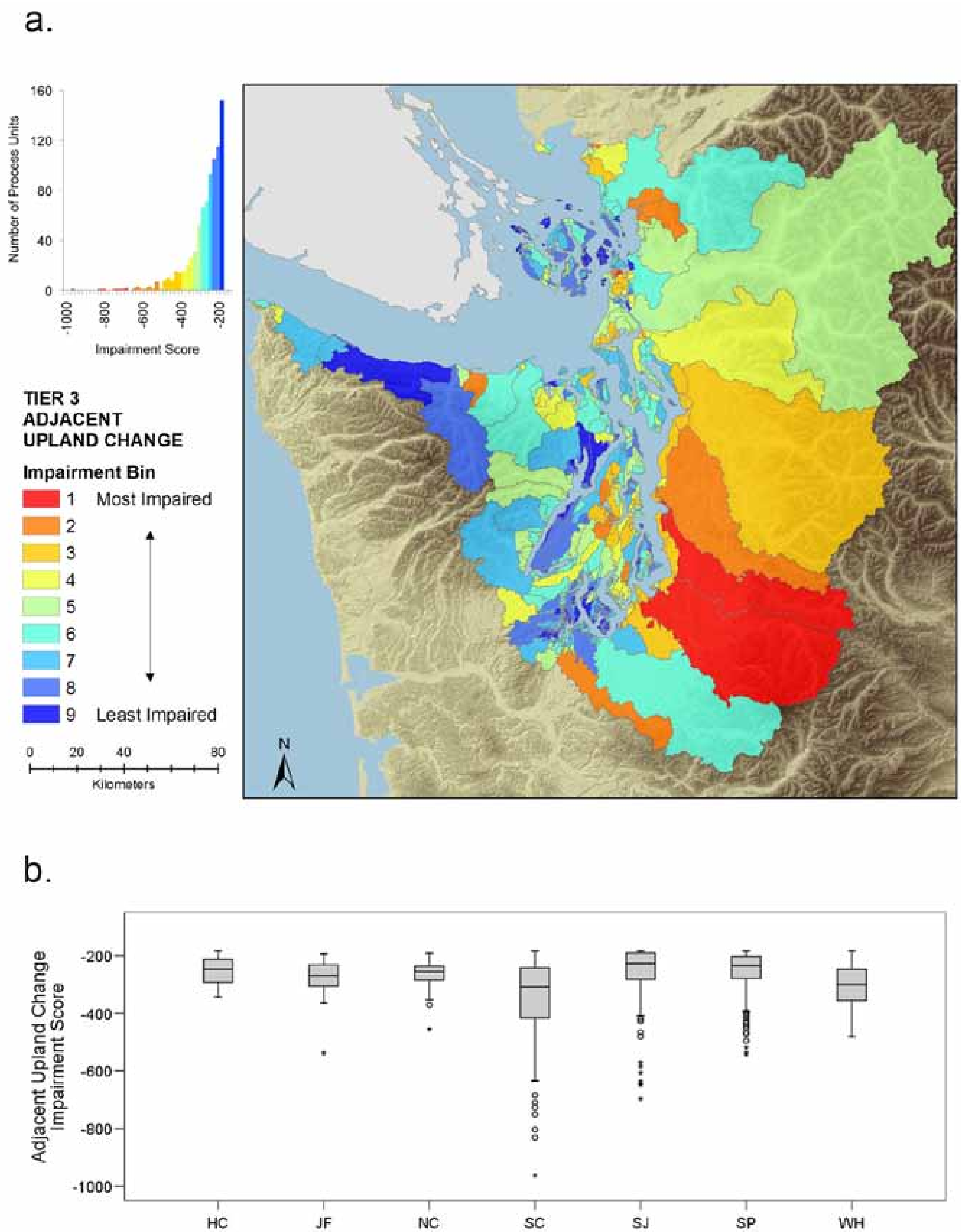


Figure 184. a) right: Potential nearshore ecosystem impairment due to adjacent upland change (Tier3) among Sound-wide process units (PU) symbolized by Impairment Bin. a) left: Frequency distribution of Impairment Scores. b) Range of Impairment Scores by sub-basin. Boxplot shows the median, interquartile range (box length), outliers (cases with values between 1.5 and 3 box lengths from the upper or lower edge of the box), and extreme cases of individual variables (cases with values more than 3 box lengths from the upper or lower edge of the box).

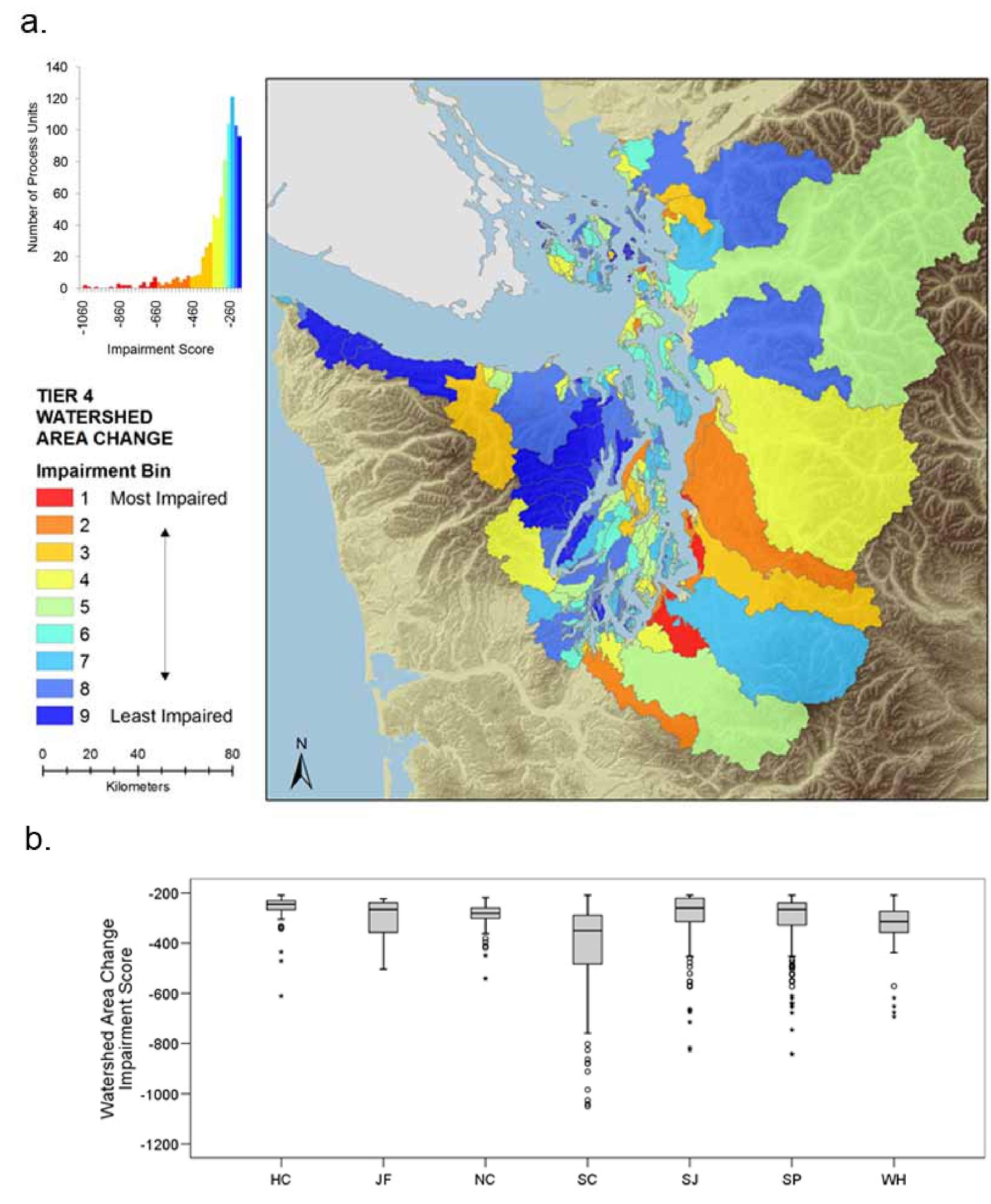


Figure 185. a) right: Potential nearshore ecosystem impairment due to watershed area change (Tier4) among Sound-wide process units (PU) symbolized by Impairment Bin. a) left: Frequency distribution of Impairment Scores. b) Range of Impairment Scores by sub-basin. Boxplot shows the median, interquartile range (box length), outliers (cases with values between 1.5 and 3 box lengths from the upper or lower edge of the box), and extreme cases of individual variables (cases with values more than 3 box lengths from the upper or lower edge of the box).

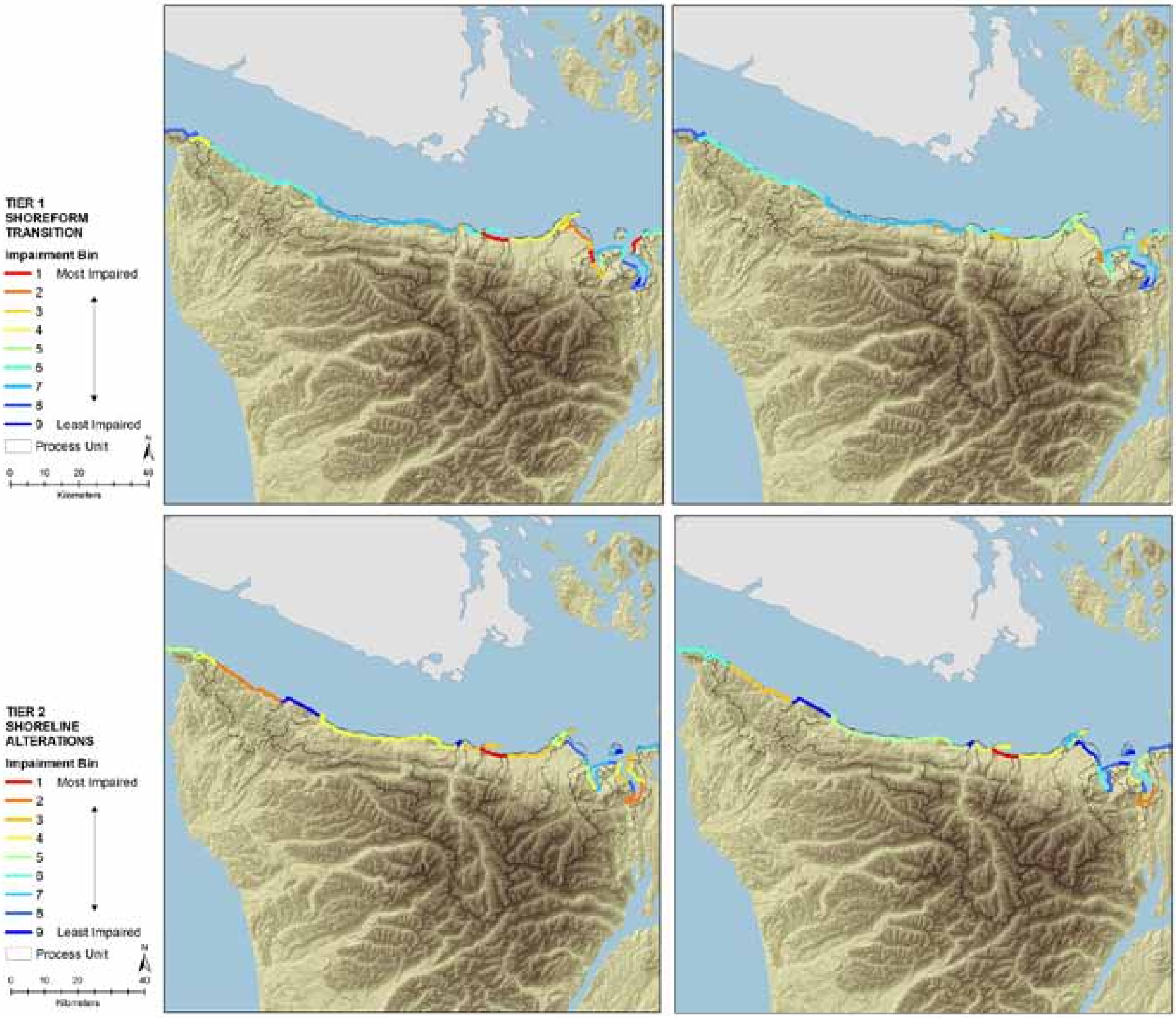


Figure 186. Sub-basin (left) and Sound-wide (right) scales of potential nearshore ecosystem impairment due to shoreform change and transition (Tier 1; top) and shoreline alterations (Tier 2; bottom) among Strait of Juan de Fuca Sub-Basin process units (PU) symbolized by impairment bin.

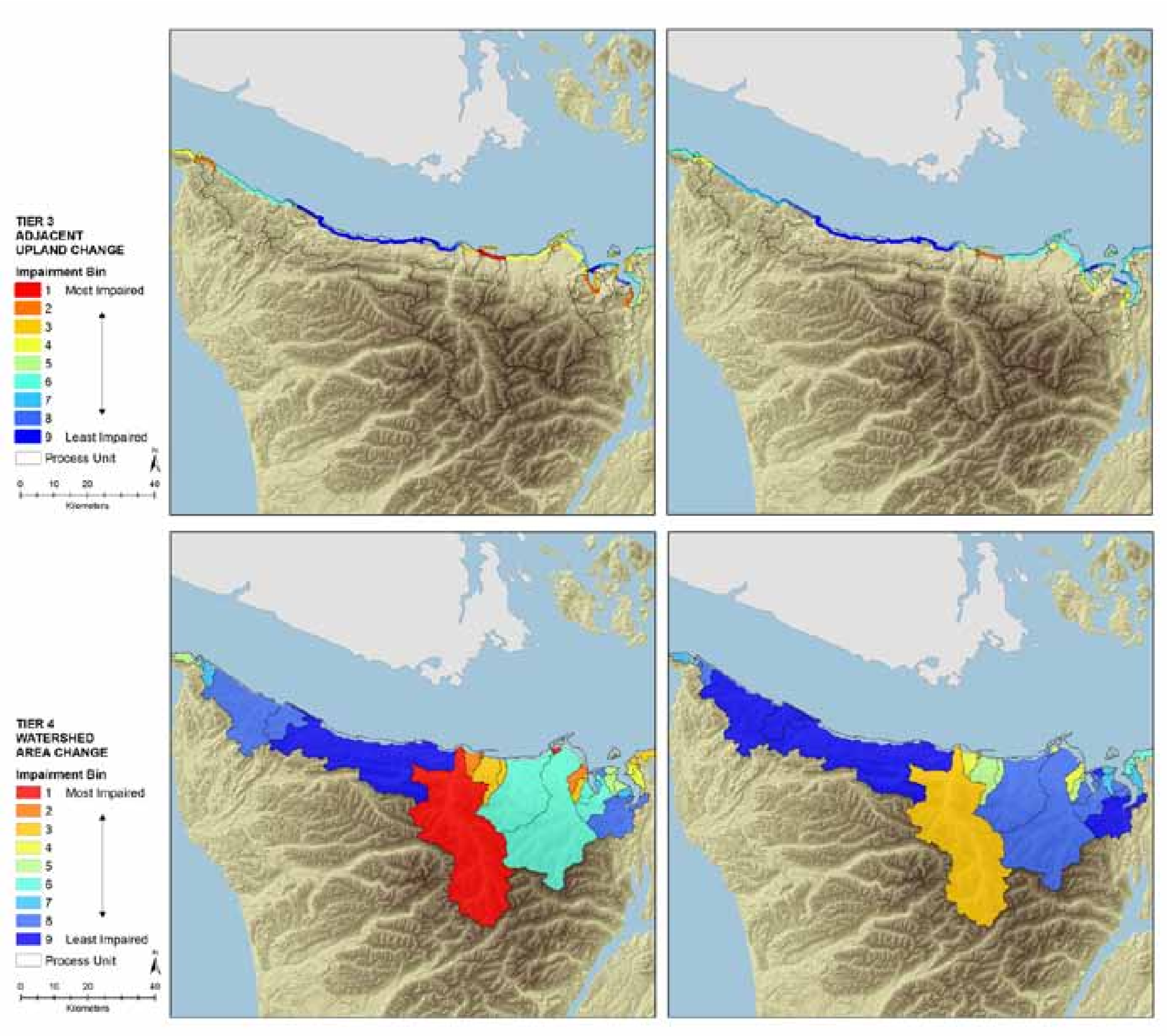


Figure 187. Sub-basin (left) and Sound-wide (right) scales of potential nearshore ecosystem impairment due to adjacent upland change (Tier 3; top) and watershed change (Tier 4; bottom) among Strait of Juan de Fuca Sub-Basin process units (PU) symbolized by impairment bin.

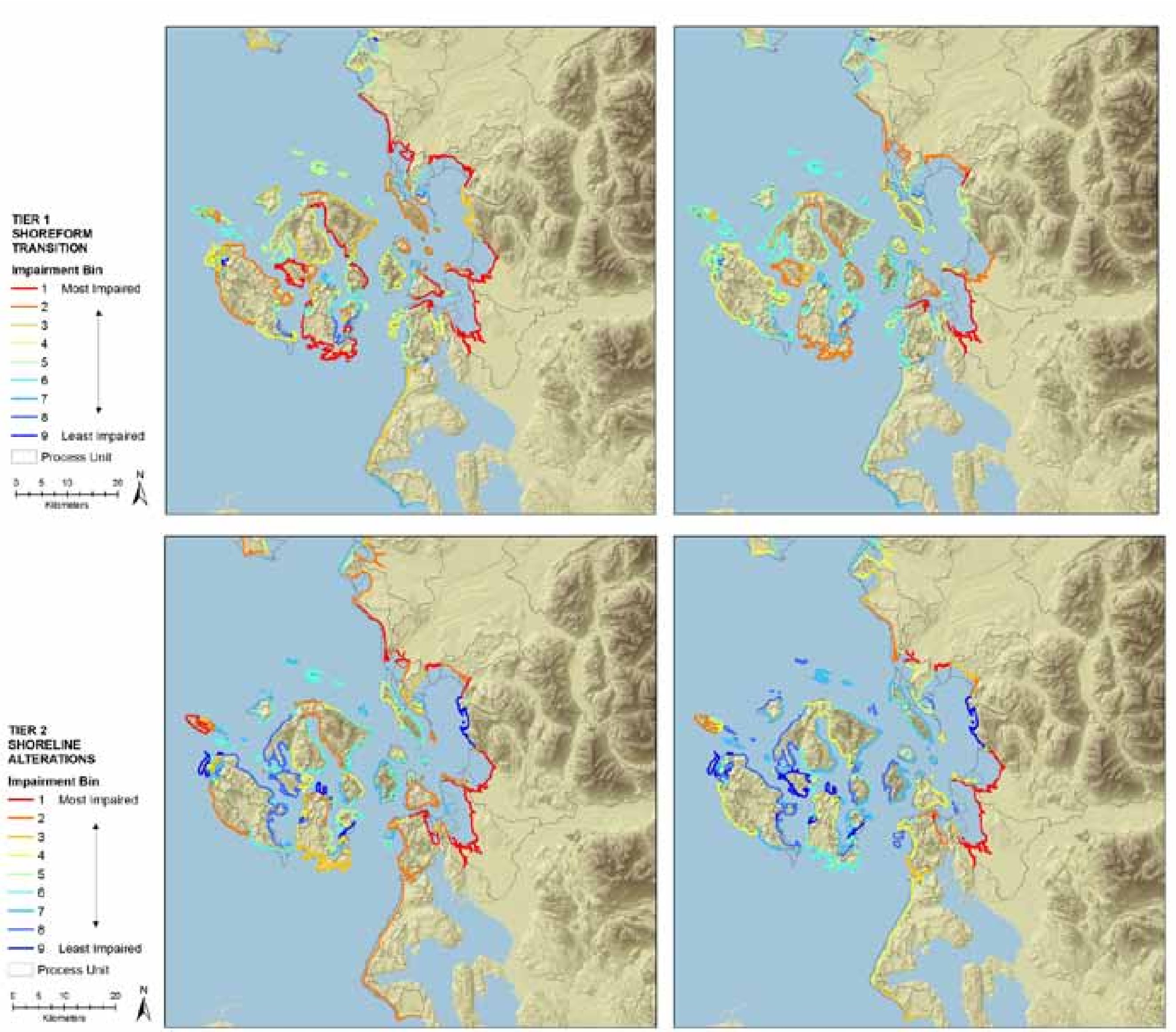


Figure 188. Sub-basin (left) and Sound-wide (right) scales of potential nearshore ecosystem impairment due to shoreform transition (Tier 1; top) and shoreline alterations (Tier 2; bottom) among San Juan Islands–Strait of Georgia Sub-Basin process units (PU) symbolized by impairment bin.

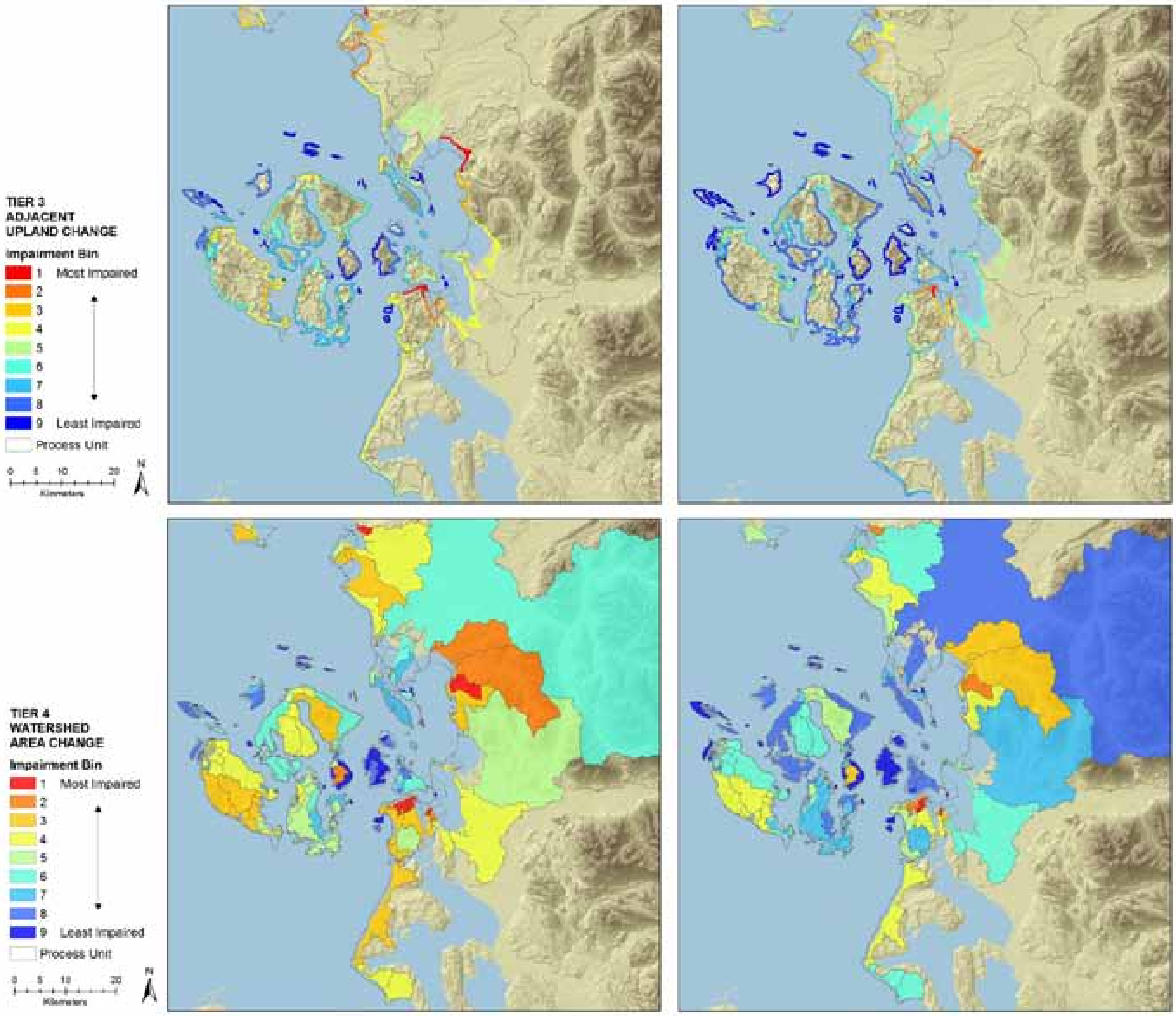


Figure 189. Sub-basin (left) and Sound-wide (right) scales of potential nearshore ecosystem impairment due to adjacent upland change (Tier 3; top) and watershed change (Tier 4; bottom) among San Juan Islands–Strait of Georgia Sub-Basin process units (PU) symbolized by impairment bin.

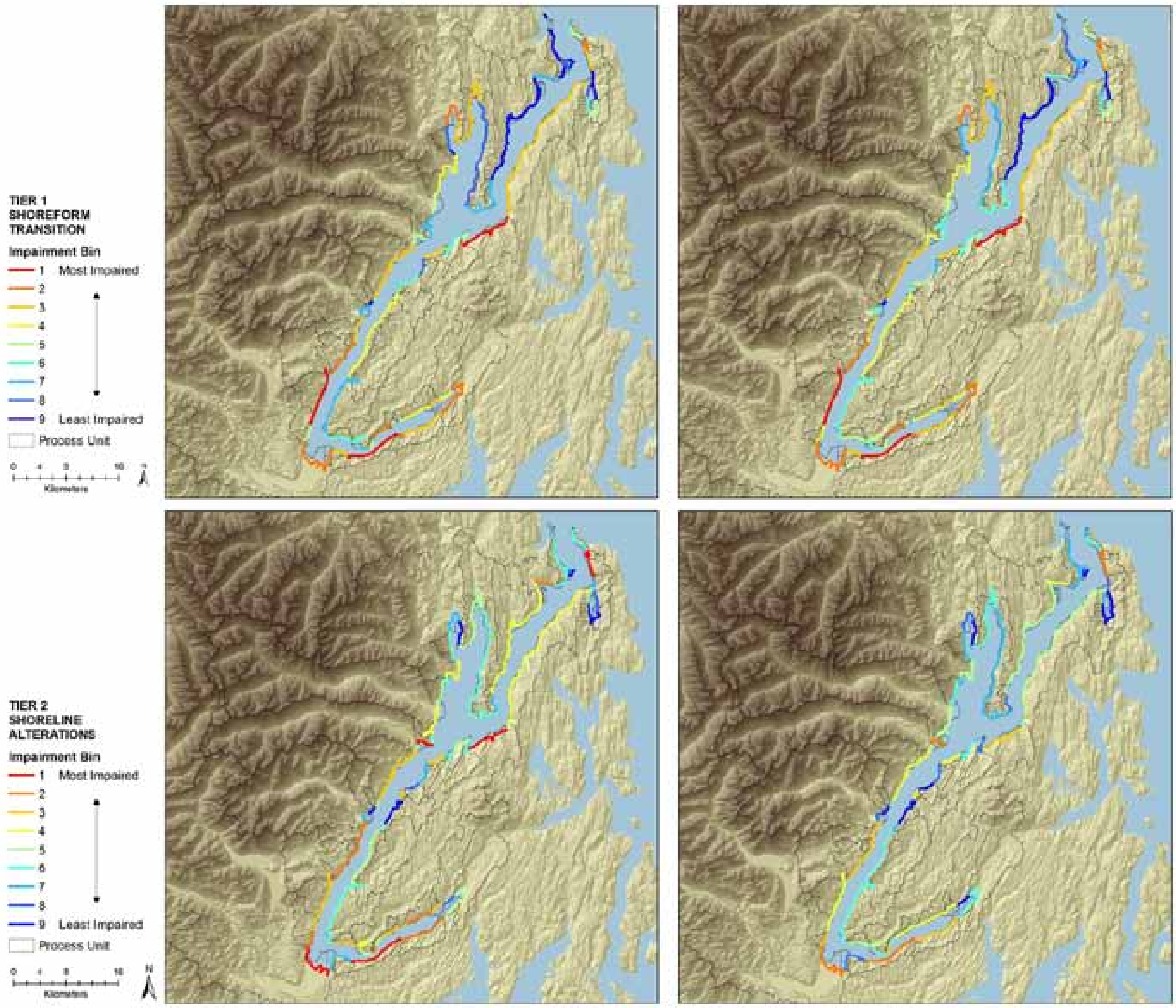


Figure 190. Sub-basin (left) and Sound-wide (right) scales of potential nearshore ecosystem impairment due to shoreform transition (Tier 1; top) and shoreline alterations (Tier 2; bottom) among Hood Canal Sub-Basin process units (PU) symbolized by impairment bin.

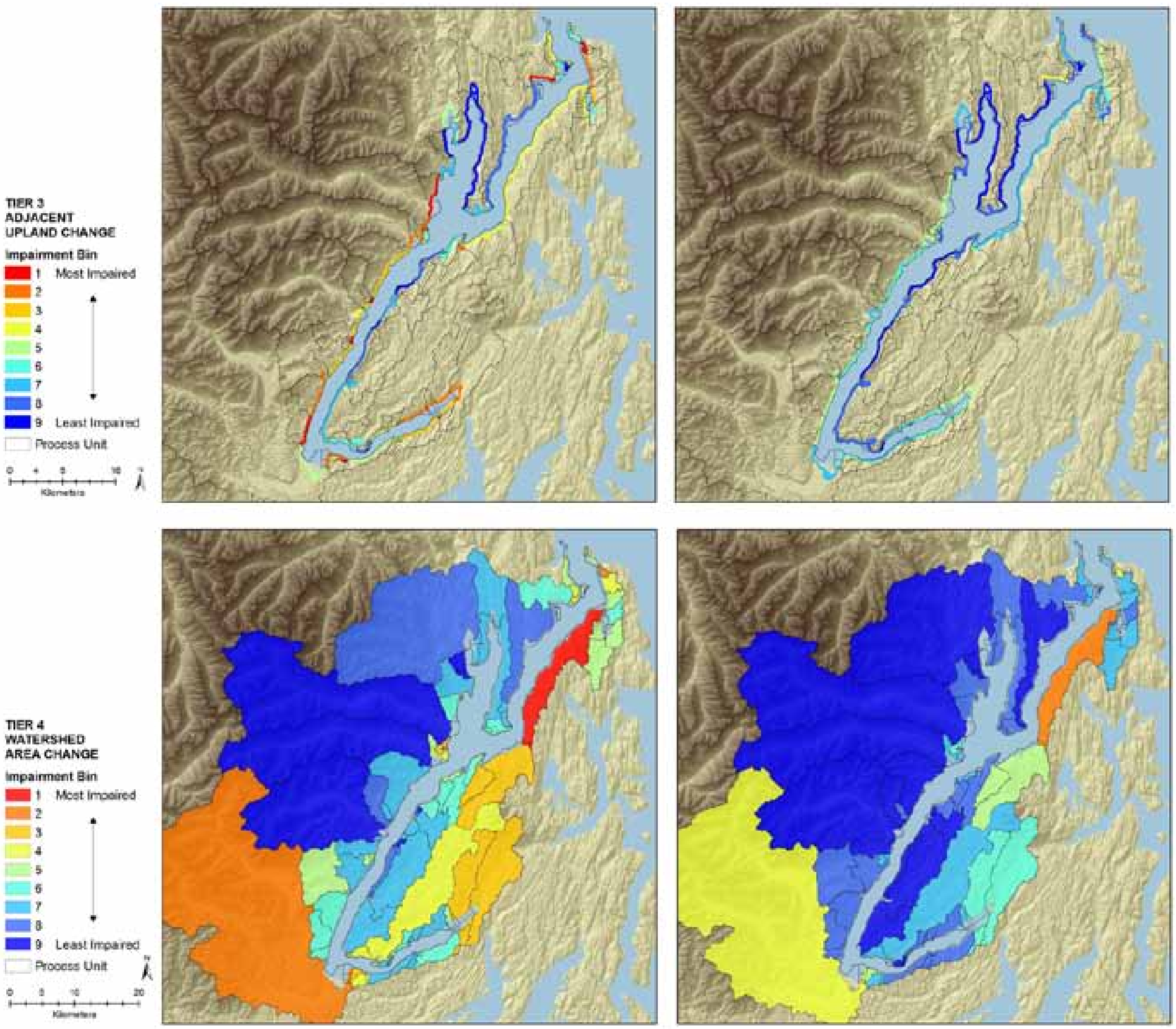


Figure 191. Sub-basin (left) and Sound-wide (right) scales of potential nearshore ecosystem impairment due to adjacent upland change (Tier 3; top) and watershed change (Tier 4; bottom) among Hood Canal Sub-Basin process units (PU) symbolized by impairment bin.

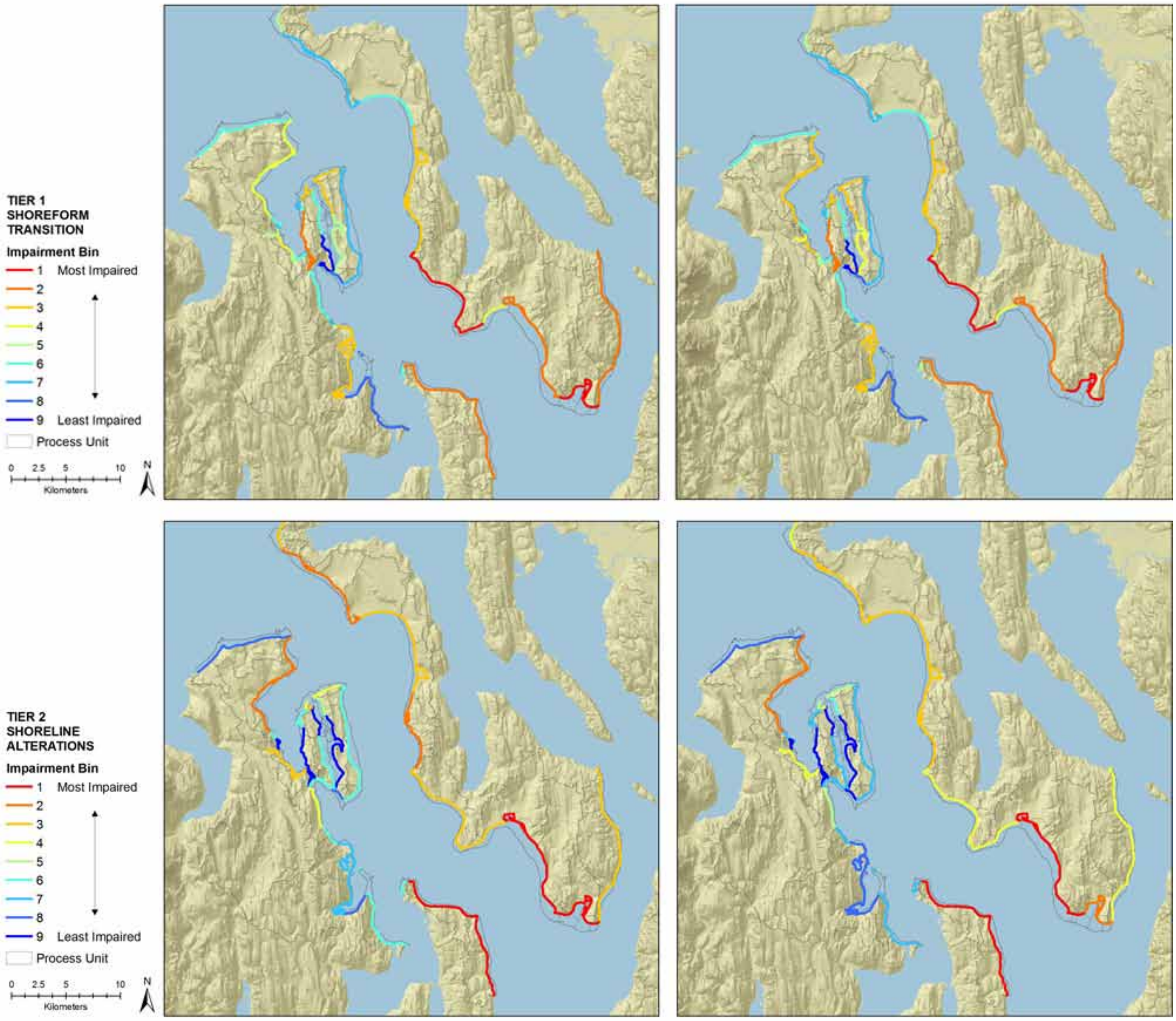


Figure 192. Sub-basin (left) and Sound-wide (right) scales of potential nearshore ecosystem impairment due to shoreform transition (Tier 1; top) and shoreline alterations (Tier 2; bottom) among North Central Puget Sound Sub-Basin process units (PU) symbolized by impairment bin.

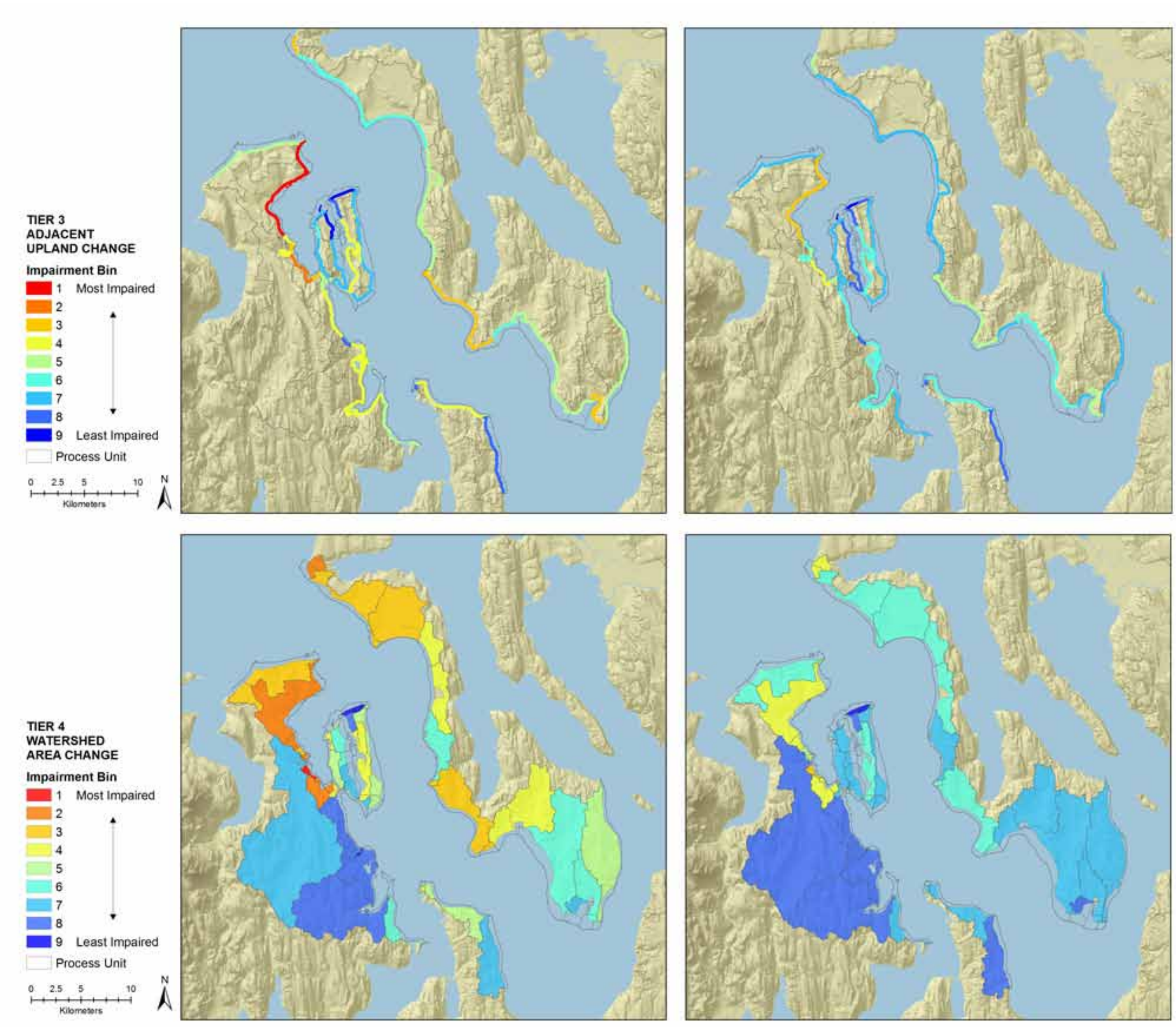


Figure 193. Sub-basin (left) and Sound-wide (right) scales of potential nearshore ecosystem impairment due to adjacent upland change (Tier 3; top) and watershed change (Tier 4; bottom) among North Central Puget Sound Sub-Basin process units (PU) symbolized by impairment bin.

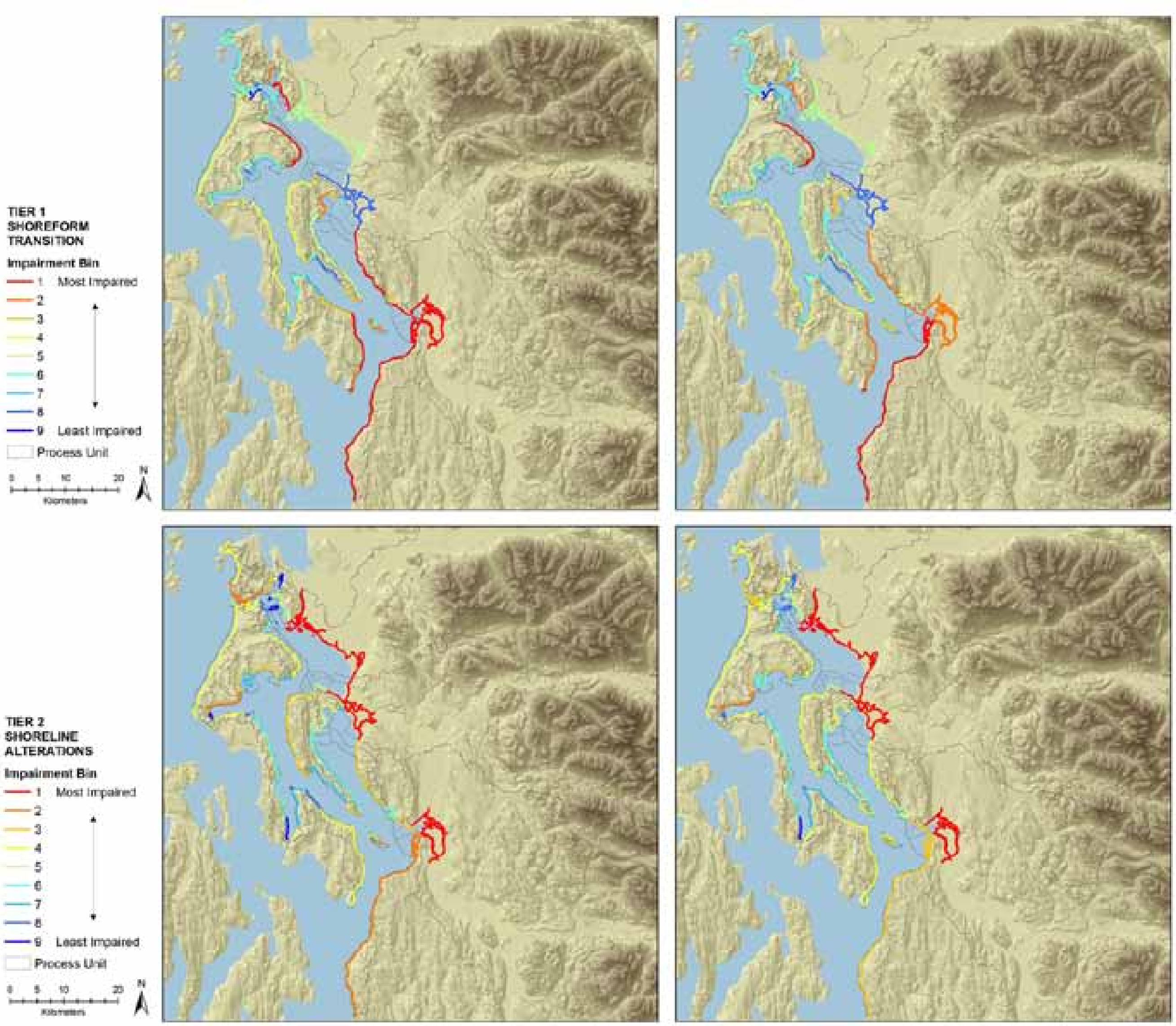


Figure 194. Sub-basin (left) and Sound-wide (right) scales of potential nearshore ecosystem impairment due to shoreform transition (Tier 1; top) and shoreline alterations (Tier 2; bottom) among Whidbey Sub-Basin process units (PU) symbolized by impairment bin.

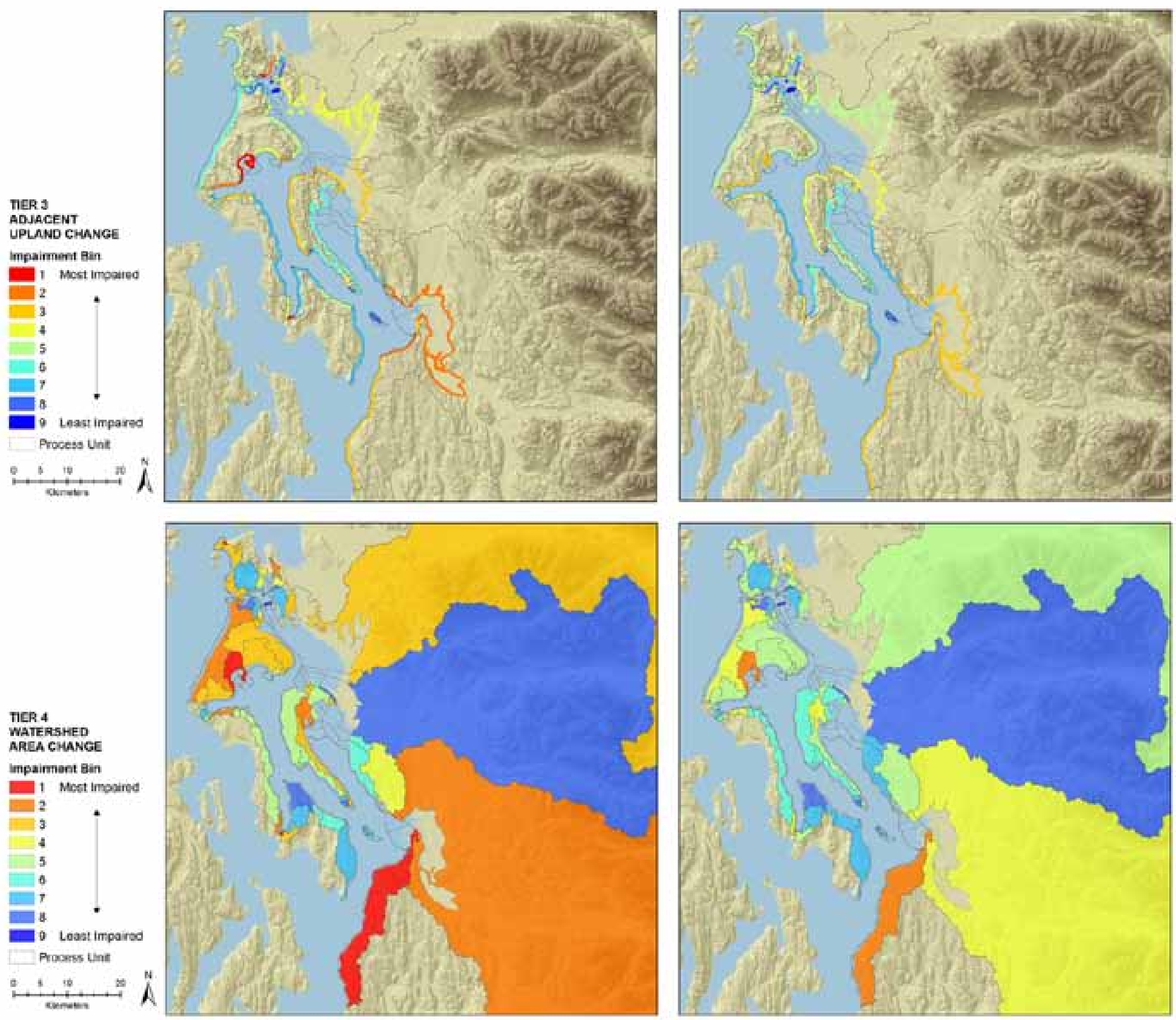


Figure 195. Sub-basin (left) and Sound-wide (right) scales of potential nearshore ecosystem impairment due to adjacent upland change (Tier 3; top) and watershed change (Tier 4; bottom) among Whidbey Sub-Basin process units (PU) symbolized by impairment bin.

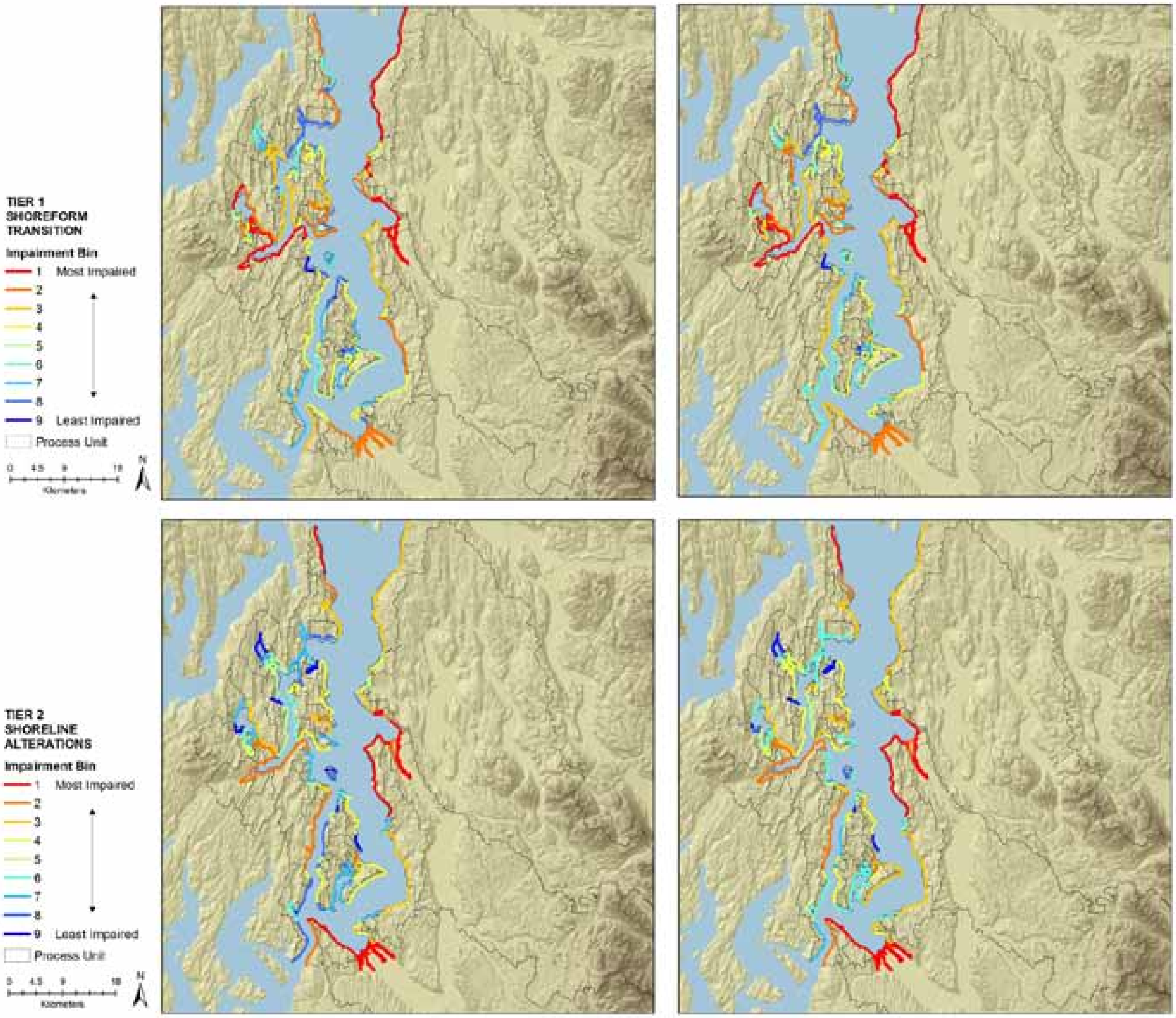


Figure 196. Sub-basin (left) and Sound-wide (right) scales of potential nearshore ecosystem impairment due to shoreform transition (Tier 1; top) and shoreline alterations (Tier 2; bottom) among South Central Puget Sound Sub-Basin process units (PU) symbolized by impairment bin.

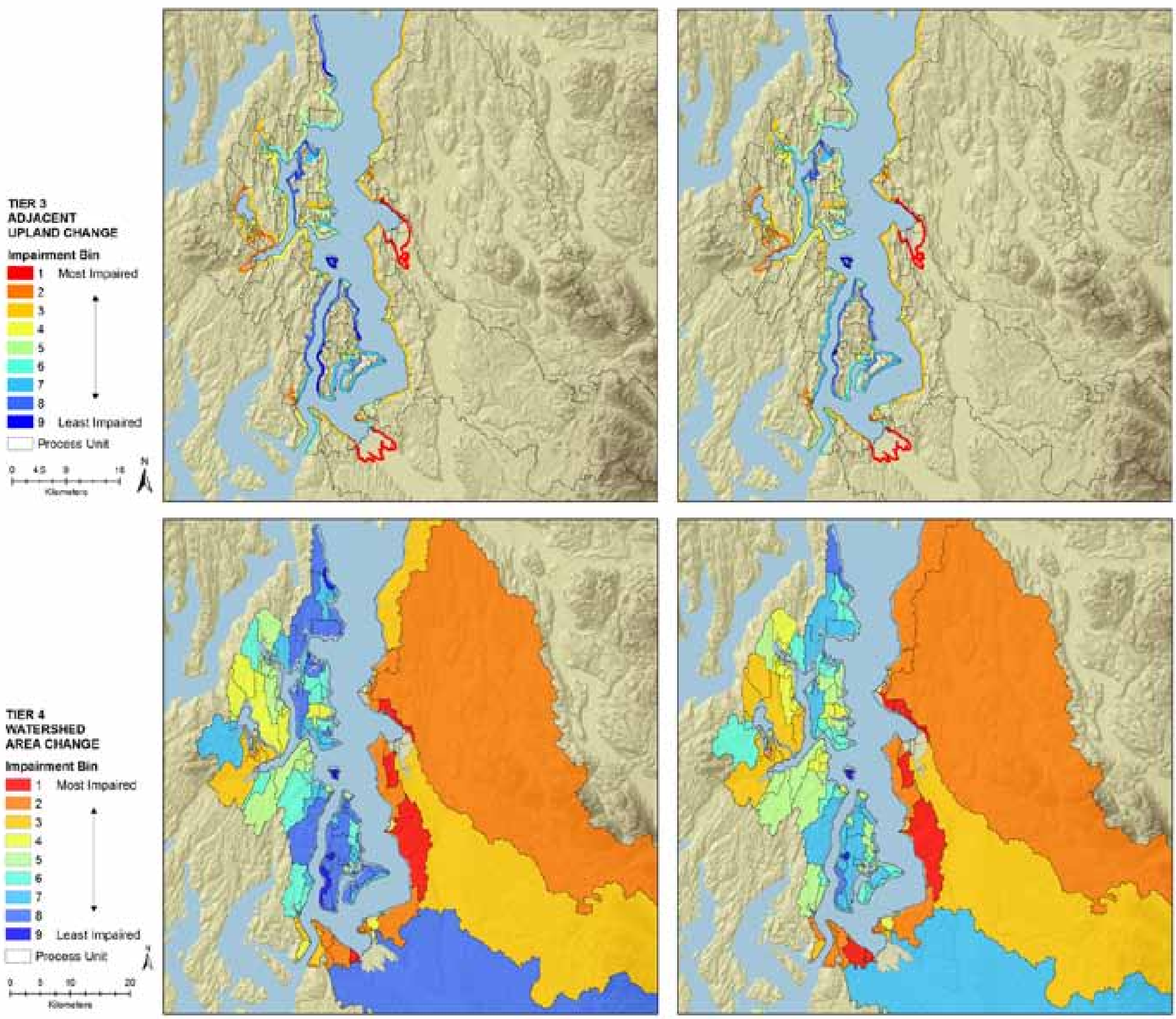


Figure 197. Sub-basin (left) and Sound-wide (right) scales of potential nearshore ecosystem impairment due to adjacent upland change (Tier 3; top) and watershed change (Tier 4; bottom) among South Central Puget Sound Sub-Basin process units (PU) symbolized by impairment bin.

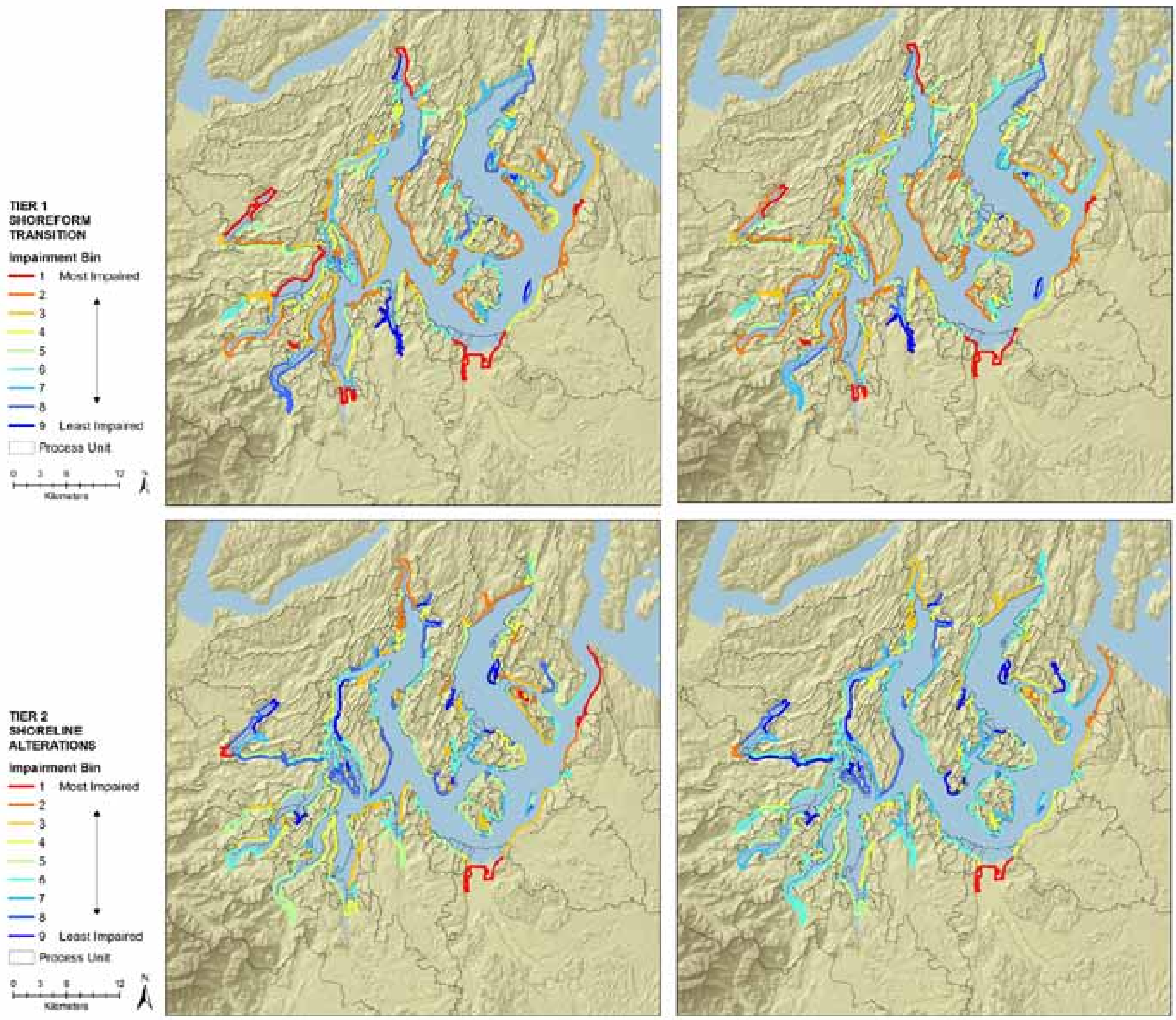


Figure 198. Sub-basin (left) and Sound-wide (right) scales of potential nearshore ecosystem impairment due to shoreform transition (Tier 1; top) and shoreline alterations (Tier 2; bottom) among South Puget Sound Sub-Basin process units (PU) symbolized by impairment bin.

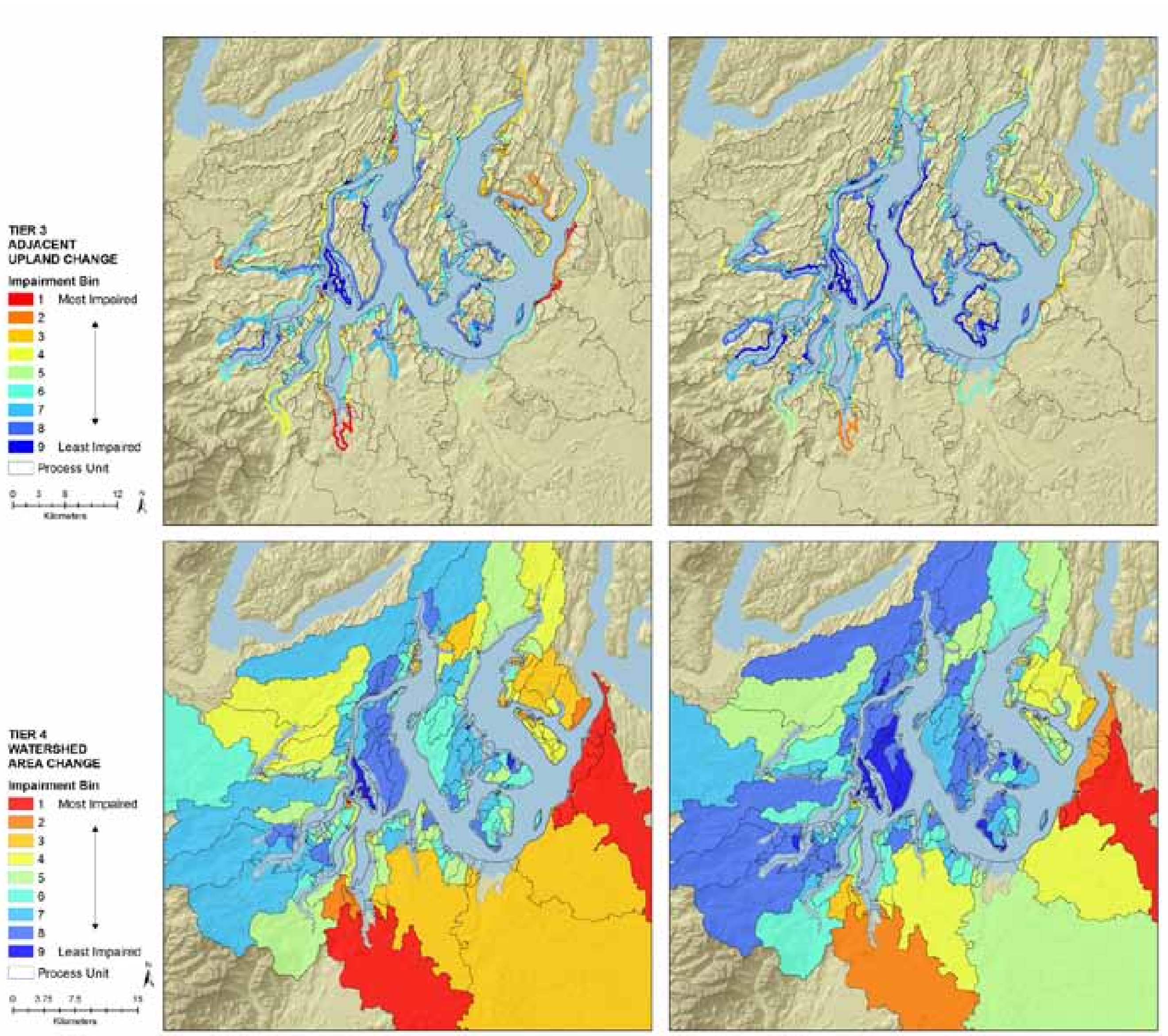


Figure 199. Sub-basin (left) and Sound-wide (right) scales of potential nearshore ecosystem impairment due to adjacent upland change (Tier 3; top) and watershed change (Tier 4; bottom) among South Puget Sound Sub-Basin process units (PU) symbolized by impairment bin.

Discussion

It is important to understand that some of the geomorphic and ecosystem changes described here can be a function of naturally dynamic shoreline processes or anthropogenically forced and relatively permanent. However, most of the uncertainty about the source of change is limited to a few (Tier 1) shoreform transitions, specifically closely related embayment shoreforms (i.e., closed lagoon and marsh, open lagoon, barrier estuary). These potential natural transitions constitute only 2 percent of the 791 observed total transitions (Table 6). The vast majority of more certain transitions involve natural shoreforms that are currently unrecognizable because they have changed to the anthropogenic "Artificial" or "Not Present" class (84 percent). The other levels of change (Tiers 2–4) are based almost entirely on verified, anthropogenic features that potentially stress or impair nearshore ecosystem processes. Without much more intensive investigation, e.g., more frequent intervals of data on geomorphic structure, we have a limited ability to determine the frequency of change in the closely related embayment shoreforms. Transition cases such as these require further investigation because these changes could have been affected by shoreline development elsewhere in the process unit, which could alter nearshore processes that modify shoreforms (e.g., reduction in sediment delivery and transport along the barrier beach to the embayment shoreform, or changes in freshwater inflow to the embayment). Similarly, some error is likely associated with interpretation of historic change in estuarine wetland areas, especially associated with large-percentage changes in estimates for small areas, made with different methods and mapping scales (Table 8). Some of these changes could be attributable to natural expansion or shifts in area of the respective wetland classes, but watershed-scale changes (e.g., river flow diversion and regulation) could also affect compositional and distributional changes in the different estuarine wetland classes.

Changes and Impairment Puget Sound-Wide

The PSNERP Change Analysis geodatabase documents changes over the (current) approximately 3970 km of Puget Sound shoreline and commensurate 36,080 km2 of drainage area. Among the seven PSNERP sub-basins, the Whidbey Sub-Basin dominates (40.7 percent) the total drainage area, followed by South Central Puget Sound Sub-Basin (17.9 percent), South Puget Sound and San Juan Islands–Strait of Georgia sub-basins (12.8–11.6 percent), Strait of Juan de Fuca and Hood Canal (9.0–7.7 percent), and North Central Sub-Basin as the smallest (1.4 percent) drainage area. However, the San Juan Islands–Strait of Georgia Sub-Basin dominates in terms of the nearshore zone (28.5 percent) and shoreline length (29.9 percent), whereas the North Central Sub-Basin ranks the lowest (5.6 percent and 6.3 percent, respectively). Stream confluences are most abundant in the Hood Canal and South Puget Sound sub-basins, and least abundant in the North Central Sub-Basin.

Change is characterized at each of 828 process units: 812 SPU and 16 DPU. Including the shoreline zone and the total watershed area, the mean area of all PU is almost 50 km2 (range 0.8–7300 km2), with most PU occurring between 1 and 10,000 km2. The mean area of the 812 SPU alone is 18.6 (min. <0.1–1,562.0 km2); the mean area of the 16 DPU is 1,619.5 km2 (204.0–7300.6 km2). Composition of the drift cell component of the SPU is quite similar among the sub-basins, where a prominent source of beach sediments from the divergence zone constitutes 2 percent to 10 percent; the sediment transport zone is 35–74 percent; and the divergence zone, where most sediments either accumulate or are transported into deep water, is 1–3 percent of the total SPU length. "No appreciable drift" is the most variable component, composing between 13 percent and 62 percent of the SPU.

Shoreform Transition (Tier 1)

Very few nearshore PU of Puget Sound are unchanged; most of the changes are due to human alterations. The most pervasive change Sound-wide is the simplification of the shoreline—reduction of SPU and DPU shoreline length. Within our acceptable level of mapping uncertainty, the shoreline of Puget Sound has declined measurably: total shoreline length of all shoreforms combined, including deltas, declined by approximately 15 percent Sound-wide. The complexity of beach, embayment, and rocky shoreforms declined the least in the Strait of Juan de Fuca (−7.2 percent averaged across all natural shoreforms) and Hood Canal (−19.1 percent), but considerably more in South Central Puget Sound (−36.4 percent) and the San Juan Islands–Strait of Georgia (−26.2 percent) sub-basins; the greatest decline in delta shoreline length was in South Central Puget Sound (−100 percent) and South Puget Sound (−73.6 percent), but the lowest decline in shoreline complexity was still significant (−37.2 percent in the Whidbey Sub-Basin). Because of the size of the deltas, the 41 percent decrease in length of that shoreform alone accounted for much of the observed simplification of nearshore Puget Sound.

Multivariate analysis of the shoreform data indicate that the historical shoreform compositions were dominated by three distinct groups of similar SPU: 1) predominantly bluff-backed beach and, to a lesser extent, barrier beach and some barrier estuary segments; 2) bluff-backed beach and open coastal inlet; and 3) plunging rocky, rocky platform, and pocket beach. Similar analysis of the current shoreform composition indicates somewhat similar statistical groups, with a loss of complexity, where bluff-backed beach and, to a lesser extent, barrier beach dominated SPU are still numerically prominent, but barrier estuaries are not represented.

The most obvious change is a group of 15 SPU distinguished entirely by artificial shoreforms.

Shoreline Alterations (Tier 2)

The total area of wetlands in Puget Sound has declined dramatically in most deltas, and particularly the more upper-estuary, fresher classes—tidal freshwater and oligohaline transition—where 115.2 (–90.0 percent) and 62.6 km2 (–97.8 percent) has disappeared, respectively. Loss of 54.5 and 40.5 km2 of estuarine mixing and euryhaline unvegetated wetlands is also notable, but proportionally less, –34.6 and –24.4 percent, respectively. The largest overall losses occurred in the South Central Puget Sound and Whidbey sub-basins. Among the individual deltas, the Skagit River delta has suffered the greatest absolute change, –22.5 and –25.7 km2 of tidal freshwater and oligohaline transition wetlands, respectively. As might be expected, the heavily industrialized and urbanized Duwamish and Puyallup River deltas have suffered the greatest proportional losses (approximately 95–100 percent in all wetland classes), but the absolute wetland loss is considerably less. However, it should be recognized that an unknown proportion of these deltas had already been changed by the time of the historical surveys. Other deltas with significant estuarine wetland losses include 47.9 km2 (–90.2 percent) and 11.7 km2 (–95.5 percent) decline of freshwater tidal wetlands in the Snohomish and Nooksack rivers deltas, respectively, and 13.1 km2 (–100 percent) loss of oligohaline transition wetlands in the Snohomish River delta.

Only 6.5 percent (54) process units surrounding Puget Sound lack any modification today. Shoreline alterations within the wetted nearshore zone, or within 25 m of the shoreline in the case of "nearshore roads" and railroads over the entire Puget Sound Basin constitute as little as 0.4 percent (abandoned railroads) to as much as 27 percent (armoring) of the shoreline length. Nearshore fill and breakwaters/jetties now completely cover almost 40 km2 and 37 km2, respectively, of the historical natural shoreline ecosystems; overwater structures cover approximately 6.5 km2 of the intertidal area. The majority of PU (517) around the Sound belong to a single group that is characterized by the loss of estuarine mixing, and the presence of armoring and nearshore roads. Other typical PU groups include gain of estuarine mixing, armoring and nearshore roads, overwater structures only, and predominantly armoring with a modest amount of overwater structures. Tidal barriers occur in only two groups, where they are either associated with gain in estuarine mixing wetlands or a combination of gain in estuarine mixing and tidal freshwater wetlands and nearshore roads, respectively. Distribution of these groups of consistent alterations appears to be somewhat homogeneous around the Sound.

Predictably, the highest spatial coincidence of shoreline alterations with specific shoreforms is associated with artificial shoreforms, e.g., 74 percent of the artificial shoreforms are armored and 62 percent are associated with nearshore fill. Among the natural shoreforms, the highest co-occurrences are armoring with bluff-backed beaches (33 percent), barrier beaches (27 percent), open coastal inlets (22 percent), and deltas (17 percent); roads associations are also most coincident with deltas (23 percent), barrier estuaries (22 percent), and open coastal inlets (17 percent). Tidal barriers are highly correlated with deltas (62 percent), but also with barrier estuaries (21 percent) and open coastal inlets (16 percent). Co-occurring stressors are most evident with armoring, which ranges in spatial coincidence from 72 percent of active railroads armored, to 22 percent of tidal barriers. Similarly, nearshore fill is highly coincident with marinas (62 percent of which co-occur with fill), breakwaters and jetties (45 percent), and overwater structures (43 percent). Other co-occurrences of interest are roads with tidal barriers (33 percent), abandoned railroads (31 percent), and breakwaters and jetties (24 percent).

Adjacent Upland and Watershed Change (Tiers 3 and 4)

The majority of the adjacent upland (Tier 3) and watershed area (Tier 4) is classified as natural land, as opposed to developed land, which includes areas of industrial, residential, and agriculture development. The ratio of developed to natural land is always higher in the adjacent upland than in the watershed area, reflecting the concentration of human activities along the Sound's shoreline. Approximately 2.5 percent of Puget Sound uplands and nearshore watersheds is covered by roads, the density of which is fairly consistent between the adjacent upland and the watershed area (total drainage area). The Puget Sound basin has 436 dams within its upland watershed area, more than a third of which are found in the South Central Sub-Basin.

The upland and watershed areas of the South Central Sub-Basin stand out as highly impacted, with all area measurements of human development (excluding the low intensity development and 0–10 percent impervious surface categories) exceeding that found in any other sub-basin. On the other hand, the vast majority of the Hood Canal Sub-Basin remains as natural land with very little area categorized as impervious surface greater than 10 percent, despite a relatively high road density in the adjacent upland.

The most common changes in adjacent uplands and watershed areas associated with the most PU were moderate development, including low-intensity and open space development, low to moderate impervious surface coverage, and roads. Another common category of PU change involved very little impact to the watershed, associated with the lowest level of impervious surface. Predictably, the most developed adjacent upland and watershed areas are the PU in the urbanized Seattle, Tacoma, Olympia, and Bellingham regions, as distinguished from other groups by higher levels of impervious surface as well as the presence of dams (impounded watershed area).

Ecosystem Functions, Goods & Services Impairment

Our summary scaling of the effects of nearshore ecosystem change on EFG&S across the Puget Sound Basin provides a qualitative indication of considerable variability among tiers of change both among and within sub-regions. The highest scales of EFG&S impairment are associated with shoreform transitions and shoreline alterations along the extensively developed eastern margin of the Puget Sound Basin, excluding the western component of the Whidbey Sub-Basin, and several other notable "pockets" of impairment, most notably in the urbanized/suburban areas of the eastern side of the South Central Sub-Basin and in southern Hood Canal. Conversely, the Strait of Juan de Fuca, San Juan Islands–Strait of Georgia, Hood Canal, and often components of South Puget Sound illustrate moderate or low relative impairment. Relative impairment of EFG&S is comparatively less for adjacent uplands and watershed areas in the Puget Sound Basin overall, although many PU along the eastern margins of the Whidbey and the western margins of the South Central (eastern shores of Kitsap Peninsula) sub-basins are moderately to highly impaired.

Variation Among Puget Sound Sub-Basins

Strait of Juan de Fuca Sub-Basin

Shoreform Composition

Historically, the Strait of Juan De Fuca Sub-Basin was composed primarily of barrier beach, bluff-backed beach, and rocky platform shoreforms. Distribution can be characterized by dominance of beaches and bluffs on the eastern end of the Strait, transitioning to a greater representation by rocky shoreforms at the western end. Change from historical to current shoreform composition reflects a proportional decline in barrier beach and bluff-backed beach and an increase in the proportion of rocky platform shoreforms, in addition to the almost 6 percent representation by artificial shoreforms. The proportional increase in the number of rocky shoreforms is attributed to omissions in historical surveys, not an actual geomorphic transition. Historically, bluff-backed beaches comprised one-third of the shoreline length. Barrier beaches and rocky platforms each accounted for ~20 percent of the shoreline length, nearly twice the Sound-wide average for these two shoreform types. The greatest change in shoreform composition by shoreline length has involved the loss of complexity in open coastal inlets, barrier lagoons, and barrier estuaries, while rocky platforms have increased proportionately in lineal extent by approximately 12 percent.

Many of these observed changes in shoreform length are concentrated in discrete locations along the sub-basin shoreline. Both the Dungeness and Elwha river deltas indicate up to approximately 50 percent loss of shoreline complexity. In addition, barrier estuaries surrounding the Dungeness are measurably reduced. Other concentrations of evident change include the southern end of Discovery Bay, Protection Island, and areas near Ediz Hook.

Shoreline Alterations

The most prevalent shoreline alterations were shoreline armoring and tidal barriers that occur in the Elwha and Dungeness river deltas. Armoring covers more than 75 percent of the shoreline in the two SPU immediately to the east of the Elwha River delta. Armoring, abandoned railroads, and tidal barriers also occur at the southern end of Discovery Bay. Abandoned railroads were uniquely common in this sub-basin, occupying 4 percent of the shoreline length, 10x greater than the Sound-wide average of 0.4 percent.

Adjacent Upland and Watershed Area Land Cover and Alterations

Both the adjacent upland area around the Strait of Juan de Fuca and the watershed area are predominantly in natural land cover, with much of that categorized as evergreen forest. Process units around the Elwha and Dungeness deltas show more non-forested land. The greatest development in the adjacent upland is found in the Port Angeles area.

Nearshore Ecosystem Impairment

Impairment associated with shoreform transitions and shoreline alterations were relatively lower for the Strait of Juan De Fuca Sub-Basin as compared to other sub-basins, and relative to Puget Sound as a whole. Adjacent upland area and watershed impairment scores were typically in the mid-range for Puget Sound sub-basins.

Unique Sub-Basin Considerations

Historical composition of barrier beaches and rocky platforms was unique in the sub-basin. As compared to other Puget Sound sub-basins, relatively few changes in shoreform and shoreline alteration conditions were observed in the Strait of Juan de Fuca. Exceptions were focused in the areas of the Elwha and Dungeness river deltas, Ediz Hook, and Discovery Bay. Western portions of the sub-basin showed few changes from historical condition and relatively levels of impairment. Prevalence of abandoned railroads is noteworthy.

San Juan Islands–Strait of Georgia Sub-Basin

Shoreform Composition

In terms of nearshore area (580 km2) and shoreline length (1187 km), the San Juan Islands–Strait of Georgia Sub-Basin is the largest of the seven sub-basins analyzed. It is also the most complex, composed of 2855 individual shoreform segments, more than one-half of the total mapped in Puget Sound. Historically, the sub-basin was composed of 1204 rocky platform and 944 pocket beach segments, and between 100 and 300-plus bluff-backed beach, barrier beach and plunging rocky segments. Compared with Puget Sound, relatively modest portions of the shoreline were composed of beach shoreforms. Conversely, the majority of Puget Sound's kilometers of rocky historical shoreforms occurred here, and comprised relatively large percentages of shoreline length (plunging rocky shoreline, 13 percent; rocky platform, 30 percent; pocket beach, 9 percent, at least three times the Sound-wide average in all cases). Proportional composition of the current shoreforms is comparable, with an increase in artificial shoreforms the only notable change. Shoreform transitions were dominated by loss of natural shoreforms (changes to artificial and absent shoreforms). Small increases in the number of rocky shoreforms in the sub-basin are attributed to omissions in historical surveys.

Substantial (>50 percent) loss of shoreline length was observed in embayment type shoreforms, including barrier estuary, barrier lagoon, and open coastal inlet. The shorelines of the two deltas (Nooksack and Samish) have been reduced by greater than 50 percent. Other noted areas of concentrations of shoreline length change include the urban and suburban modified shorelines of Bellingham Bay and Drayton Harbor/Birch Bay, and reductions of embayment shoreforms around Lummi and Lopez islands.

Multivariate analysis identified a dominant historical assemblage of shoreforms composed of all three rocky types—plunging rocky, rocky platform, and pocket beach. A distinct, but less prevalent, group characterized by bluff-backed beach and barrier beach was also defined. The rocky group dominated the shorelines of the San Juan Islands and some segments of the exposed shore of the eastern margin of the sub-basin, while the bluff-backed and barrier beach group is a more common nearshore feature along the east margin. Analysis of current shoreform compositions shows similar groupings, with the notable observation that artificial shoreforms have become a frequent component. This is especially true more in the developed regions around Bellingham Bay.

Shoreline Alterations

The most heavily modified portion of the San Juan Islands–Strait of Georgia Sub-Basin is the eastern "mainland" component, where armoring is relatively pervasive along most of the shoreline. This alteration becomes particularly common (>50 percent) from Lummi Bay to south of Anacortes, and is further compounded by nearshore roads, particularly in the Anacortes region. Nearshore fill, overwater structures, and marinas are concentrated around Anacortes and Birch Bay; they cover up to 50 percent of the aquatic zone area in Birch Bay. Active railroads are also relatively common, comprising 1.6 percent of the shoreline length, higher than the Puget Sound average. All of the reported railroad length (nearly 20 km) in the sub-basin is along the eastern shore adjacent to Samish and Bellingham bays.

The islands themselves are less modified; the Lummi Island component of the sub-basin does not contain much shoreline alteration except for moderate armoring around the northern and western shorelines of Guemes Island. The Orcas Island component is not heavily altered except for the large marina coverage on the east side of East Sound. Armoring and some coincident nearshore roads are more common in the Lopez Island component, especially the northwest corner of Lopez Island, where marina coverage approaches 20 percent of the nearshore aquatic area. The San Juan Island component of this sub-basin is relatively free of shoreline alterations, with overwater structures and marinas indicating only scattered coverage in the region of Roche Harbor, in the northwestern corner of the island.

Adjacent Upland and Watershed Area Land Cover and Alterations

As with shoreline alterations, the eastern component of the sub-basin has the most heavily developed upland and watershed areas, particularly between Bellingham Bay and Anacortes. The islands of the sub-basin are dominated by evergreen or mixed forest cover.

Nearshore Ecosystem Impairment

Compared with other Puget Sound sub-basins, the San Juan Islands–Strait of Georgia Sub-Basin shows moderate or low relative impairment, especially from the standpoint of changes in the adjacent upland and total watershed area. Notable exceptions occur, especially for shoreform transition and shoreline alterations along the eastern margins of the sub-basin. The sub-basin has small, relatively undeveloped watersheds, yielding impairment based on changes in adjacent upland and total watershed area that is generally among the lowest in Puget Sound.

Unique Sub-Basin Considerations

Compared to other Puget Sound sub-basins, the San Juan Islands–Strait of Georgia Sub-Basin shows moderate or low relative impairment, especially from the standpoint of changes in the adjacent upland and total watershed area. Notable exceptions occur, especially for shoreform transition and shoreline alterations along the eastern margins of the sub-basin. The sub-basin has small, relatively undeveloped watersheds, yielding adjacent upland and watershed area change impairment scores that are generally among the lowest in Puget Sound.

Hood Canal Sub-Basin

Shoreform Composition

In terms of watershed area, as well as nearshore length and area, the Hood Canal Sub-Basin is small relative to the other six Puget Sound sub-basins analyzed. It does, however, contain a relatively high number of stream confluences and five of the 16 major river deltas analyzed (Skokomish, Hamma Hamma, Duckabush, Dosewallips, and Quilcene).

Bluff-backed beaches and barrier beaches were the most common shoreform types (by count) in the historical condition. Barrier estuaries and closed lagoon/marsh were also relatively prevalent. As a function of length, bluff-backed beaches dominated, comprising nearly one-half of the Hood Canal Sub-Basin shoreline. Barrier beach and estuary were the only other shoreform types that exceeded 10 percent of the overall length. Bluff-backed beach and barrier estuary composition of shoreline length (45 percent and 12 percent, respectively) was slightly higher than the Sound-wide averages for these shoreform types (35 percent and 7 percent).

Transitions to artificial and shoreform-absent categories dominated (89 percent–100 percent) the observed changes, irrespective of the historical shoreforms. The exception was open coastal inlet transitions, where 43 percent were classified as changes to barrier estuaries.

Several pockets of shoreform length change occur in the northern component of the Hood Canal Sub-Basin, including approximately 30 percent–50 percent declines in shoreline length in the deltas of the Dosewallips and Quilcene rivers. Other concentrations of observed change include the embayment shoreforms surrounding much of Dabob Bay and Foulweather Bluff. In southern Hood Canal, measurable reductions in shoreline length were notable for barrier estuaries and open coastal inlets near the edges of the Duckabush, Hamma Hamma, Skokomish, and Union river deltas. Other notable reductions were embayment shoreform decreases on the eastern margin of the Canal between Misery Point and the Great Bend.

Multivariate analysis demonstrates another facet of simplification of nearshore ecosystems in the Hood Canal Sub-Basin. Loss of the closed lagoon/marsh shoreform has contributed to a simplification from eight to six distinct groups of shoreform types. It is particularly notable that several regions historically had a mosaic of different shoreform groups where now the shore is more monotypic.

Shoreline Alterations

Shoreline armoring is common throughout the northern component of the Hood Canal Sub-Basin, and approaches 50 percent of the shoreline length near Foulweather Bluff. Extensive nearshore fill and some overwater structures and marina fill are also evident in this area. Nearshore roads tend to be concentrated around Dabob Bay and the eastern margin of the Toandos Peninsula. Tidal barriers are prominent on the Quilcene and Dosewallips river deltas. Overwater structures and marinas cover close to 50 percent of the aquatic area on the southern margin of the Dosewallips River delta.

In contrast to the northern component, southern Hood Canal's shoreline is extensively and almost continuously armored, particularly inside the "Hook," along both shores around Lynch Cove, and on the southwest shore of the Canal. Nearshore roads compound the armoring along much of the same shoreline, approaching or exceeding 50 percent of the shoreline length in many locations, and occupy a greater proportion of the shoreline length (13 percent) than is found in all of Puget Sound (8 percent). Tidal barriers are most prominent in the Skokomish, Hamma Hamma, and Duckabush river deltas, and also occur within many embayments along the western shoreline.

Adjacent Upland and Watershed Area Land Cover and Alterations

The adjacent uplands and total watershed area have a proportionally high natural land cover, approximately 90 percent in the adjacent upland and 95 percent in the watershed. Development is a minor proportion of the watershed area land cover. A contiguous stretch of the western shoreline south of Misery Point remains particularly low in development impacts throughout both the adjacent upland and the watershed area.

Nearshore Ecosystem Impairment

Impairment scores associated with shoreform transitions are relatively high compared to other Puget Sound sub-basins. This is especially true along the eastern shore from the Duckabush River delta south through the Great Bend and into Lynch Cove. Impairment based on shoreline alterations is slightly lower, but still includes long reaches of relatively high degrees of impairment. Conversely, impairment based on adjacent upland and total watershed area change is relatively low, when evaluated on the Puget Sound scale.

Unique Sub-Basin Considerations

Hood Canal is unique in its number of river deltas and associated estuarine wetlands. Once prevalent coastal embayments have been extensively modified. Extensive armoring and nearshore roads, particularly along southern Hood Canal, account for much of the shoreline alteration. Generally good watershed conditions were observed throughout the sub-basin.

North Central Puget Sound Sub-Basin

Shoreform Composition

The North Central Puget Sound Sub-Basin is the smallest of the sub-basins analyzed, in terms of nearshore and watershed areas, shoreline length, and the number of shoreform segments. Based on count of shoreform segments, barrier beaches and bluff-backed beaches were the most common historical shoreform types, each comprising about 25 percent. Other shoreforms with greater than 10 percent were rocky platforms and closed lagoon marshes. The other four natural shoreform types were present historically, but were relatively rare (1 percent to 7 percent). In terms of shoreline length, bluff-backed beaches were dominant, comprising nearly 40 percent of the sub-basin. Barrier estuaries and barrier beaches were also common, each comprising nearly 20 percent of the shoreline length. Both of these percentages substantially exceed Sound-wide averages for these shoreforms. Other shoreform types comprised less than 10 percent of the total length. Barrier lagoons and closed lagoon/marshes were relatively more common than the Sound-wide average. Thus, three of four coastal embayment shoreforms were historically more prevalent in this sub-basin compared to Puget Sound as a whole.

Based on shoreline length reduction, nearshore change in the North Central Puget Sound Sub-Basin was greatest for barrier estuary and barrier lagoon shoreforms (88 percent and 53 percent, respectively). Modest (~25 percent) reductions in closed lagoon/marsh and open coastal inlet shorelines were observed. These transitions were almost always to artificial shoreforms or shoreform-absent conditions (56 of 61 observed transitions). One closed lagoon/marsh appeared in the current dataset – a form that had been historically absent, while 14 closed lagoon/marsh shoreforms disappeared completely from the sub-basin.

Barrier estuaries exhibited extensive reduction in shoreline length throughout the sub-basin's shoreline, particularly along southwestern Whidbey Island and north of Admiralty Head. In the vicinity of Port Townsend Bay, barrier estuaries, pocket beaches, and closed lagoon/marsh were measurably reduced. Barrier lagoons were also reduced, most prominently along southwestern Whidbey and the northwestern end of Marrowstone Island.

Multivariate analysis of shoreform composition and transitions suggests that the sub-basin was historically represented by three groups of bluff-backed and barrier beaches combined with barrier lagoons (group f), barrier estuaries (group c), or both (group e) (Fig. 108). One or more of the three rocky shoreforms distinguish other groups. The complexity of shoreform composition is reduced by half under current conditions, with the disappearance of barrier lagoons and barrier estuaries, and the addition of artificial shoreforms. A vast majority of the sub-basin's shoreline has been reduced to comparatively simple bluff-backed and barrier beach SPU.

Shoreline Alterations

The North Central Puget Sound Sub-Basin shoreline is not extensively armored, but armoring does occur to some extent in 75 percent of the SPU (Fig. 111); roads are coincident in about half of the SPU. Although not associated with large river deltas, tidal barriers are persistent along the shoreline, approaching or exceeding 25 percent of the shoreline length, especially around the southern end of Port Townsend Bay and southern Whidbey Island. All shoreline alterations evaluated as a percentage of shoreline length (tidal barriers, roads, railroads, armoring) were much less prevalent in this sub-basin as compared to Sound-wide averages.

Adjacent Upland and Watershed Area Land Cover and Alterations

The landscape of the North Central Puget Sound Sub-Basin is largely forested, with some herbaceous land cover in the adjacent upland area. Development is focused around the east side of Port Townsend Bay.

Nearshore Ecosystem Impairment

Impairment based on shoreform transitions in the North Central Puget Sound Sub-Basin are similar (median, interquartile range) to those of South Central Puget Sound Sub-Basin; together they represent some of the most impaired shorelines for this category. Impairment based on shoreline alterations is slightly less than the South Central Puget Sound Sub-basin, but still more highly impaired than the rest of Puget Sound. Impairment scores for the adjacent upland and total watershed area were low relative to Puget Sound.

Unique Sub-Basin Considerations

Considerable loss of embayment shoreforms was observed in this relatively small sub-basin, yielding a shorter, less complex shoreline. These shoreforms were once quite prevalent in the sub-basin, compared with the rest of Puget Sound. However, relatively low levels of shoreline alteration were observed.

Whidbey Sub-Basin

Shoreform Composition

The Whidbey Sub-Basin contains the largest drainage in Puget Sound (Skagit River) and two other moderately sized watersheds (Snohomish, Stillaguamish). Nearly 50 percent of the drainage area analyzed lies within the sub-basin, making it more than twice as large as the next largest (South Central Puget Sound). It has the second-largest nearshore area. However, in terms of nearshore length, it is fourth largest, one of several modest-sized sub-basins, all with less than half of the shoreline length contained in the San Juan Island Sub-Basin.

Historically, delta shoreforms comprised 40 percent of the length of this sub-basin, by far the highest percentage for this type in all of the Puget Sound sub-basins. Bluff-backed beaches were also historically prevalent (30 percent historical length) and barrier beaches comprised 10 percent of the shoreline length; no other shoreform types exceeded 10 percent. Barrier lagoons occupy 4 percent of the shoreline length, comparable to the Puget Sound average. All other shoreforms comprise proportionally less of the shoreline in the sub-basin, compared to Sound-wide totals. Once-dominant deltas have been significantly reduced in the Whidbey Basin, with a nearly 40 percent decrease in shoreline length. Barrier estuary, barrier lagoon, and closed lagoon marshes have all been decreased by 50 percent or more. Other shoreform changes involved less than 15 percent reduction in shoreline length.

In addition to the 20 percent to 50 percent reductions in delta shoreline lengths, the most notable concentrations of reduced shoreform length in the eastern portion of the Whidbey Sub-Basin include: reduced barrier estuary complexity around Similk Bay, barrier estuary and coastal lagoon/marsh reductions between the Skagit and Stillaquamish river deltas, barrier estuary reductions north of the Snohomish River delta, and closed lagoon/marsh reductions around Gedney Island. The western component of the Whidbey Sub-Basin illustrates one of the few significant reductions in the length of bluff-backed beach shoreform in the region, in the Rocky Point and Crescent Harbor areas of Whidbey Island. Barrier lagoon and closed lagoon/marsh shoreforms were also reduced to some degree on east side of Whidbey Island.

Shoreline Alterations

The Whidbey Sub-Basin shoreline is pervasively armored along the "mainland" eastern shore, as well as the coastline of Whidbey Island, approaching 50 percent on the eastern margin. Nearshore roads are coincident along much of the same shoreline. Although tidal barriers occur in the western component, they are more common, and often extensive (approaching 100 percent), in and around the Skagit, Stillaguamish, and Snohomish river deltas. Tidal barriers occupy more than 30 percent of the shoreline in the sub-basin, nearly three times the Sound-wide average.

Adjacent Upland and Watershed Area Land Cover and Alterations

As on the shoreline, development is fairly pervasive throughout the adjacent upland and in many areas of the watershed area of the Whidbey Sub-Basin. High-intensity development makes up a considerable proportion of the watershed area around Oak Harbor, and the areas between Everett and Seattle. Much land is devoted to agriculture (hay/pasture) around the Skagit and Stillaguamish river deltas.

Nearshore Ecosystem Impairment

Impairment scores resulting from shoreform changes (Tier 1) are generally in the mid-range for Puget Sound sub-basins. Impairment scores based on shoreline alteration (Tier 2) indicate relative high levels of impairment, especially in the eastern portion of the sub-basin around the three river deltas. The median scores for adjacent upland impairment are relatively high, comparable to the highly impaired South Central Puget Sound Sub-Basin. Watershed area (Tier 4) impairment is moderate, when compared to other Puget Sound sub-basins, though relatively higher areas of impairment are centered around Everett and on Whidbey Island near Oakville.

Unique Sub-Basin Considerations

Extensive modification of major river deltas is the most obvious change in the sub-basin. Modification by tidal barriers has led to shoreform transitions and indications of significant impairment of Ecosystem Functions, Goods and Services. While watershed conditions are generally good, the shoreline is substantially more developed than other parts of the Sound, leading to disproportionately higher levels of impairment. Coastal embayments have also been widely impacted in the sub-basin, with historical shoreforms closest to deltas often lost to development.

South Central Puget Sound Sub-Basin

Shoreform Composition

Bluff-backed beach and barrier beach shoreform segments dominated the historical composition of the South Central Puget Sound Sub-Basin, with approximate equal number of segments accounting for nearly 65 percent of those mapped. Bluff-backed beaches accounted for 60 percent of the shoreline length, substantially greater than the Sound-wide average of 35 percent. Barrier beaches and open coastal inlets each comprised approximately 10 percent of the shoreline; other shoreforms were 8 percent or less of the total length.

The South Central Puget Sound Sub-Basin contains the most developed region of Puget Sound, stretching from Tacoma, through Seattle, to just south of Everett. It has lost considerable proportions of its barrier estuary, barrier lagoon, closed lagoon/marsh, and open coastal inlet shoreline length, and virtually 100 percent of its delta (Duwamish and Puyallup rivers) shoreline. The largest losses of shoreform segments involve closed lagoons/marshes and barrier lagoons. Additionally, the South Central Sub-Basin has lost more barrier beach segments than any of the other sub-basins.

Pervasive reductions in natural shoreforms, especially bluff-backed beaches, barrier estuaries, barrier lagoons, and open coastal inlets, accompanied by increases in artificial shoreforms, were particularly observable along the eastern shoreline of the sub-basin. Artificial shoreforms now comprise nearly 30 percent of the length of the shoreline here; the Sound-wide average is approximately 10 percent. The decrease in bluff-backed beach shoreforms is particularly notable from Elliott Bay south to Seahurst, and along the southern margin of Commencement Bay. Significant alterations in south Kitsap were noted around Gig Harbor, Sinclair Inlet, and Port Orchard. Large declines in open coastal inlet shoreline lengths, as well as reductions in barrier estuaries and bluff-backed beaches, occurred from Liberty Bay to Burke Bay. The east side of Bainbridge Island shows declines in barrier lagoon and closed lagoon/marsh shoreforms. Changes on Vashon Island include reductions of barrier estuaries and barrier lagoons in the region of Tramp Harbor and Quartermaster Harbor. Multivariate analysis of these transitions leads to observations that shoreform groups in the South Central Sub-Basin are frequently totally or partially artificial.

Shoreline Alterations

The South Central Puget Sound Sub-Basin shoreline has been extensively altered, with shoreline armoring present in almost all process units, often exceeding 50 percent of the SPU length. More than 60 percent of the total shoreline length is armored, compared with 27 percent Sound-wide. Along the eastern shoreline between Tacoma and Seattle, the entire length of seven contiguous SPU have nearly total armoring, with associated tidal barriers and roads, nearshore fill, and overwater structures, especially around the industrialized deltas. Nearshore roads sporadically compound the armoring throughout the sub-basin and reach high proportions in South Kitsap and Vashon Island. Outside of the eastern shoreline, nearshore fill, overwater structures, and marinas are relatively isolated except in concentrated population areas such as around Gig Harbor and Sinclair Inlet/Bremerton. In addition to shoreline armoring, the percent of shoreline occupied by tidal barriers (12 percent), roads (11 percent), and railroads (3 percent) all exceed Sound-wide averages.

Adjacent Upland and Watershed Area Land Cover and Alterations

The South Central Puget Sound Sub-Basin is pervasively developed, not only on the shoreline, but throughout both the adjacent upland and the total watershed area. This is especially the case around Seattle and Tacoma, where natural land cover has been converted to moderate- to high-intensity development. This upland development pattern is also evident around the cities of Gig Harbor and Bremerton. The proportion of open space and low-intensity development is comparatively greater in the North Kitsap and Vashon Island, making up roughly one-third to one-half of the land cover, with the remaining area mostly forested.

Nearshore Ecosystem Impairment

As compared to all the other Puget Sound sub-basins, the median impairment levels were highest (most impaired) for all levels (tiers) of change in the South Central Sub-Basin. Areas around the Duwamish and Puyallup river deltas were consistently most impaired. Vashon Island and areas of North Kitsap showed more moderate levels of impairment.

Unique Sub-Basin Considerations

By most measures of PSNERP analysis, South Central Puget Sound is the most extensively modified of all seven sub-basins. Once-prevalent bluff-backed beaches have the most armoring. Prominent nearshore stressors–including tidal barriers, roads, railroads, and armoring–all exceed Sound-wide averages. More barrier beach segments have been lost in this sub-basin. Duwamish and Puyallup river deltas have been nearly completely replaced with artificial shoreforms; artificial shoreforms now account for nearly 30 percent of the shoreline in the sub-basin. Estuarine wetland losses range from 60 percent to nearly 100 percent for the four classes. While development is concentrated along the shoreline, many PUs also have highly impaired adjacent upland and watershed conditions. Developed land cover classes greatly exceed Sound-wide averages, with nearly one-third of the sub-basins drainage area classified as developed.

South Puget Sound Sub-Basin

Shoreform Composition

The South Puget Sound Sub-Basin is moderate in size compared to other sub-basins in terms of watershed area, nearshore area, and shoreline length. The number of shoreform segments analyzed is relatively large (nearly 1000), second to the San Juan Island Sub-Basin, indicative of a complex shoreline.

The majority of shoreform segments and nearly 50 percent of the shoreline length were historically bluff-backed beach. Open coastal inlets were uniquely prevalent in South Puget Sound, comprising approximately 20 percent of the shoreline length. This accounts for nearly one-half of the total length of this embayment shoreform in all of Puget Sound. Barrier beach and barrier estuary shoreforms each accounted for nearly 10 percent of the South Puget Sound shoreline historically.

The most dramatic change is the nearly 75 percent decrease in the Nisqually River delta shoreline. There is also a pervasive decline in embayment complexity; barrier estuaries, barrier lagoons, closed lagoons/marshes, and open coastal inlets have current shorelines that are 30 percent to 75 percent less than their historical length.

Shoreline Alterations

Shorelines in all components of the South Puget Sound Sub-Basin are almost contiguously armored, often extensively (75 percent–100 percent of SPU length), except for the Harstine Island and Balch Passage regions. The sub-basin is the second most heavily armored (35 percent), exceeding the Sound-wide average. Other alterations are more intermittent along the shoreline except for the active railroad and nearshore fill in the reach north of the Nisqually River delta.

Adjacent Upland and Watershed Area Land Cover and Alterations

Although the shoreline of the South Puget Sound Sub-Basin is heavily modified, the adjacent upland is approximately 75 percent natural land cover, most of this as evergreen and mixed forest, along with forested and emergent wetlands. Development is fairly consistent throughout the sub-basin, with concentrations between Tacoma and the Nisqually delta and around Olympia near the Deschutes River delta.

Nearshore Ecosystem Impairment

This sub-basin shows median impairment scores based on shoreform transition comparable to North and South Central Puget Sound and the Hood Canal sub-basins. It has less shoreline alteration than the South Central and Whidbey sub-basins, with median scores intermediate among sub-basins. Areas with highest levels of shoreline alteration impairment generally occurred from the Nisqually River delta north to Point Defiance. Impairment scores based on adjacent upland and total watershed area changes were generally quite low, with notable exceptions of very high impairment associated with the Deschutes River watershed and the shoreline near Point Defiance.

Unique Sub-Basin Considerations

The South Puget Sound Sub-Basin, once unique in its historical composition of open coastal inlets, has suffered a substantial loss of diversity of coastal embayments. Major river deltas in this sub-basin have been substantially impacted and shoreline armoring is a pervasive alteration.

Utility for Strategic Restoration and Preservation Needs

These data and relationships provide the source for the PSNERP Strategic Needs Assessment (SNA). The spatial organization of change that affects nearshore ecosystems and the processes that structure them are intended to support development of restoration and protection strategies that can incorporate spatial principles that support a landscape approach.

Revision and Expansion of Change Analysis Geodatabase

While PSNERP does not plan to update the geospatial database, we have designed it as a template to accommodate future additions and expansion, both in terms of the comprehensive datasets but also in the resolution within any one data type or attribute.

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Appendix A

Glossary

barrier beach
linear ridge of sand or gravel extendeing above high tide, built by wave action and sediment deposition seaward of the original coastline; includes a variety of depositional coastal landforms such as spits, tombolos, cuspate forelands and barrier islands (Shipman 2008)

barrier estuary
estuary isolated from open Puget Sound waters by a barrier, with tidal exchange occurring through a narrow entrance channel (Shipman 2008)

barrier lagoon
barrier-build lagoons that lack a significant freshwater source, only coincidentally associated with streams of significant upland catchment areas (Shipman 2008)

beach
gently sloping zone of unconsolidated sediment along the shoreline that is moved by waves, wind and tidal currents (Shipman 2008)

bluff-backed beach
a barrier beach backed by a steep bank or slope rising from the shoreline, generally formed by erosion of poorly consolidated material such as glacial or fluvial sediments

closed marsh and lagoon
back barrier marsh and lagoon wetlands that typically maintain a subsurface hydrologic connection with marine waters, but that lack a persistent tidal channel (Shipman 2008)

conceptual model
numerical or diagrammatic model that sumamries and describes the relationships and interactions among specified model components (see Simenstad et al. 2006 for specific PSNERP conceptual model)

CZ
Convergence Zone (see drift cell)

delta
a deposit of sediment formed at a stream or river moutn, or other locations where slowing of flow results in sediment deposition; deltas can occur at many scales and large river deltas—complex systems in themselves—are distinguished from smaller steram and tidal deltas commonly found in a wide variety of geomorphic settings (Shipman 2008)

Delta Process Unit
PSNERP change analysis designation for segments of Puget Sound shoreline occupied by large river deltas wherein the mixing of freshwater and saltwater is regularly influenced by tidal action (see delta)

drift cell
a length of beach within which longshore sediment transport is relatively contained; drift cells will typically include sediment sources (Divergence Zone, DZ), sediment sinks (Convergence Zone, CZ), and transport segments (Left-to-Right Drift and Right-to-Left Drift); in Puget Sound, two adjacent drift cells will often share a common Divergence Zone); reas where littoral drift is not evident are designated as No Appreciable Drift (NAD).

DZ
Divergence Zone (see drift cell)

ecosystem
a community of organisms and their physical and chemical environment interacting as an ecological unit

Ecosystem Functions, Goods and Services (EFG&S)
diverse benefits that humans derive from natural ecosystems; for the purposes of determining how these functions, goods and services provided by natural nearshore ecosystems of Puget Sound may have been impaired by historic shoreline changes, PSNERP adapted definitions and lists of EFG&S modified for Puget Sound by World Resources Institute (WRI 2007) and Earth Economics (Batker et al. 2008)

ecosystem processes
interactions among physicochemical and/or biological attributes of an ecosystem that involve changes in chatacter of the ecosystem and its components; processes are generally characterized as reates or patterns of change over time, and operate at various, hierarchical spatial and temporal scales

embayment
a broad term for an inlet or indentation in the coastline; in PSNERP convention, features partly isolated from the rest of Puget Sound by their configuration and sufficiently small to limit wave action and beach processes and including wetalnds or other back-barrier water bodies isolated from direct tidal influence, barrier estuaries, lagoons and some stream mouths and the heads of small bays (Shipman 2008)

estuary
a semi-enclosed coastal body of water that extends to the effective limit of tidal influence, within which sea water entering from one or more free connections with the open sea, or any other saline coastal body of water, is significantly diluted with fresh water derived from land drainage, and can sustain euryhaline biological species from either part or the whole of their life cycle (Perillo 1995)

GSU
Geographical Scale Units; hierarchy of units of different scales that compose segments of Puget Sound shoreline

landform
One of the multitudinous features that taken together make up the surface of the earth. It includes all broad features, such as plain, plateau, and mountain, and also all minor features, such as hill, valley, slope, canyon, arroyo, and alluvial fan. (Bates and Jackson 1984)

lagoon
shallow body of water, such as a pond or lake, isolated from Puget Sound bya barrier beach or other narrow body of land, which may or may not have a permanent tidal connection (Shipman 2008)

landscape
a heterogeneous land area composed of a cluster of interacting ecosystems that are repeated in similar form throughout (Forman and Godron 1986)

mosaic
pattern of interacting patches, corridors and matrix across a landscape

NAD
No Appreciable Drift (see drift cell)

nearshore
PSNERP operational definition is "estuarine delta/marine shoreline, beaches and areas of shallow water from the top of the coastal bank or bluffs, and tidal waters from the head of tide to depth of the lower limit of the photic zone, about 10 m relative to Mean Lower Low Water"

open coastal inlet
inlets or estuaries whose size or configuration precludes significant wave action, but where the inlet itself is not significantly enclosed bya a barrier or other restriction (Shipman 2008)

plunging rocky shorelines
rocky shorelines that have undergone negligible erosion and retreat and therefore lack distinct nearshore platform (Woodroffe 2002)

pocket beach
beaches isolated between rocky headlands and promontories, where coarse sediment is available due to either erosion of the shoreline or delivery by a local stream; they may form barriers, partially or completely isolating a back-barrier lagoon or wetland (Shipman 2008)

Puget Sound
All inland marine waters of Washington State inside of the entrance to the Strait of Juan de Fuca and including Georgia Stratit south of the Canadian border

rocky platform
a narrow platform or ramp formed where erosion of a rocky shoreline has occurred, creating a more gradually sloping intertidal zone (Trenhaile 2002)

Shoreline Process Unit (SPU)
PSNERP change analysis designation for segments of Puget Sound shoreline where beach sedimentary processes are confined by drift cell indicators of sediment transport zone and adjacent divergence and convergence zones, or areas of no appreciable drift.

shoreform
A term often used in Puget Sound to describe a coastal landform. The term is generally used to describe landscape features on the scale of hundreds to thousands of meters in scale, such as coastal bluffs, estuaries, barrier beaches, or river deltas.

stressor
an external process or action that exerts stress on a biotic or abiotic component, or so modifies or eliminates an ecosystem process that the structure and function of the ecosystem changes fundamentally

Appendix B

Nearshore Ecosystem Processes

PSNERP Nearshore Ecosystem Processes

Introduction

In developing a large-scale, comprehensive strategy to protect and restore the natural processes and functions in nearshore environments of Puget Sound, the Puget Sound Nearshore Ecosystem Project (PSNERP) is focusing on understanding how fundamental ecosystem processes in nearshore Puget Sound have become impaired. As described elsewhere in PSNERP documentation, by addressing the mechanisms whereby nearshore ecosystems are formed and maintained, process-based restoration integrated with strategic preservation should provide the maximum likelihood of recovering sustainable ecosystem functions. We take into account: how natural processes shape the structure (what we see) and the dynamics (how it changes) of nearshore ecosystems around Puget Sound; how these processes are affected by stressors (such as shoreline development); and how restoration of degraded ecosystem processes and preservation of intact ecosystems should be used in conjunction with one another to improve ecological functions.

The objective of this document is to define and distinguish nearshore ecosystem processes that occur at different spatial and temporal scales. In the process, we intend to emphasize the types and scales of processes that are most likely to be the focus of PSNERP actions (Management Measures) intended for sustainable restoration of nearshore structure and functions.

Definitions

We define *ecosystem processes* as those *interactions* among physical, chemical, and/or biological attributes of an ecosystem that lead to change in character of the ecosystem and its components, i.e., changes in ecosystem *state*. Processes are generally characterized as *rates* or patterns of change over time, and operate at various hierarchical spatial and temporal scales. In the context of the PSNERP-NST Conceptual Model (Simenstad *et al*. 2006), ecosystem processes maintain and alter ecosystem *structure*. Together, processes and structure result in the *functions* of nearshore ecosystems.

Note that processes interact with each other within and among scales to create nearshore structures and functions. For instance, the function of a barrier estuary is influenced by fluvial processes (delivery of freshwater and sediment) originating in the watershed, localized nearshore tidal processes that maintain channels (erosion, tidal flow) and salt marsh (accretion), and coastal processes (sediment transport), that modify the tidal inlet and modify the spit that shapes the feature. Processes are distinguished from the *agent* (mechanism) initiating or maintaining the process, such as: light and nutrients (the agents) increasing algal production (the process), or waves (the agents) causing sediment transport (the process).

The backdrop for ecosystem processes (*Regional Influences*) consists of large-scale, long-term factors such as climate, wave exposure, geology (which influences resistance to erosion and sediment availability), inherited physiography (shape and steepness of coastline), sea level history, and tidal regime.

We define *impaired processes* as those nearshore ecosystem processes that are modified by human intervention either within the nearshore domain or from adjacent watersheds or offshore.

Process Scales

Ecosystem processes that influence the beaches, estuaries and deltas of Puget Sound occur and vary over diverse spatial and temporal scales. We classify them into three general scales of influence on nearshore ecosystems: 1) regional influences, 2) broad physiographic processes, and 3) local geochemical and ecological processes. However, these three categories of nearshore ecosystem processes vary in how feasible it is to alter them by restoration or preservation actions and how they relate to ecosystem functions, goods and services of benefit to human beings. Although we seek to be comprehensive in this listing of nearshore ecosystem processes, PSNERP planning for restoration and preservation tends to focus on the scale of processes that shape coastal landforms, which in turn encompass the geochemical and ecological processes of interest.

Regional Influences

Regional influences provide the backdrop for all ecosystems across hundreds of kilometers. They ultimately control water and sediment conditions over the Puget Sound Basin, and thus affect any suite of physiographic processes. If they change, they will alter physiographic processes over a large spatial scale. They are seldom modified by restoration and preservation actions, but often constrain the feasibility or performance of particular restoration actions.

- **Climate**
  - energy input such as solar irradiance, winds, or other atmospheric forcing
  - precipitation and accompanying deposition of dissolved and particulate matter
- **Geology/Tectonics**
  - earthquake-caused deformations
  - glacial and other morphogenic processes that provide the inherited ("legacy") shape of the land
  - volcano-caused inputs of particulate, gaseous, and dissolved material

- **Tides and Waves**
  - tidal regime
  - energy inputs from oceanic waves
- **Sea Level Change**
  - global to regional influences on relative sea level (interacts with geology/tectonics)
- **Freshwater Inflow**
  - pervasive freshwater input from large rivers that, at least seasonally, modifies salinity regimes of large reaches of Puget Sound

Broad Physiographic Processes

Broad physiographic processes are what we consider the landscape-forming processes, i.e., they are responsible for creating and maintaining the different complexes of shore-forms and energy regimes that characterize Puget Sound's shorelines. They are embedded within regional influences, but vary considerably on scales of kilometers or fractions thereof.

- **Sediment Input**
  - flux of sediment from bluff, stream, and marine sources; depending on landscape setting, can vary in scale from acute, low frequency (hillslope mass wasting from bluffs) to chronic, high frequency (some streams and rivers)
- **Sediment Transport**
  - bedload and suspended transport of sediments and other matter by water and wind along (longshore) and across (cross-shore) the shoreline
- **Erosion and Accretion of Sediments**
  - erosion (coastal retreat) of coastal bluffs and shorelines
  - deposition (dune formation, delta building) of non-suspended (e.g., bedload) sediments and mineral particulate material by water, wind, and other forces
  - settling (accretion) of suspended sediments and organic matter on marsh and other intertidal wetland surfaces
- **Tidal Flow**
  - localized tidal effects on water elevation and currents, differing significantly from regional tidal regime mostly in tidal freshwater and estuarine ecosystems
- **Distributary Channel Migration**
  - change of distributary channel form and location caused by combined freshwater and tidal flow
- **Tidal Channel Formation and Maintenance**
  - geomorphic processes, primarily tidally driven, that form and maintain tidal channel geometry
  - natural levee formation
- Freshwater Input
  - freshwater inflow from surface (streamflow) and groundwater (seepage)
- **Detritus Import and Export**
  - import and deposition of particulate (dead) organic matter
  - soil formation
  - recruitment, disturbance, and export of large wood
- **Exchange of Aquatic Organisms**
  - organism transport and movement driven predominantly by water (tidal, fluvial) movement
- **Physical Disturbance**
  - change of shoreline shape or character caused by exposure to local wind and wave energy input
  - localized disturbance such as large wood movement, scour, and overwash
- **Solar Incidence**
  - exposure, absorption and reflectance of solar radiation (e.g., radiant heat) and resulting effects

Local Geochemical and Ecological Processes

Local processes are those that occur within a given landscape structure, which in turn has been shaped by regional influences and broad physiographic processes. While the broad physiographic processes are usually the focus of restoration actions in Puget Sound, local geochemical and ecological processes are typically responsible for the desirable functions that we attribute to natural nearshore ecosystems. They vary on the order of meters, within the local structure of nearshore ecosystems.

- **Hydrogeological**
  - burial
  - sediment (grain size) sorting and stratification
  - infiltration and exfiltration
  - seepage
- **Geochemical**
  - conversion between dissolved and particulate organic matter by physical (e.g., flocculation) or biochemical (e.g., uptake by organisms) mechanisms
  - conversion of inorganic nutrients into organic (e.g., uptake of nitrogen by plants and incorporation into their organic structure)
  - changes in inorganic nutrient states (e.g., nitrification or volatilization)
- **Primary Production**
  - autotrophic production (production of living plant matter)
  - heterotrophic production (microbial decomposition of organic matter)

- **Food Web**
  - primary consumption (herbivory/grazing of living plant material)
  - secondary and tertiary production (production of living animal biomass)
  - secondary or tertiary consumption (feeding/predation on other animals)
- **Physiological and Metabolic**
  - excretion
  - respiration
  - salinity/temperature resistance
  - Ecological and Habitat
  - reduction in predation risk (refuge)
  - individual growth
  - reproduction
  - recruitment
  - competition
  - symbiosis
  - behavior, such as migration, social or other responses to abiotic and biotic factors

Relationship to Puget Sound Nearshore Geomorphic Systems

The following tables illustrate the variation in different types of dominant ecosystem processes associated with the four nearshore geomorphic systems (Rocky Coasts, Beaches, Embayments, and River Deltas) found on Puget Sound (Shipman 2008). In addition, we have listed Local Geochemical and Ecological Response processes that vary among these systems, and common impairments to the Broad Physiographic Processes.

Rocky Coasts (Plunging, Platform, Pocket)

Regional Influences: *Climate; Geology/Tectonics; Tides and Waves; Sea Level Change*

Broad Physiographic Processes	Local Geochemical and Ecological Response	Impairments
Freshwater Input. Freshwater reaches the beach in stream flow and from groundwater seepage. Influences aquatic chemistry. Where streams intersect marine water, estuarine mixing occurs.	Sediment, chemical, detritus and large wood input from drainage area	Watershed modifications affect volume and rate of freshwater input to shoreline. Regulation, diversion or extraction of stream flow by dams or other modifications. Shoreline modifications may alter nature of groundwater seepage. Upland drainage control tends to concentrate flows in fewer locations. Concentrated outfall may result in beach erosion. Pipes and outfalls may result in freshwater bypassing beach face.
Tidal Flow. Rise and fall of tides leads to periodic flooding of beach face, wetting and drying, floating and redepositing organic material. Position and rate of change of tides influences locus of wave energy on beach, porewater hydrology, and ecological processes. Tidal currents occur at regional and local scales, transporting chemical constituents, organic material, and sediment.	Infiltration and exfiltration Primary production	Blockage of tidal currents by overwater structures
Exchange of Aquatic Organisms.	Recruitment and reproduction (of biota) Secondary or tertiary consumption	
Physical Disturbance. Moderate to high wave energy often impacts shore.	Changes in predation, individual growth, competition and behavior (of biota)	
Solar Input. Light and heat. Warms water and substrate, provides energy for photosynthesis	Autotrophic production	Shading by overwater structures. Changes in radiation through water column due to turbidity.

Beaches (Bluffs, Barriers)

Regional Influences: *Climate; Geology/Tectonics; Tides and Waves; Sea Level Change*

Beaches are formed and maintained primarily by wave action. The dominant geomorphological processes are transport of sediment by direct wave action, wave-induced currents, and to a lesser extent, tidal currents. Beaches generally fall into two general categories: Bluffs, where erosion and bluff recession have resulted in beaches shifting landward into previously terrestrial areas, and Barriers, where beaches have build seaward of the original coastline.

Broad Physiographic Processes	Local Geochemical and Ecological Response	Impairments
Tidal Flow. Rise and fall of tides periodically flood the beach face, wetting and drying, and floating and redepositioning organic material. Position and rate of change of tides influences locus of wave energy on beach and porewater hydrology. Tidal action drives water table fluctuations below beach surface and in backshore. Tidal currents occur at regional and local scales, transporting chemical constituents, organic material, and sediment.	Sediment (grain size) sorting and stratification	Sediment, chemical, detritus and large wood input from drainage area
Sediment Delivery. Beach sediment derives from coastal watersheds, from shoreface erosion, and from bluff erosion (mass-wasting). Sediment supply is function of sediment availability, delivery mechanisms (landslides or dump trucks), and the magnitude of stream/wave processes.	Conversion between dissolved and particulate organic matter by physical or biochemical processes	Infiltration and exfiltration Primary production
Sediment Transport. Movement of sediment, by water, either in suspension or as bedload, or by wind, leading to wind erosion and dune formation. Sediment moves directly under the influence of gravity as mass-wasting (landslides). **Fluvial Transport**. Transport of sediment by stream flow to shoreline and across beach. Depending on relative magnitude of stream and marine processes, and configuration of shoreline near stream mouth, this may result in a subaerial delta, an intertidal delta fan, or small estuarine embayment. **Longshore Transport**. Shore drift, littoral drift. Redistribution of sediment along the coastline, resulting in areas of accretion and erosion. Net transport requires that some areas are sources of sediment (Sediment Delivery) and others are sinks. Configuration of coastline relative to incident wave action divides shoreline into independent sediment cells. **Cross-Shore Transport**. Sediment transport perpendicular to shoreline, usually by wave action, which is the origin of seasonal variation in beach profile. Cross-shore transport may be facilitated by stream flow and seepage flows across beach at low tides. Sediment may be transported within the intertidal zone by swash currents or may be transported into the backshore during high water events by overwash.	Sediment (grain size) sorting and stratification Recruitment (of biota) Sediment, detritus and large wood input from drainage area Food web Ecological and habitat	Fluvial transport is affected by modifications in stream discharge or sediment yield due to land use changes in watershed or modifications to stream channels, including flow regulation, sediment detention, dredging, straightening, upstream sediment storage, dams, etc. Longshore transport is impeded by groins and jetties or fill that extends onto/across beach. Rate of transport may be altered by modifications in wave interaction with beach by shore parallel structures (seawalls). Changes in sediment supply directly affect volume of sediment available for longshore transport. Cross-shore transport is limited by encroachment of structures and fill over upper portion of beach, and may be altered by structural modifications that affect wave interaction with beach. Will change if substrate is modified directly or indirectly.

continued

Broad Physiographic Processes	Local Geochemical and Ecological Response	Impairments
Bluff and Beach Erosion/Accretion. Horizontal movement of beaches over time from net losses or gains in sediment. Beaches may erode or accrete. Barrier beaches may migrate or shift configuration. Bluffs retreat landward.	Autrotrophy Burial	Seawalls prevent migration of beaches landward over time, resulting in passive erosion of beach face. Seawalls prevent bluff retreat.
Freshwater Input. Fresh water reaches the beach in stream flow and from groundwater seepage. Impacts aquatic chemistry. Where streams intersect marine water, estuarine mixing occurs.	Seepage Conversion of inorganic nutrients into organic	Watershed modifications modify volume and rate of freshwater input to shoreline. Regulation of stream flow by dams or other modifications. Diversions and extraction [as in first box]. Shoreline modifications may alter nature of groundwater seepage. Upland drainage control tends to concentrate flows in fewer locations. Concentrated outfall may result in beach erosion. Pipes and outfalls may result in fresh water bypassing beach face.
Detritus Recruitment and Deposition, Retention and Incorporation, and Export. Delivery of organic detritus to shoreline by stream flow, shoreline erosion. Includes both small detritus and large wood. Recruitment and accumulation of marine detritus.	Heterotrophic production Reduction in predation risk	Change in detritus quality from upland (vegetation changes) or marine waters, or decreased delivery of detritus from upland (erosion control). Change in beach morphology or wave interaction that modifies recruitment or storage capacity of beach (loss of upper beach and berm).
Solar Radiation. Light and heat. Warms water and substrate, provides energy for photosynthesis,	Autotrophic production	Shading by overwater structures. Reduction in shade by removal of riparian vegetation. Changes in radiation through water column due to turbidity.

Embayments (Inlets, Estuaries and Lagoons)

Regional Influences: *Climate, Geology/Tectonics, Tides and Waves, and Sea Level Change*

Small inlets and estuaries are protected by from significant wave action by their shape or by their occurrence in low-energy areas (heads of larger inlets, for example) and are often formed or influenced by barrier beaches. They may also be categorized by presence or absence of significant fluvial input or by presence or absence of restricted tidal inlet.

Broad Physiographic Processes	Local Geochemical and Ecological Response	Impairments
Tidal Flow. Tidal hydrology typically dominates the processes and functions in embayments, since stream gradients are reduced and wave action diminished. Tidal flows in and out of an embayment are a function of tidal range and of the tidal prism. Large tidal prisms result in large flows. In small embayments, tidal prism may not be sufficient to maintain channel entrance or to flush sediment out of the lagoon or estuary, which results in further shoaling and filling and may eventually lead to closure of the inlet and complete elimination of the embayment.	Sediment (grain size) sorting and stratification Infiltration and exfiltration Primary and secondary production	Modifications to tidal prism (typically by filling and dredging) change tidal flows in and out of embayment. Conversion of open tidal entrance channel to tide gate. Changes to tidal hydrology impact circulation, sediment transport, and salinity distribution within embayment.

continued

Broad Physiographic Processes	Local Geochemical and Ecological Response	Impairments
Sediment Delivery. Sediment supply is function of sediment availability, delivery mechanisms (streams, landslides), and magnitude of stream/wave processes. Often difficult to distinguish from sediment transport. **Fluvial Sediment Delivery**. Where a stream enters an embayment, terrestrial sediment can be delivered by fluvial action. This sediment may be deposited within the embayment, typically in a delta, or may be carried through the embayment and into the open marine environment. **Marine Sediment Delivery**. Sediment may enter an embayment from the marine system via wave action and tidal currents. Wave action may carry sediment over a barrier into the embayment (overwash) or through an entrance channel (forming flood tide delta). Tidal currents can carry sediment into and out of barrier estuaries and lagoons.	Burial Sediment (grain size) sorting and stratification	Stream, watershed and shoreline modifications may change amount and rate of sediment delivery to shoreline. Alteration of stream mouth (channelization, pipes, filling of estuary, and altered tidal prism) may change sediment delivery. Regulation and modification of stream flow, increase or decrease in sediment availability within watershed, sediment trapping by dams, obstructions, or artificial ponds, dredging of stream sediment. Clearing and development may increase sediment loads. Stormwater detention and sediment control facilities reduce sediment loads. Changes to stream mouths alter routing of sediment through estuary. Changes to tidal prism, relative influence of stream flow, availability of beach sediment due to shoreline modifications updrift, and configuration of tidal inlet can affect import of marine sediment into embayment.
Sediment Transport. Sediment may be transported into, through, or out of an embayment by stream flow, tidal currents, or wave action. Hard to separate from sediment supply below.	Autotrophy Heterotrophy Conversion between dissolved and particulate organic matter	Modification of tidal prism, stream discharge, and yield. Change in watershed characteristics (land cover, impervious surface), or embayment configuration. Decrease in storage capacity (loss of flats or other off-channel areas.)
Modification of tidal prism, stream discharge, and yield. Change in watershed characteristics (land cover, impervious surface), or embayment configuration. Decrease in storage capacity (loss of flats or other off-channel areas.)	Seepage Conversion of inorganic nutrients into organic Salinity/temperature resistance	Regulation and modification of stream flow. Changes to watershed land cover. Freshwater diversions (drinking water, stormwater systems).
Solar Input	Autotrophic production	Autotrophic production
Tidal Channel Formation and Maintenance. Drainage of tidal waters from intertidal areas forms and maintains tidal channels.	Conversion of inorganic nutrients into organic Seepage	Modification of contributing tidal prism
Sediment Erosion and Accretion. In protected areas where vegetation can become established, such as emergent marshes, sediment can be trapped. Vice versa, trapped sediment builds elevation into tidal regimes where vegetation can become established (marsh formation).	Changes in inorganic nutrient states Ecological and habitat	Direct burial or dredging of marsh. Loss of sediment supply (marine or fluvial). Change in tidal hydrology.
Detritus Import and Export.	Heterotrophic production Ecological and habitat	Seawalls covering high shore zones

River Deltas (River-Dominated, Wave-Dominated, Tide-Dominated, Fan Deltas)

Regional Influences: *Climate, Geology/Tectonics, Tides and Waves, Sea Level Change, Freshwater Inflow*

Deltas are formed by extensive sediment accumulations at the mouths of large rivers that drain regional-scale watersheds (from Olympic or Cascade crest).

Broad Physiographic Processes	Local Geochemical and Ecological Response	Impairments
Fluvial sediment supply. Deltas are constructed over time by the deposition of sediment eroded from the watershed and carried to the delta by the river. Leads to delta progradation (growth and expansion). If sediment supply is limited, marine processes may result in erosion.	Conversion between dissolved and particulate organic matter by physical or biochemical possesses	Supply related to sediment availability within watershed and stored in the river system upstream. Also related to river discharge (volume and timing), which is tied to watershed land cover change and to regulation of river flows.
Sediment transport. Sediment carried through delta within distributary channels as both bedload and suspended sediment. During floods, sediment is carried out of the channels into delta plain, where it is typically deposited.	Burial Reduction in predation risk (refuge) due to turbidity Recruitment/depletion of biota due to accretion/erosion	Transport modified by alterations in river discharge (river flow regulation;, watershed changes). Also altered by changes in tidal hydrology. Routing of sediment within delta strongly influenced by channel modifications (levee construction, dredging). At smaller scale, sediment transport may be by sheet flow or by channel flow.
Freshwater Input. Rivers deliver freshwater to river mouth and delta, influencing vegetation growth and character of estuarine mixing with salt water. Volume and timing of discharge impact delta processes.	Conversion between dissolved and particulate organic matter by physical or biochemical possesses Salinity/temperature resistance	Modifications to river discharge (timing and volume) due to changes in watershed runoff characteristics, regulation of river flows (dams), or modifications to river channel system (dikes for flood control and loss of upstream storage).
Tidal Flow. Estuarine mixing is result of interaction between fresh water and salt water at the mouth of the river, and is influenced by the relative flow of the river and tidal flow and by the shape of the river mouth. Tidal inundation of intertidal flats and influence of tidal stage on water levels in upstream fluvial portions of delta.	Salinity/temperature resistance Reduction in predation risk (refuge) Competition (of biota) Behavior (of biota)	Tidal hydrology altered by changes in tidal access (areas subject to tidal inundation), modifications of tidal channel networks, changes in tidal prism (reduction due to filling, increase due to dredging).
Distributary Channel Migration. As fluvial sediment is deposited at the mouth of a stream, the stream becomes progressively inefficient, and typically will shift to a lower area of the delta plain (channel migration). Deltas build up over time (subside) as rivers grow delta seaward, points upstream rise in elevation.	Burial Recruitment (of biota)	Prevented by channelization of river and by reduction of peak flood events.

continued

Broad Physiographic Processes	Local Geochemical and Ecological Response	Impairments
Tidal Channel Formation and Maintenance. Tidal waters flood lower portions of delta plain and river floods flood upper portions. Drainage of tidal and flood waters results in formation and maintenance of channels.	Reduction in predation risk (refuge) Conversion of inorganic nutrients into organic	Modification of contributing tidal prism (by levee construction).
Sediment Erosion and Accretion. Sediment is deposited on emergent marsh surface, resulting in rise in elevation of marsh surface. Presence of vegetation increases sediment trapping.	Conversion of inorganic nutrients into organic Changes in inorganic nutrient states Ecological and habitat	Direct burial or dredging of marsh. Loss of sediment supply (marine or fluvial) by change in tidal/fluvial flooding caused by tidal barriers. Change in marsh vegetation.
Detritus Import and Export. Detritus may be derived externally (from upriver or from marine environment) or generated internally (salt marsh, riparian vegetation). Detritus is also exported from delta to other marine environments.	Conversion of inorganic nutrients into organic Changes in inorganic nutrient states	Reduction in external sources of detritus. Reduction in area available for generating detritus within delta system (and reduction in connectivity of these areas). Loss of areas suitable for storing detritus (flats, off-channel areas, marsh surface).

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Appendix C

Ecosystem Function Goods & Services Relative Ranking

Three-Phase Ranking Process

The Ecosystem Function, Goods and Services (EFG&S) Relative Ranking process was conducted in three phases by PSNERP Nearshore Science Team (NST). Each phase was supported by on-line resources for posting views or questions among participants with or without anonymity, sharing images or graphics of locations or shoreforms that typified conceptualized EFG&S, and a moderator for insuring timely results. Each phase also included on-line questionnaires and/or download and upload functions of these questionnaires, allowing maximum flexibility for each member of the science team to participate. Each phase was completed by all participants before the science team as a group moved on to the next phase of the process. At the end of each phase, a briefing was provided to the science team as a whole and a schedule for the next phase was established. A final workshop was held at the conclusion of the process, at which the process as a whole was reviewed and group consensus and approval of all results was established.

Phase I: Defining and Selecting EFG&S Appropriate for Puget Sound

In this phase, the participants reviewed and discussed three documents which laid the foundation for the definitions and selection of EFG&S that could be applied to the shoreforms of Puget Sound:

- Guidance for the Protection and Restoration of the Nearshore Ecosystems of Puget Sound (Fresh et al. 2004)
- The Millennium Ecosystem Assessment (MEA 2003; World Resources Institute 2005)
- A Geomorphic Classification of Puget Sound Nearshore Landforms (Shipman 2008)

The participants were required to acknowledge their review of the documents and to participate in the EFG&S selection process (Fig. D.1). All NST members (n=11) completed this step in the process including registration for on-line restricted access accounts.

Following a complete review of existing documents and establishing on-line access to supporting collaborative resources, each participant was asked to review, suggest changes to, and approve each EFG&S as appropriate for future consideration within the Puget Sound Nearshore context. This process was carried out by the use of an on-line questionnaire (Fig. D.2). In the review of 29 potential EFG&S, 34 suggested changes in the wording of the definition were posted by participants, 17 EFG&S definitions were agreed to be included by all participants without modification while 12 were suggested to be excluded by at least one participant. At the conclusion of this step a final set of 29 EFG&S and associated definitions were agreed upon by all participants.

Phase II: Assigning Relative Ranks for each Category of Change

In this phase, the participants assigned ranks for each of the shoreform transitions (tier 1), shoreline attribute (tier 2), or change in adjacent upland and total drainage area characteristics (tiers 3 and 4) in terms of how these changes would affect each of the EFG&S (Fig. D.3). Each participant again acted independently and in anonymity while being reminded of all on-line resources for collaborative discussion and review of existing material. During this phase both on-line versions of surveys as well as download and upload versions were available to participants. Both versions of the survey form were designed to insure that shoreforms, shoreline attributes, and drainage area characteristics were ranked relative to each other and that each EFG&S was considered independent of all other EFG&S. In this way, each EFG&S received a relative rank for each shoreform, attribute, or characteristic.

The shoreform (tier 1) survey asked that the participants provide a rank (1 the lowest rank through 14 the highest rank), which indicates each shoreform's relative ability (compared to the other shoreforms) to provide, regulate, support, or enhance human well-being for each of the EFG&S.

The survey to assess the effects of changes in shoreline attributes (tier 2) on EFG&S asked that the participants provide a rank (1 the lowest rank thru13 the highest rank) to indicate the relative impairment (compared to the other attributes) that affects the ability of each nearshore ecosystem to provide, regulate, support, or enhance human well-being in each EFG&S.

In the surveys for adjacent upland and total watershed area change (tiers 3 and 4), participants were asked to provide a rank (1 the lowest rank through 16 the highest) that indicates the relative impairment (compared to the other attributes) that ditto affects the ability of each nearshore ecosystem to provide, regulate, support, or enhance human well-being in each EFG&S.

The participants were surveyed for their independent ranking one tier at a time and all participants reviewed the group results for that tier and made comments and adjustments to ranks before reaching consensus for that tier; they then began the same process for the next tier.

Phase III: Consensus and Overall Rankings

In this phase, the individual rankings by each participant were combined to create a group ranking. The moderator of the process was responsible for deriving a group rank for each shoreform, shoreline attribute, or upland drainage area characteristic for each EFG&S and for summarizing those EFG&S group rankings into an overall relative rank that encompassed all the EFG&S for each category of change. This was an iterative process that provided feedback to the participants during the phase two proceedings and contributed to the cumulative rankings for each tier.

The group rank and overall rank for each shoreform, shoreline attribute, or adjacent upland and total watershed area characteristic was determined:

1) first, on the rank order of the Median of respondents values
2) second, when equal median scores occur (ties), shoreforms or attributes are ranked lower based upon the lower Mode value [exception for a MODE=0 meaning that no single value occurred more frequently], i.e., less consistency, and a higher ranking is assigned
3) third, when equal combined median and mode assignments occur, shoreforms are ranked lower by the higher Range value
4) fourth, if equal rankings still occur at that point, higher ranks are assigned based upon the highest individual ranking obtained
5) fifth and finally, if a clear rank cannot be determined at this point the Rank Sum value is then used

After each of the tiers was completed, an EFG&S in-person workshop was held to make final adjustments to the overall ranks and to reach consensus on the final results. The participants agreed that "rough consensus" would represent the judgment of the group where any dissent to any final ranking would be resolved such that all participants were unanimous in the final results and qualification or explanations would be used to completely represent the opinion of the group. In this way, the workshop and final results was inclusive of all opinions, participatory in group interaction, cooperative in reaching consensus, and solution-oriented in documenting individual opinions.

Consensus Ranking

Shoreform (Tier 1)

Of the 14 shoreforms considered, River-Dominated Deltas were recognized as the highest ranked for provisioning, regulating, and supporting a broad array of EFG&S (Fig. D.4). The Artificial and/or Modified shoreform was ranked lowest among these shoreforms in supporting EFG&S, along with the Plunging Rocky Coast shoreform.

Shoreline Attribute (Tier 2)

The attributes of the shoreline viewed as being the most impairing to the provision of EFG&S were the occurrence of roads near the shore, and the loss of oligohaline transition and tidal fresh water wetlands (Fig. D.5). Overwater structures were viewed as having the lowest relative impairment to the whole list of EFG&S, although participants acknowledged that these may severely impair some EFG&S.

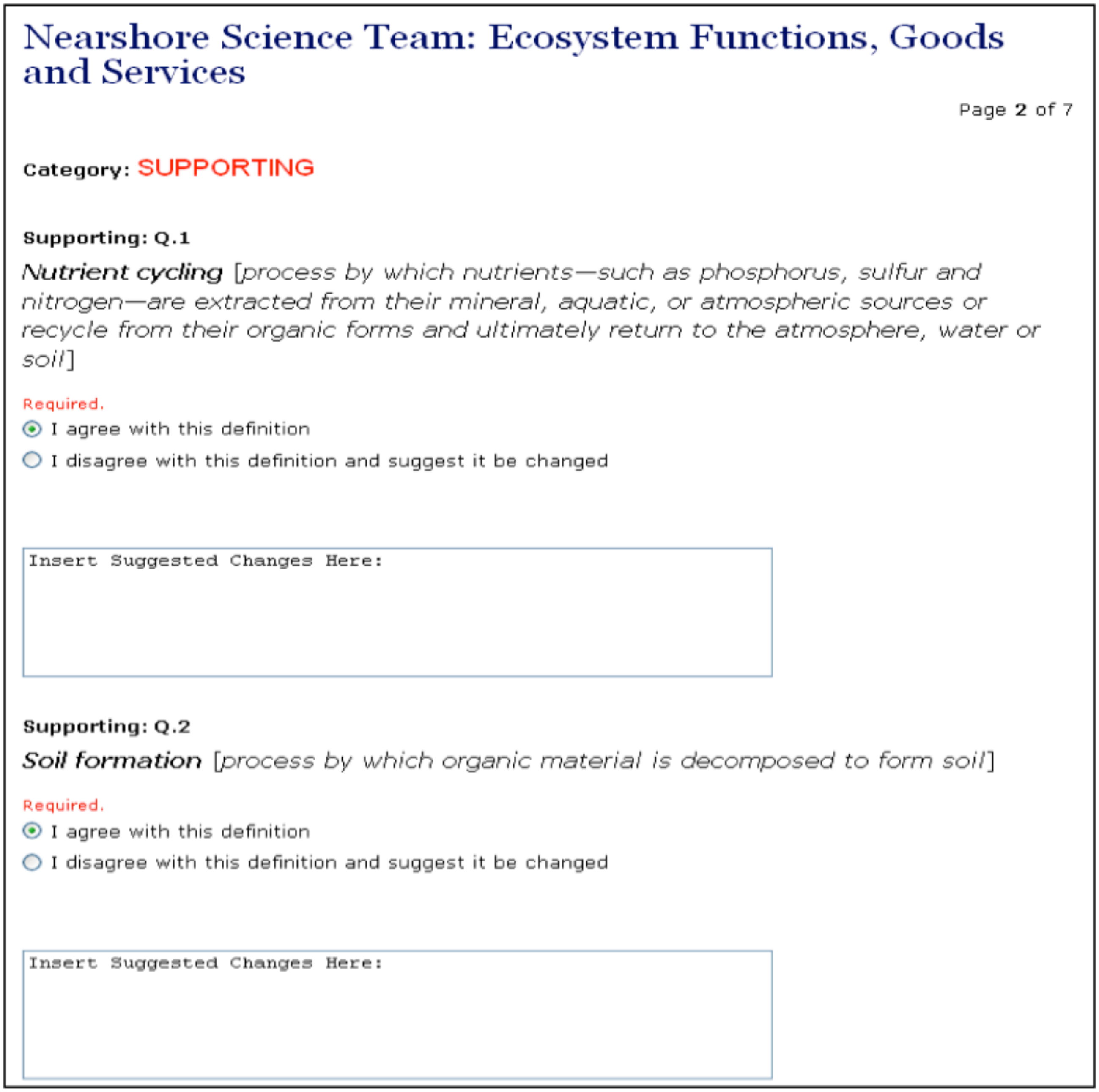
Adjacent Upland Land Cover (Tier 3)

The upland immediately adjacent to the shoreline was viewed as being most impaired when (relative to other attributes) it has 50–100 percent of its area in impervious surfaces (Fig. D.6). This is also true when the percent of impervious surfaces is as low as 30 percent. The extent of open space, nearshore road, and/or hay or pastures was viewed as having the lowest impairment on shoreline process units.

Total Watershed Area (Tier 4)

The upland drainage area was viewed as being most impaired when it has 50–100 percent of its area in impervious surfaces (Fig. D.7). This is also true when the percent of impervious surfaces is as low as 30 percent. The extent of open space, nearshore road, and/or hay or pastures was viewed as having the lowest impairment. By group consensus at the final workshop, the attributes of Extent of Impounded Drainage Area and Extent of Drainage Area Reduction were ranked very high in relative impairment potential.

Figure D.1. Review of background material and agreeing to future participation



Nearshore Science Team: Ecosystem Functions, Goods and Services

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Category: SUPPORTING

Supporting: Q.1

Nutrient cycling [*process by which nutrients—such as phosphorus, sulfur and nitrogen—are extracted from their mineral, aquatic, or atmospheric sources or recycle from their organic forms and ultimately return to the atmosphere, water or soil*]

Required.

- (selected) I agree with this definition
- ( ) I disagree with this definition and suggest it be changed

Insert Suggested Changes Here:

Supporting: Q.2

Soil formation [*process by which organic material is decomposed to form soil*]

Required.

- (selected) I agree with this definition
- ( ) I disagree with this definition and suggest it be changed

Insert Suggested Changes Here:

Figure D.2. Defining and Selecting EFG&S for future consideration

EFG&S		
Provisioning	Food	Crops
		Livestock
		Captured fisheries
		Aquaculture
		Wild foods
	Fiber	Timber and wood
		Other fibers
		Biomass Fuel
	Fresh Water (quantity)	
	Genetic resources	
	medicienes	
Regulating	Air quality regulation	
	Global Climate	
	Regional and local Climate	
	Water (quantity)	
	treatment	
	Disease	
	Pests	
	Pollination	
	Natural Hazards	
Cultural	Ethical	
	Existence	
	Recreation and ecotourism	
	Educational	
Supporting	Nutrient Cycling	
	Soil Formation	
	Food Web	
	Photosynthesis	
	Sediment Supply	

Tier 1

For each of the Shoreforms listed below, please enter a rank (1 the lowest rank, thru 14 the highest rank) which indicates that shoreforms' relative ability to provide, regulate, support, or enhance human well-being in each of the EFG&S listed on the rows.

Rocky Coast			Beaches		Embayments				River Deltas				Artificial
Plunging	Platform	Pocket Beaches	Bluffs	Barriers	Open Coastal Inlets	Barrier Estuaries	Barrier Lagoons	Closed Lagoons, Marshes	River-dominated	Wave-dominated	Tide-dominated	Fan	

Tier 2

For each of the Shoreline Attributes listed below, please enter a rank (1 the lowest rank, thru 13 the highest rank) which indicates the relative impairment that each affects the ability of the nearshore ecosystems to provide, regulate, support, or enhance human well-being in each of the EFG&S listed on the rows.

Loss of:				Addition of:								
Wetlands (marine => tidal freshwater)											Railroads	
Euryhaline unvegetated	Estuarine mixing	Oligohaline transition	Tidal fresh water	Armoring	Breakwaters & Jetties	Tidal Barriers (levees, dikes)	Overwater Structures	Fill	Marinas	Roads	Active	Abandoned

Tier 3 & 4

For each of the Attributes listed below, please enter a rank (1 the lowest rank, thru 14 the highest rank) which indicates the relative impairment that each affects the ability of the nearshore ecosystems to provide, regulate, support, or enhance human well-being in each of the EFG&S listed on the rows.

Land Cover/Land Use										Extent of Road Area	Extent of Road and Other Stream Crossings	Extent of Railroads	
Extent of Cultivated Crops	Extent of Hay /Pasture	Extent Dev., High Intensity	Extent of Dev., Medium Intensity	Extent Dev., Low Intensity	Extent Of Dev., Open Space	1-9% Imp. Surface	10-29% Imp. Surface	30-49% Imp. Surface	50-100% Imp. Surface			Active	Abandoned

Figure D.3. Survey architecture used to rank the effect on EFG&S for each category (tier) of nearshore ecosystem change. Relative ranks of impairment to each EFG&S was assigned by each participant for each shoreform (tier1), shoreline attribute (tier 2) and adjacent upland and total watershed area land cover (tiers 3 & 4)

EFG&S			Rocky Coast			Beaches		Embayments				River Deltas				Artificial and/or Modified	Sum of "Range"	Order of Disimilarity in EFG&S Ranking
			Plunging	Platform	Pocket Beaches	Bluffs	Barriers	Open Coastal Inlets	Barrier Estuaries	Barrier Lagoons	Closed Lagoons and Marshes	River-dominated	Wave-dominated	Tide-dominated	Fan			
Provisioning	Food	Crops	1	2	3	4	5	6	7	9	10	14	12	13	11	8	52	29
		Livestock	1	2	3	4	5	6	7	8	9	14	12	13	11	10	53	28
		Captured fisheries	6	4	5	2	8	12	9	7	3	14	10	13	11	1	140	13
		Aquaculture	1	3	4	2	13	9	11	10	14	8	5	6	7	12	159	1
		Wild foods	3	4	7	2	6	11	9	8	5	14	10	12	13	1	157	2
	Fiber	Timber and wood	1	2	5	13	12	7	10	4	8	14	11	9	6	3	137	14
		Other fibers	1	2	3	11	5	6	8	7	9	14	12	13	10	4	132	19
		Biomass Fuel	1	2	8	13	11	4	9	5	7	14	10	12	6	3	148	5
	Fresh Water (quantity)		2	3	5	6	4	7	10	8	9	14	13	11	12	1	130	21
	Genetic resources		5	8	9	13	6	4	2	7	11	14	12	10	3	1	124	24
	Biochemicals, natural medicienes		2	3	5	7	4	8	6	10	9	14	13	12	11	1	146	7
Regulating	Air quality regulation		1	2	3	11	6	7	10	9	8	14	12	13	5	4	142	9
	Global Climate		2	3	5	13	4	12	8	7	9	14	10	11	6	1	145	7
	Regional and local Climate		2	3	4	8	6	10	11	9	7	14	12	13	5	1	133	17
	Water (quality)		2	3	4	5	6	7	8	10	11	14	13	12	9	1	133	17
	Erosion		1	5	3	13	10	9	7	4	2	11	12	6	8	14	154	4
	Water purification and wate		2	3	4	6	5	7	11	8	10	14	12	13	9	1	137	14
	Disease		2	3	5	7	6	10	8	4	9	14	12	13	11	1	128	22
	Pests		2	3	4	6	5	7	10	9	8	14	12	13	11	1	124	24
	Pollination		2	3	5	4	6	9	8	7	12	14	13	11	10	1	120	27
	Natural Hazards		1	2	5	10	8	9	7	6	4	14	11	13	12	3	132	19
Cultural	Ethical		8	3	6	10	9	7	5	4	2	14	12	13	11	1	134	16
	Existence		14	4	2	12	13	9	7	10	5	11	6	8	3	1	142	9
	Recreation and ecotourism		7	11	8	13	14	5	4	1	2	10	3	12	6	9	155	3
	Educational		12	7	10	3	11	5	9	4	2	14	6	8	13	1	121	26
Supporting	Nutrient Cycling		2	3	4	6	5	8	12	7	13	14	10	11	9	1	128	22
	Soil Formation		1	3	4	5	7	8	10	9	11	13	14	12	6	2	141	11
	Food Web		6	4	3	7	5	10	11	9	2	14	12	13	8	1	141	11
	Photosynthesis		8	7	4	3	2	6	10	9	5	14	12	13	11	1	148	5
RANK SUM			99	107	140	219	207	225	244	209	216	389	314	332	254	90		
MEDIAN			2	3	4	7	6	7	9	8	8	14	12	12	9	1		
MODE			1	3	5	13	5	7	10	9	9	14	12	13	11	1		
RANGE			13	9	8	11	12	8	10	9	12	6	11	7	10	13		
RANK			2	3	4	7	5	6	10	8	9	14	12	13	11	1		

Lowest in series
Highest in series
Under 1 std.
Over 1 std.

Figure D.4. Ranking matrix used by PSNERP Nearshore Science Team to assess contributions to provisioning, regulating, cultural and supporting ecosystem functions, goods and services (EFG&S) by respective shoreforms (Tier 1).

EFG&S			Loss of: Wetlands (marine => tidal freshwater)				Addition of:									Sum of Range	Order of Disimilari ty
			Euryhaline unvegetated (mud/sandflat)	Estuarine mixing	Oligohaline transition	Tidal fresh water	Armoring	Breakwaters & Jetties	Tidal Barriers (levees, dikes)	Overwater Structures	Fill	Marinas	Roads	Railroads Active	Railroads Abandoned		
Provisioning	Food	Crops	4	7	12	13	1	3	6	2	9	5	11	10	8	119	9
		Livestock	5	7	9	13	1	2	6	3	10	4	12	11	8	117	10
		Captured fisheries	8	13	12	11	4	9	10	6	7	5	2	3	1	114	13
		Aquaculture	10	7	2	4	9	8	12	6	11	13	5	3	1	128	3
		Wild foods	9	10	11	13	3	2	6	1	12	5	7	8	4	127	4
	Fiber	Timber and wood	1	3	10	13	5	4	7	2	11	6	12	9	8	92	28
		Other fibers	1	8	12	13	3	4	6	2	11	5	10	9	7	106	21
		Biomass Fuel	3	7	8	10	5	2	4	1	11	6	13	12	9	113	14
	Fresh Water (quantity)		2	5	7	13	6	4	9	1	8	3	10	12	11	107	19
	Genetic resources		9	10	12	13	2	3	5	1	11	7	8	6	4	115	12
	Biochemicals, natural medicienes		9	11	12	13	1	2	6	3	10	7	8	5	4	116	11
Regulating	Air quality regulation		4	10	12	13	1	2	6	3	8	7	11	9	5	108	18
	Global Climate		6	11	12	13	1	2	10	3	9	8	7	5	4	92	28
	Regional and local Climate		7	11	12	13	3	2	5	1	10	8	9	6	4	107	19
	Water (quantity)		5	10	11	13	2	3	12	1	8	4	9	7	6	105	22
	Water purification and waste		9	11	12	13	2	3	10	1	8	7	6	5	4	109	16
	Disease		2	6	11	13	3	4	7	1	8	10	12	9	5	106	22
	Pests		3	11	12	13	4	2	10	1	7	8	9	6	5	102	25
	Pollination		1	11	12	13	3	4	8	2	10	6	9	7	5	97	27
	Natural Hazards		2	11	12	13	8	6	9	1	10	3	7	5	4	104	24
Cultural	Ethical		9	12	11	13	7	4	3	5	10	8	6	2	1	126	6
	Existence		9	12	11	13	7	4	3	5	10	8	6	2	1	127	4
	Recreation and ecotourism		10	12	11	13	4	6	5	8	9	7	3	2	1	131	1
	Education		9	13	11	12	4	8	7	6	10	5	3	2	1	131	1
Supporting	Nutrient Cycling		12	11	12	13	4	6	9	2	8	7	5	3	1	109	16
	Soil Formation		10	13	11	12	9	5	8	1	7	2	6	4	3	123	7
	Food Web		9	11	12	13	7	2	5	4	10	8	6	3	1	112	15
	Photosynthesis		6	11	13	12	2	4	9	10	7	8	5	3	1	102	25
	Sediment Supply		3	5	6	4	13	10	7	2	9	1	11	12	8	121	8
Rank Sum			177	280	311	351	124	120	210	85	269	181	228	180	125		
Median			6	11	12	13	4	4	7	2	10	7	8	6	4		
Mode			9	11	12	13	1	2	6	1	10	8	6	3	1		
Range			11	10	11	9	12	8	9	9	5	12	11	10	10		
Rank			6	11	12	13	3	4	7	1	10	8	9	5	2		

Lowest in series
Highest in series

Figure D.5. Ranking matrix used by PSNERP Nearshore Science Team to assess relative impairment of EFG&S by shoreline attributes (Tier 2).

EFG&S			Extent of Cultivated Crops	Extent of Hay /Pasture	Extent Dev., High Intensity	Extent of Dev., Medium Intensity	Extent Dev., Low Intensity	Extent 0f Dev., Open Space	1-9% Imp. Surface	10-29% Imp. Surface	30-49% Imp. Surface	50-100% Imp. Surface	Extent of Road Area	Extent of Road and Other Stream Crossings	Extent of Railroads: Active	Extent of Railroads: Abandoned	Sum of "Range"	Order of Disimilarity in EFG&S Ranking
			Land Cover/Land Use															
Provisioning	Food	Crops	1	2	12	11	4	3	6	10	13	14	8	9	5	11	131	12
Provisioning	Food	Livestock	1	2	12	11	4	3	6	10	13	14	8	9	5	7	132	10
Provisioning	Food	Captured fisheries	1	2	12	9	5	3	4	7	13	14	10	11	8	6	137	5
Provisioning	Food	Aquaculture	1	2	12	11	5	3	4	8	13	14	10	9	7	6	136	6
Provisioning	Food	Wild foods	1	2	12	11	5	3	4	10	13	14	8	7	9	6	138	3
Provisioning	Fiber	Timber and wood	3	2	12	11	9	1	7	10	13	14	8	5	6	4	74	22
Provisioning	Fiber	Other fibers	1	2	12	11	8	3	5	10	13	14	9	7	6	4	71	23
Provisioning	Fiber	Biomass Fuel	1	2	12	11	8	3	5	10	13	14	9	7	6	4	65	24
Provisioning		Fresh Water (quantity)	2	4	12	11	10	1	3	9	13	14	8	7	6	5	138	3
Provisioning		Genetic resources	3	4	13	11	9	1	6	10	12	14	7	5	8	2	141	2
Provisioning		Biochemicals, natural	3	4	13	11	9	1	6	10	12	14	7	5	8	2	142	1
Regulating		Air quality regulation	7	5	12	11	10	1	6	9	13	14	8	4	3	2	130	14
Regulating		Global Climate	8	6	12	11	10	1	5	9	13	14	7	3	4	2	127	19
Regulating		Regional and local Climate	8	6	12	11	10	1	5	9	13	14	7	3	4	2	128	17
Regulating		Water (quality)	3	2	12	11	9	1	4	10	13	14	8	7	6	5	0	10
Regulating		Water purification and waste	6	3	12	11	9	1	5	10	13	14	8	7	4	2	135	7
Regulating		Disease	6	4	12	11	9	2	7	10	13	14	8	3	5	1	133	9
Regulating		Pests	5	3	12	11	8	2	7	10	13	14	9	4	6	1	131	12
Regulating		Pollination	3	1	12	11	9	2	7	10	13	14	8	6	5	4	129	16
Regulating		Natural Hazards	5	2	12	11	9	1	6	10	13	14	8	7	4	3	128	17
Cultural		Ethical	4	1	13	11	3	2	8	10	12	14	5	6	7	9	125	20
Cultural		Existence	4	1	13	11	3	2	8	10	12	14	5	6	7	9	122	21
Cultural		Recreation and ecotourism	4	1	13	11	9	2	8	10	12	14	5	6	7	3	130	14
Cultural		Education	4	1	13	11	9	2	8	10	12	14	5	6	7	3	130	14
Supporting		Nutrient Cycling	2	1	12	11	6	5	10	9	13	14	8	7	3	4	62	25
Supporting		Soil Formation	2	1	12	11	6	5	10	9	13	14	8	7	3	4	62	25
Supporting		Food Web	2	1	12	11	6	5	10	9	13	14	8	7	3	4	62	25
Supporting		Photosynthesis	2	1	12	11	5	4	7	8	13	14	10	9	3	6	48	28
Supporting		Sediment Supply	3	2	12	9	8	1	7	10	13	14	11	6	5	4	0	28
RANK SUM - Tier3			96	70	354	315	214	65	184	276	371	406	228	185	160	125		
Median			3	2	12	11	8	2	6	10	13	14	8	7	6	4	Lowest in series	
Mode			1	2	12	11	9	1	6	10	13	14	8	7	6	4	Highest in series	
Range			7	5	1	2	7	4	7	3	1	0	6	8	6	10		
Rank			3	2	12	11	9	1	5	10	13	14	8	7	6	4		

Figure D.6. Ranking matrix used by PSNERP Nearshore Science Team to assess relative impairment of EFG&S by adjacent upland land cover (Tier 3); note the lack of summed range values above the 1st standard deviation.

EFG&S			Extent of Cultivated Crops	Extent of Hay/ Pasture	Extent Dev., High Intensity	Extent of Dev., Medium Intensity	Extent Dev., Low Intensity	Extent of Dev., Open Space	1-9% Imp. Surface	10-29% Imp. Surface	30-49% Imp. Surface	50-100% Imp. Surface	Extent of Road Area	Extent of Road and Other Stream Crossings	Extent of Railroads: Active	Extent of Railroads: Abandoned	Extent of Impounded Drainage Area	Extent of Drainage Area Reduction	Sum of "Range"	Order of Disimilarity in EFG&S Ranking
			Land Cover/Land Use																	
Provisioning	Food	Crops	1	2	10	11	4	3	5	12	13	14	9	8	7	6			39	27
Provisioning	Food	Livestock	1	2	10	11	4	3	5	12	13	14	9	8	7	6			41	26
Provisioning	Food	Captured fisheries	2	1	12	8	5	3	4	6	13	14	7	11	9	10			109	8
Provisioning	Food	Aquaculture	2	1	9	8	3	4	5	12	13	14	10	7	6	11			110	7
Provisioning	Food	Wild foods	2	1	9	7	3	4	5	12	13	14	10	6	8	11			107	10
Provisioning	Fiber	Timber and wood	1	2	11	10	5	3	4	12	13	14	9	8	6	7			58	17
Provisioning	Fiber	Other fibers	1	2	12	10	8	3	5	11	13	14	9	7	6	4			58	17
Provisioning	Fiber	Biomass Fuel	1	2	12	11	5	3	4	10	13	14	9	8	6	7			57	19
Provisioning		Fresh Water (quantity)	3	5	13	10	4	1	2	11	12	14	8	9	7	6			70	13
Provisioning		Genetic resources	1	3	12	10	6	2	4	11	13	14	9	7	7	5			118	2
Provisioning		Biochemicals, natural	1	3	12	10	6	2	4	11	13	14	9	7	8	5			118	2
Regulating		Air quality regulation	1	2	11	10	6	4	5	12	13	14	8	9	7	3			56	20
Regulating		Global Climate	1	2	12	10	6	4	5	11	13	14	8	9	7	3			59	16
Regulating		Regional and local Climate	1	2	12	10	6	4	5	11	13	14	8	9	7	3	Final Stage, Group Concensus addition	Final Stage, Group Concensus addition	60	15
Regulating		Water (quantity)	2	1	11	10	5	3	6	12	13	14	8	9	7	4			0	28
Regulating		Water purification and waste	2	1	10	11	3	4	6	12	13	14	8	9	7	5			62	14
Regulating		Disease	2	1	11	10	5	4	6	12	13	14	8	9	7	3			54	21
Regulating		Pests	2	1	12	10	8	3	5	11	13	14	9	6	7	4			53	22
Regulating		Pollination	1	2	12	10	6	3	4	11	13	14	8	9	7	5			43	25
Regulating		Natural Hazards	2	1	10	11	4	3	5	12	13	14	8	9	6	7			53	22
Cultural		Ethical	2	1	12	11	6	3	8	10	13	14	4	5	7	9			102	12
Cultural		Existence	2	1	12	11	5	3	8	10	13	14	4	6	7	9			103	11
Cultural		Recreation and ecotourism	3	1	12	11	8	2	9	10	13	14	4	5	6	7			108	9
Cultural		Education	3	1	12	11	8	2	9	10	12	14	4	5	6	7			130	1
Supporting		Nutrient Cycling	5	7	11	9	2	1	12	10	13	14	8	6	3	4			114	4
Supporting		Soil Formation	6	7	12	10	3	1	9	11	13	14	8	2	4	5			53	22
Supporting		Food Web	2	7	11	9	3	1	12	10	13	14	8	6	4	5			112	6
Supporting		Photosynthesis	2	3	12	11	4	1	9	10	13	14	8	7	5	6			113	5
Supporting		Sediment Supply	3	2	12	9	8	1	7	10	13	14	11	6	5	4			0	28
Rank Sum - Tier4			58	67	329	290	149	78	177	316	376	406	230	212	186	171				
Median			2	2	12	10	5	3	5	11	13	14	8	7	7	5			Lowest in original series(10)	
Mode			2	1	12	10	6	3	5	12	13	14	8	9	7	5			Highest in original series	
Range			5	6	4	4	6	3	10	6	1	0	7	9	6	8				
Rank			2	1	12	10	6	3	4	11	13	14	9	8	7	5				
Final Rank Sum - Tier4			77	78	439	379	196	102	209	412	495	534	306	278	245	210				
Final Rank			2	1	14	10	6	3	4	13	15	16	9	8	7	5	11	12		

Figure D.7 Ranking matrix used by PSNERP Nearshore Science Team to assess relative impairment of EFG&S by total watershed area land cover (Tier 4).

Appendix D

Puget Sound Sub-Basin Component Maps

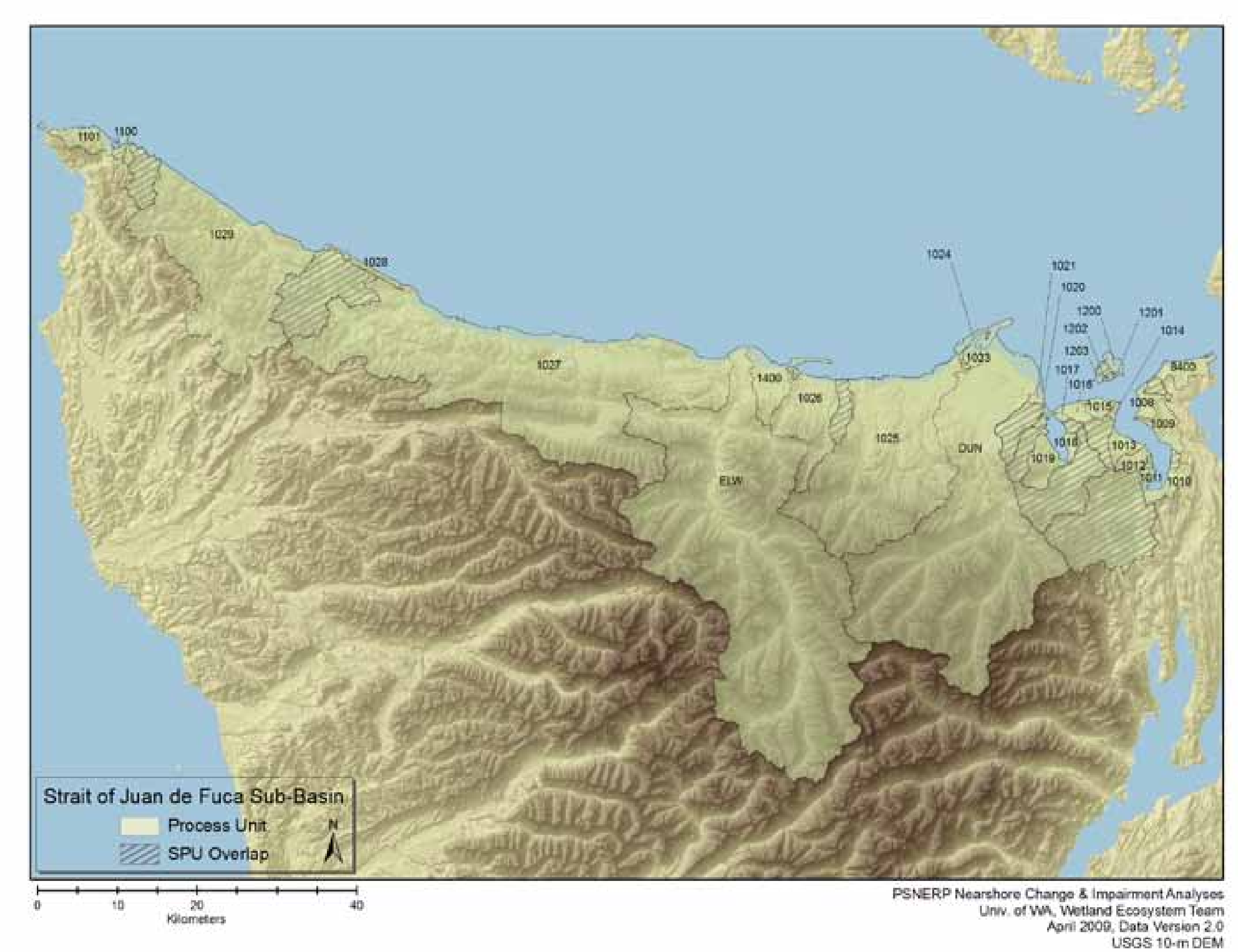

Figure E.1. Process units (PU) in Strait of Juan de Fuca Sub-Basin.

Figure E.2. Process units (PU) in eastern component of San Juan Islands–Strait of Georgia Sub-Basin.

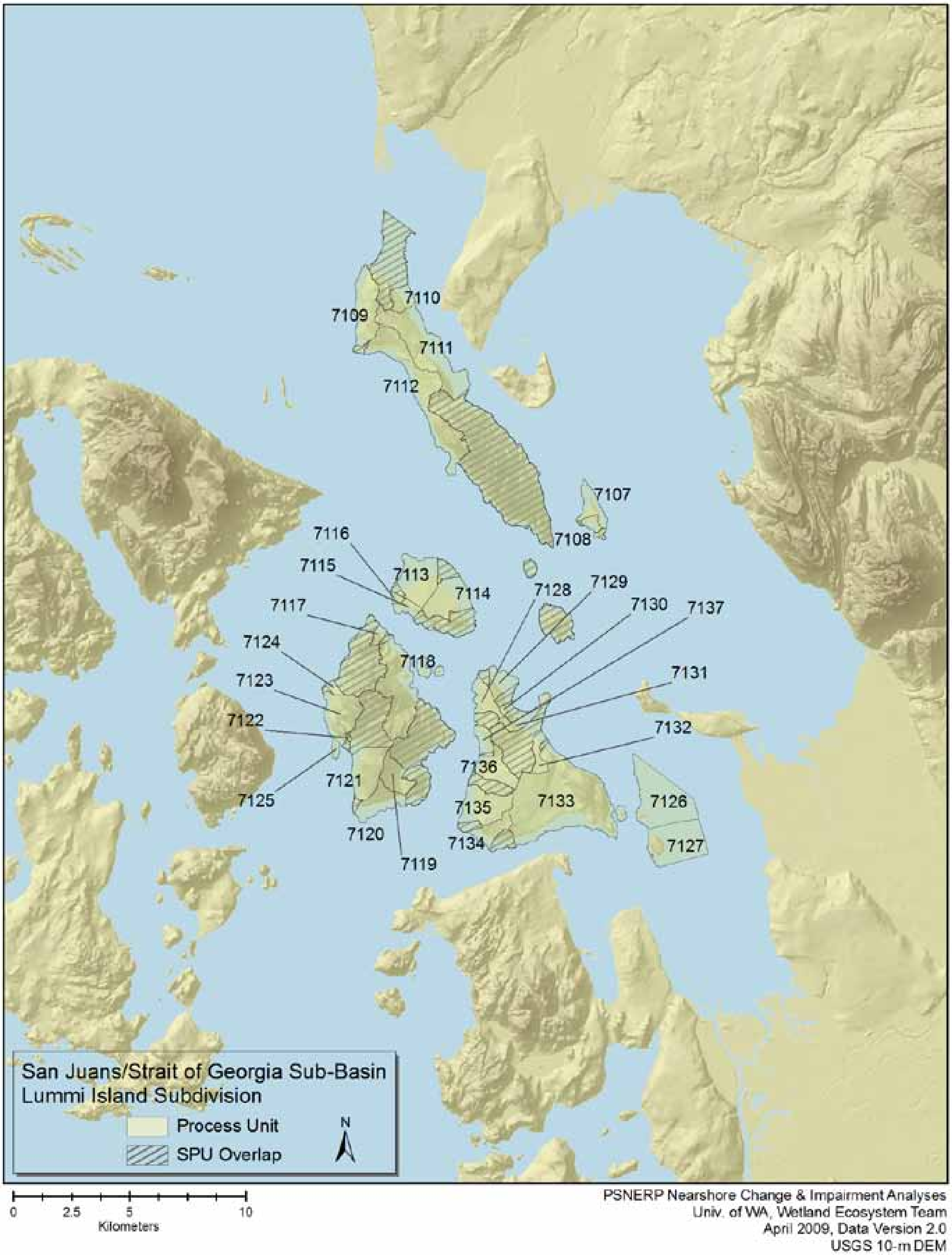

Figure E.3. Process units (PU) in the central (Lummi Island) component of the San Juan Islands–Strait of Georgia Sub-Basin.

Figure E.4. Process units (PU) in the Orcas Island component of San Juan Islands–Strait of Georgia Sub-Basin.

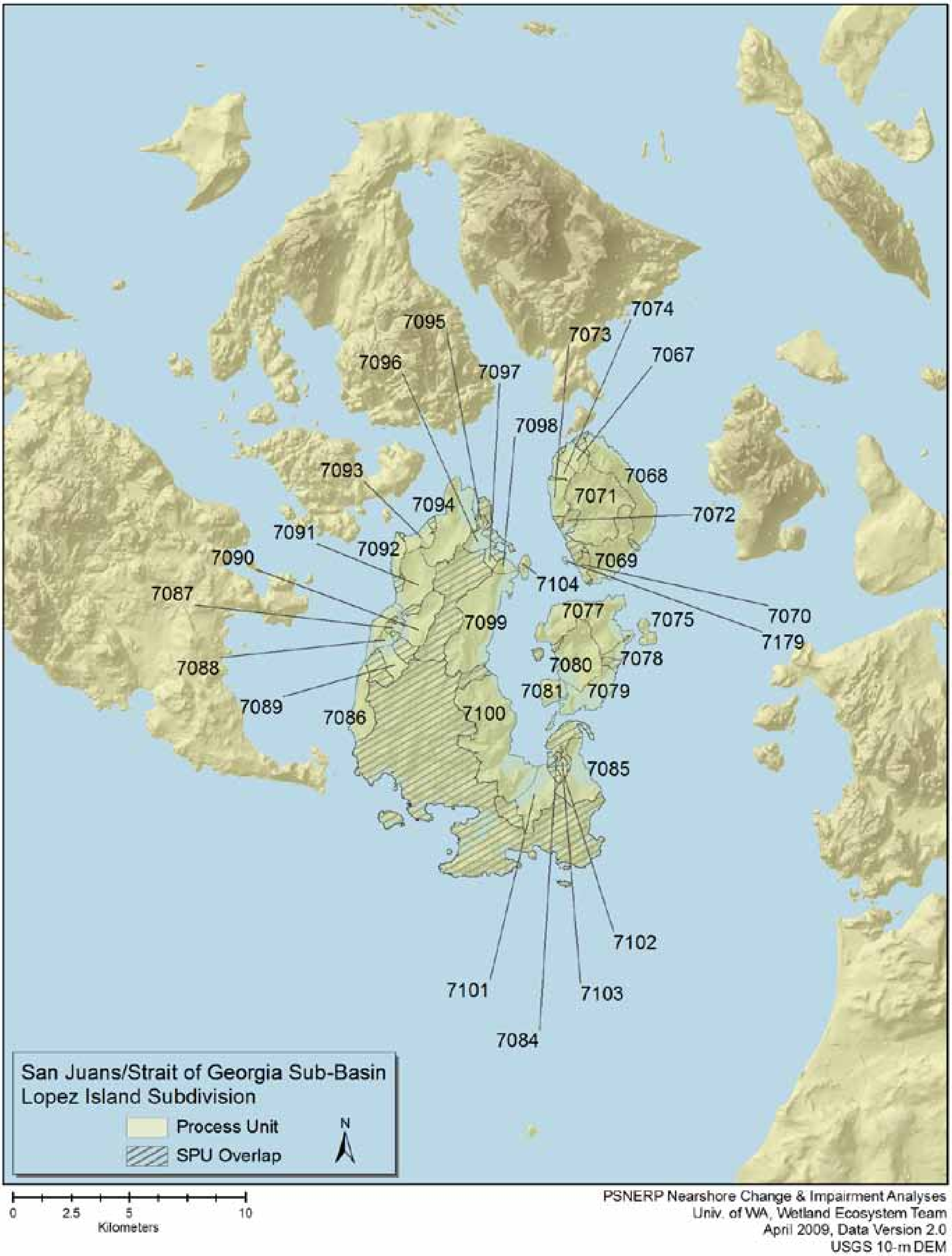

Figure E.5. Process units (PU) in the Lopez Island component of the San Juan Islands–Strait of Georgia Sub-Basin.

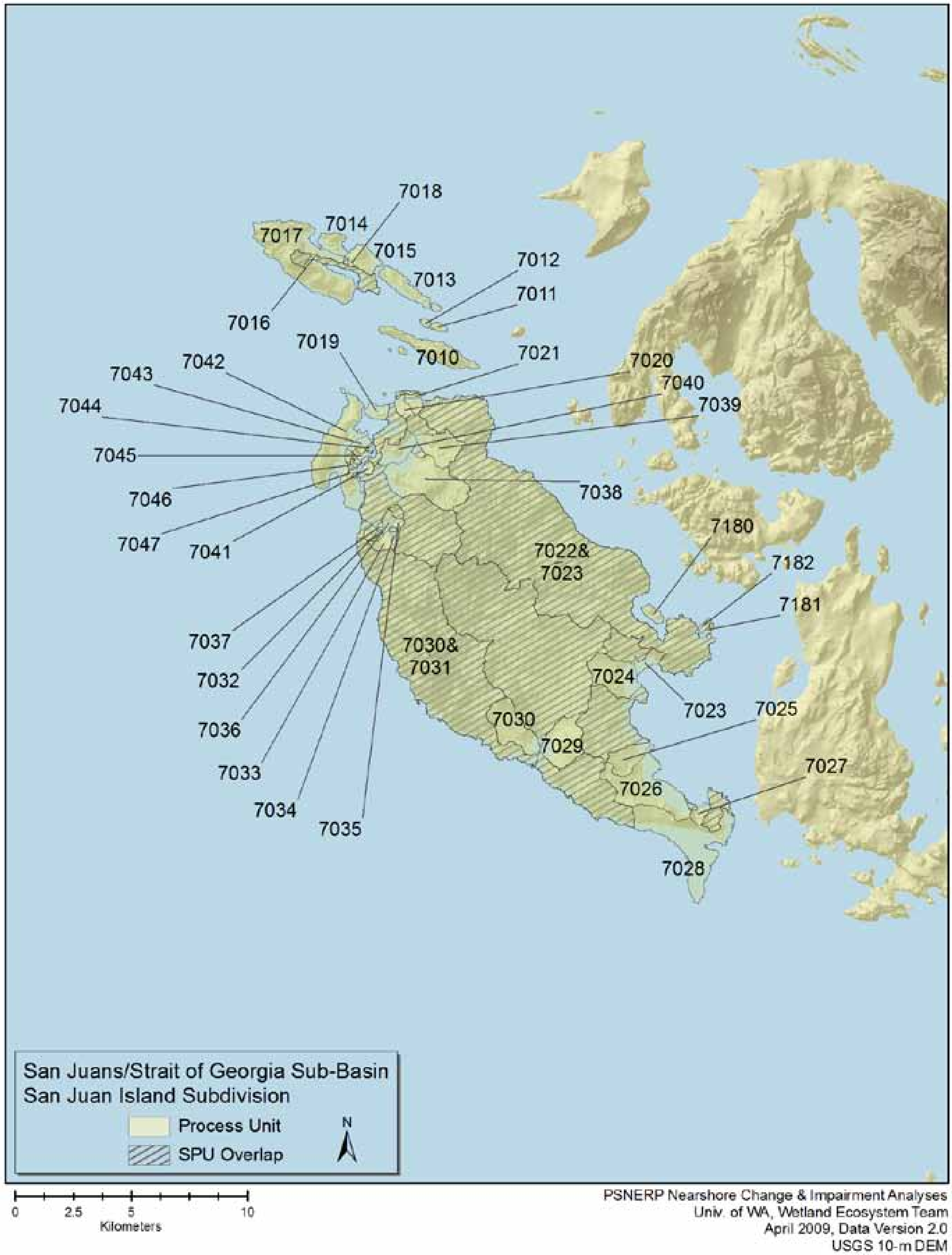

Figure E.6. Process units (PU) in San Juan Island component of the San Juan Islands–Strait of Georgia Sub-Basin.

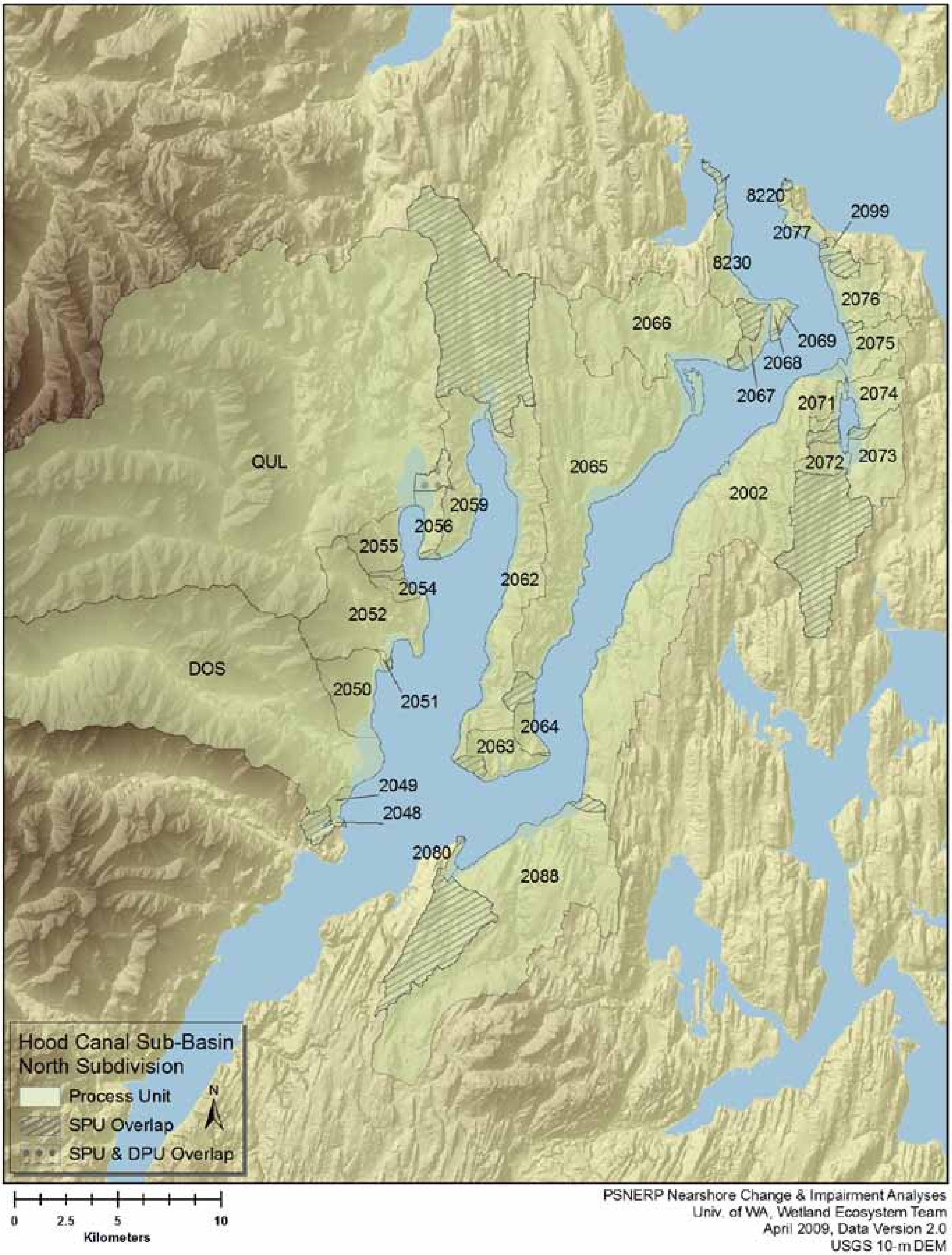

Figure E.7. Process units (PU) in northern component of Hood Canal Sub-Basin.

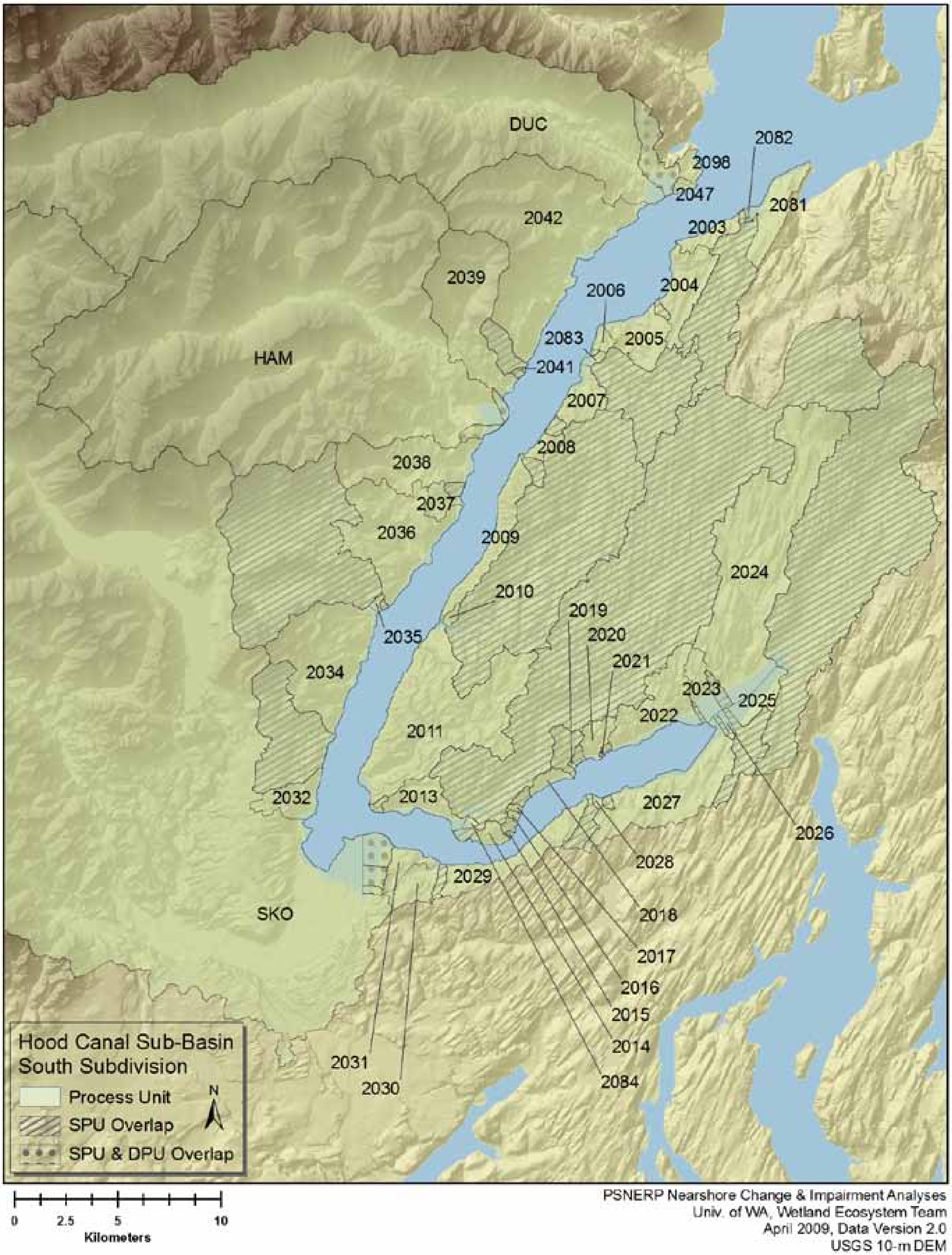

Figure E.8. Process units (PU) in southern component of Hood Canal Sub-Basin.

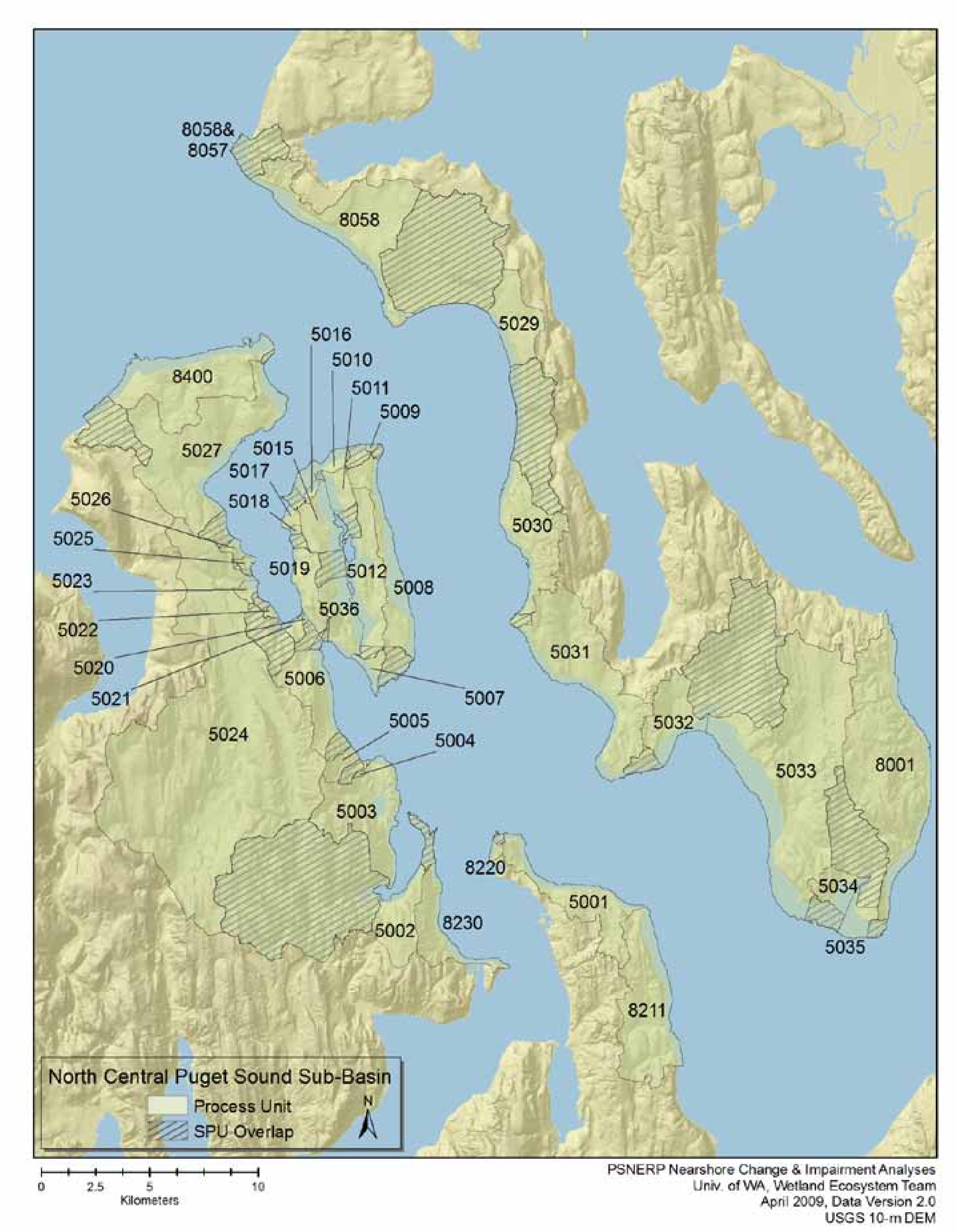

Figure E.9. Process units (PU) in North Central Puget Sound Sub-Basin

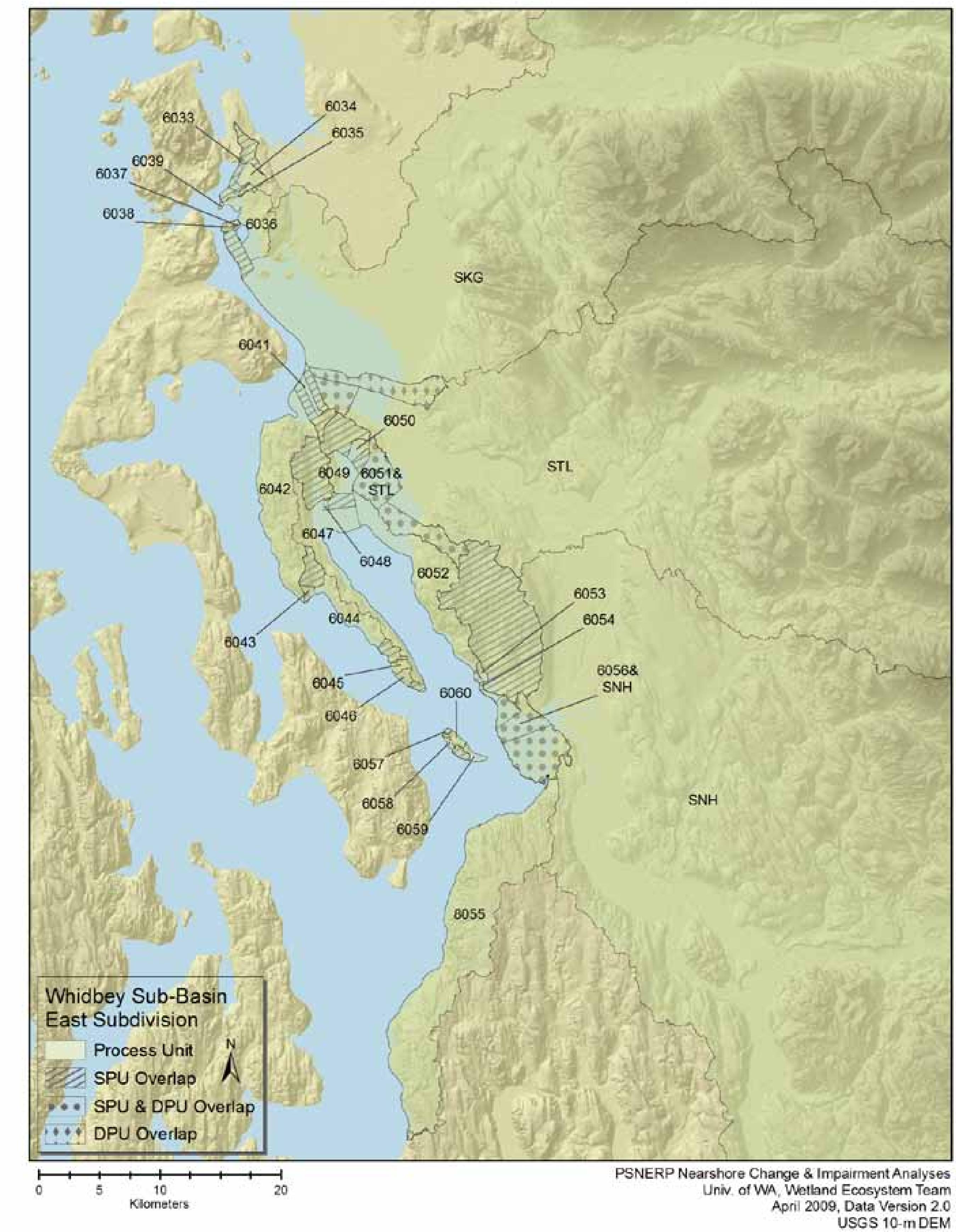

Figure E.10. Process units (PU) in eastern component of the Whidbey Sub-Basin.

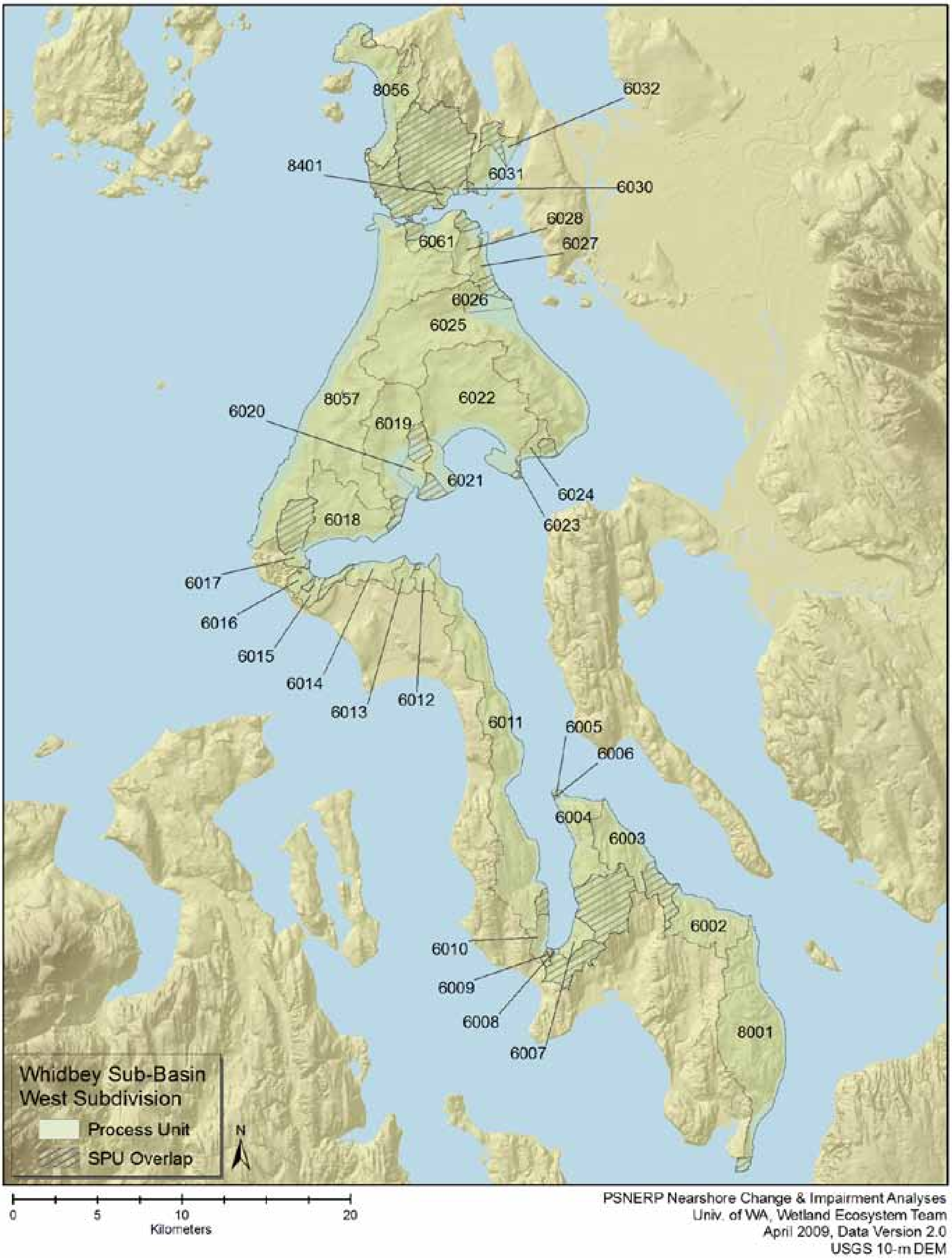

Figure E.11. Process units (PU) in western component of Whidbey Island Sub-Basin.

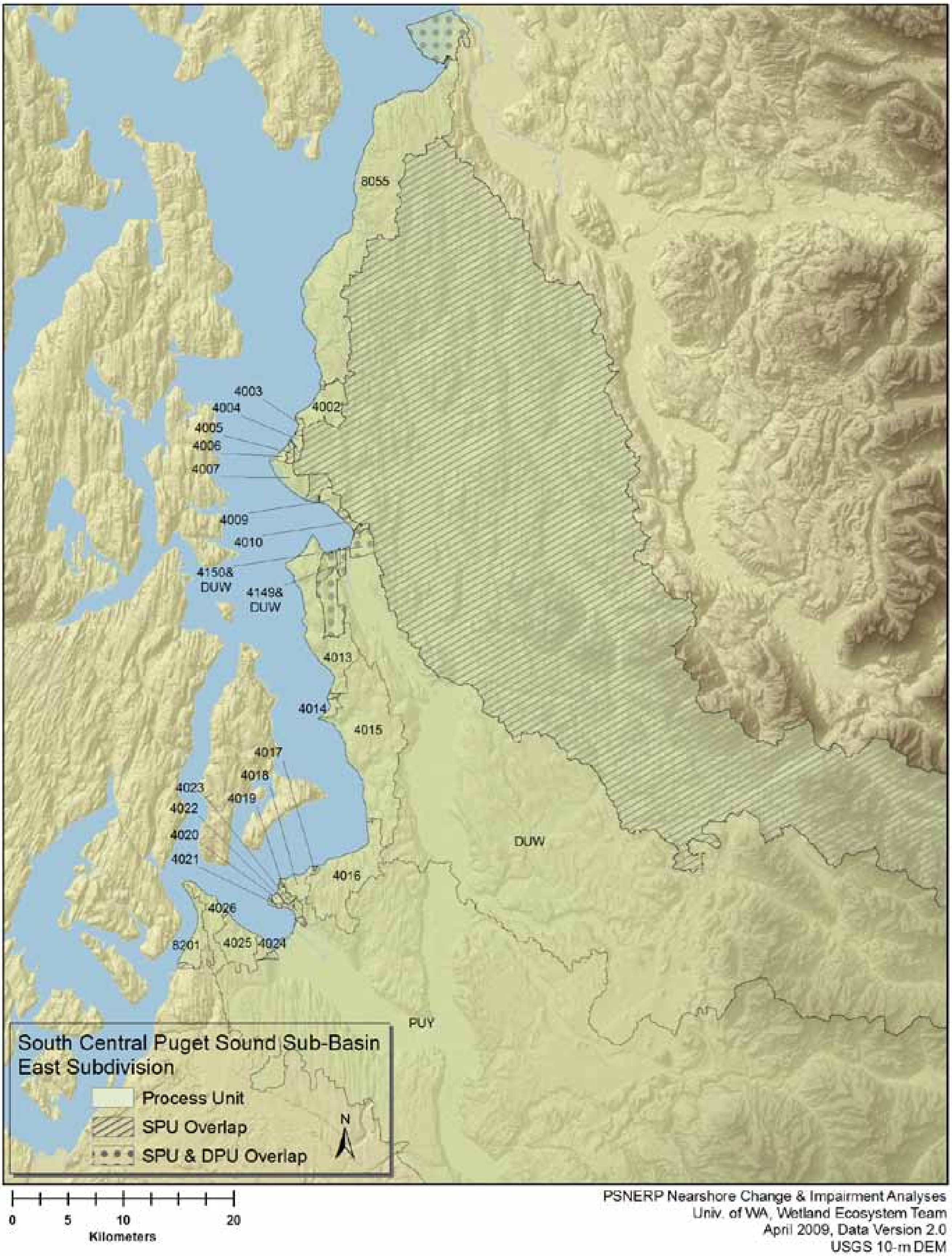

Figure E.12. Process units (PU) in eastern component of South Central Puget Sound Sub-Basin.

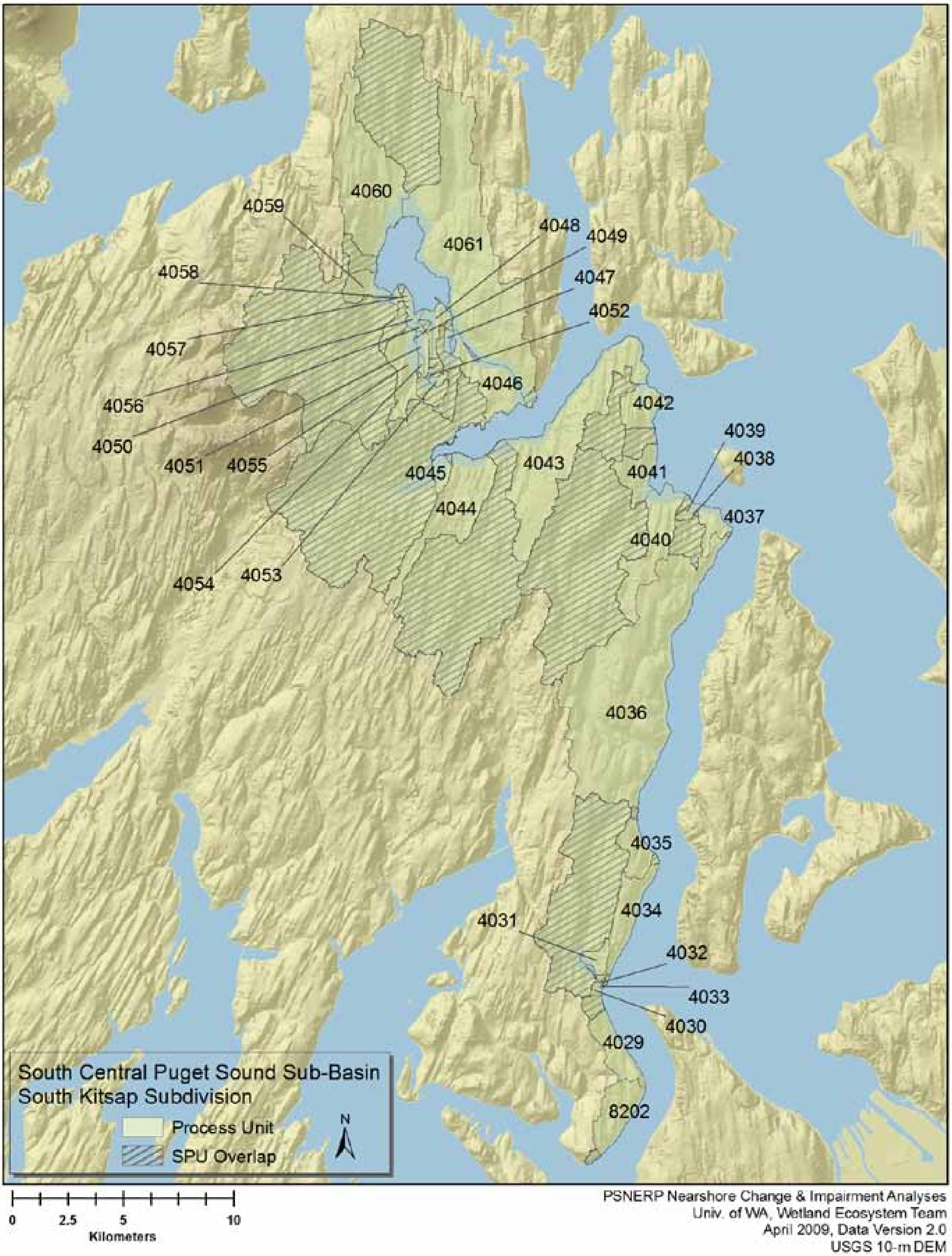

Figure E.13. Process units (PU) in the South Kitsap component of the South Central Puget Sound Sub-Basin.

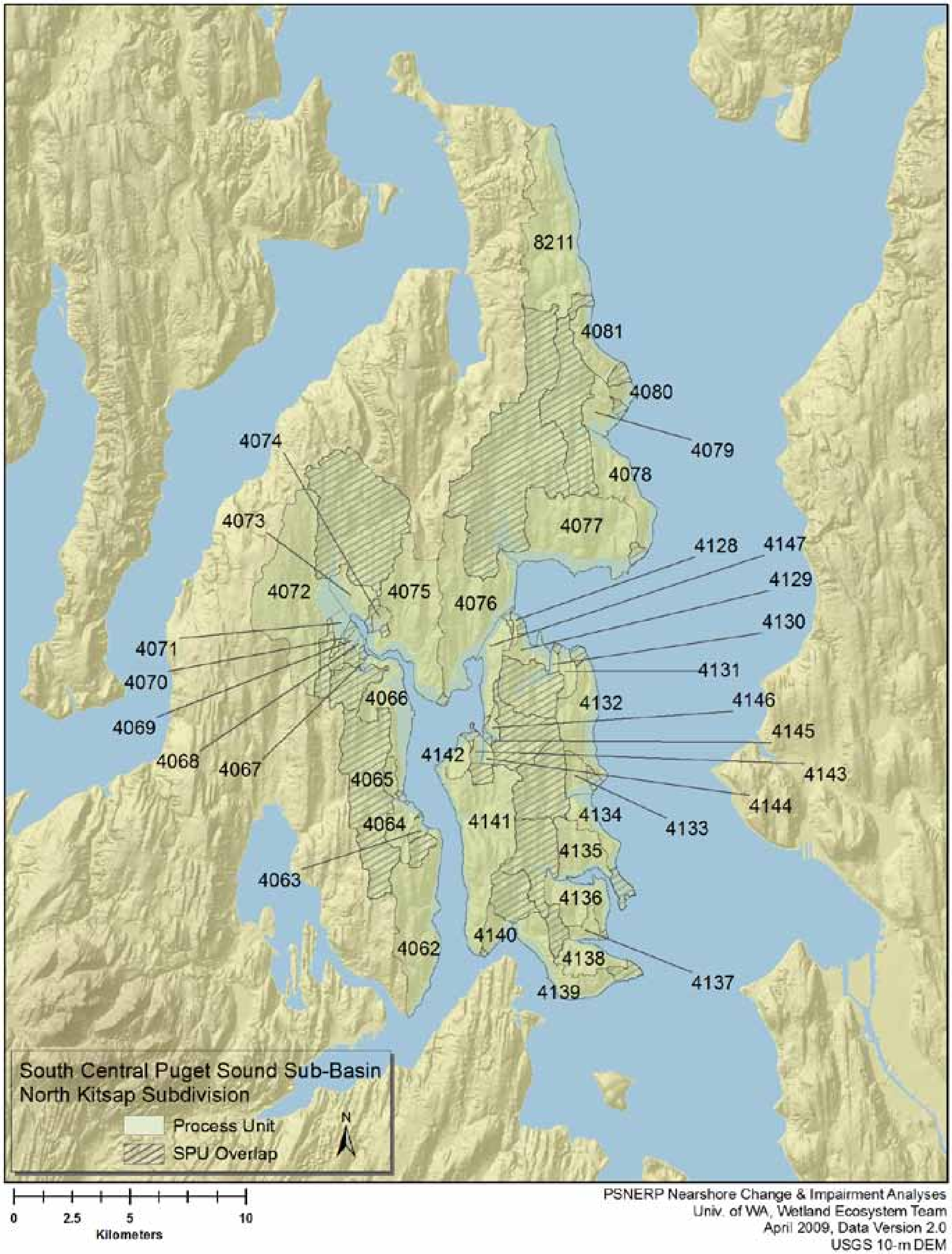

Figure E.14. Process units (PU) in the North Kitsap component of the South Central Puget Sound Sub-Basin.

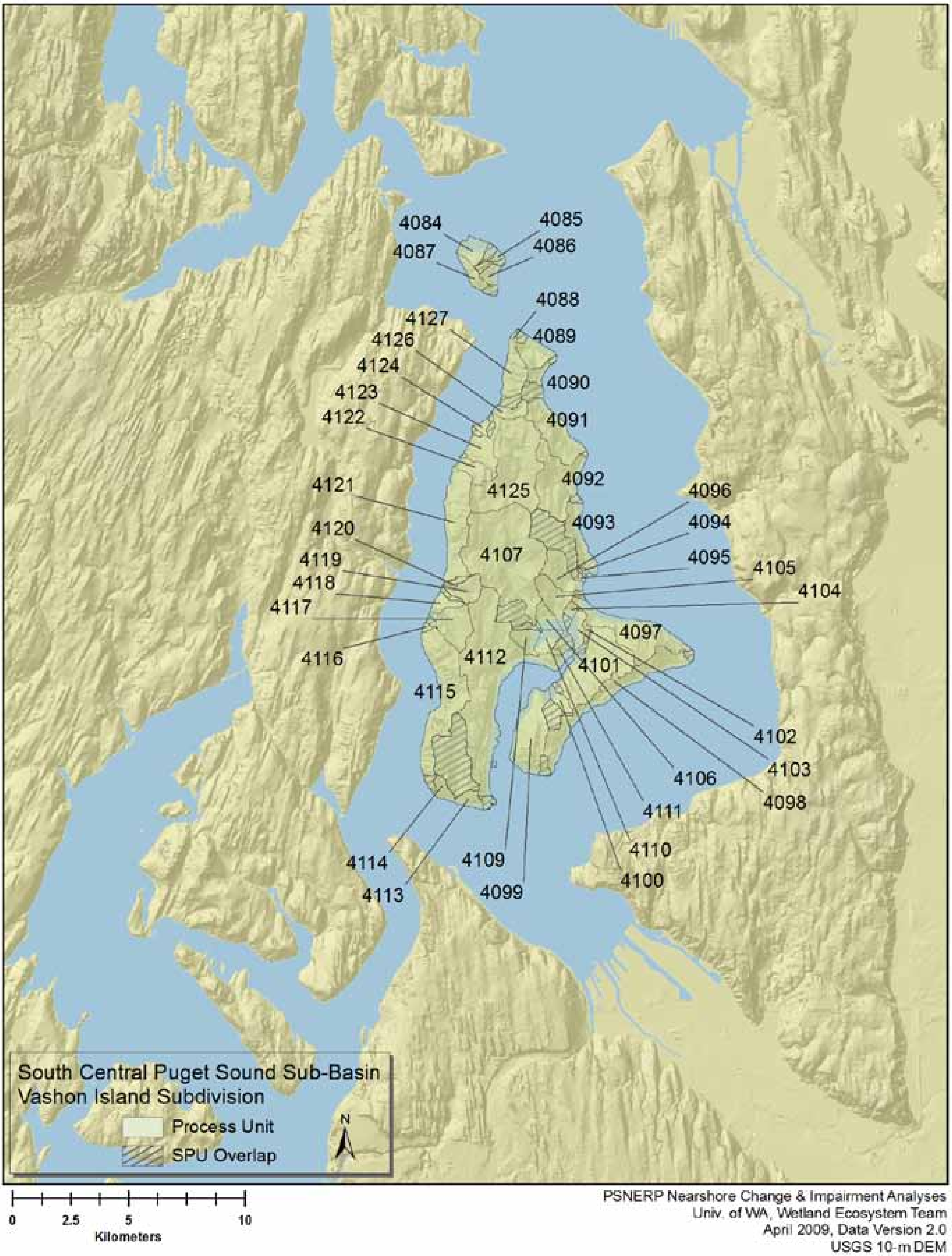

Figure E.15. Process units (PU) in the Vashon Island component of the South Central Puget Sound Sub-Basin.

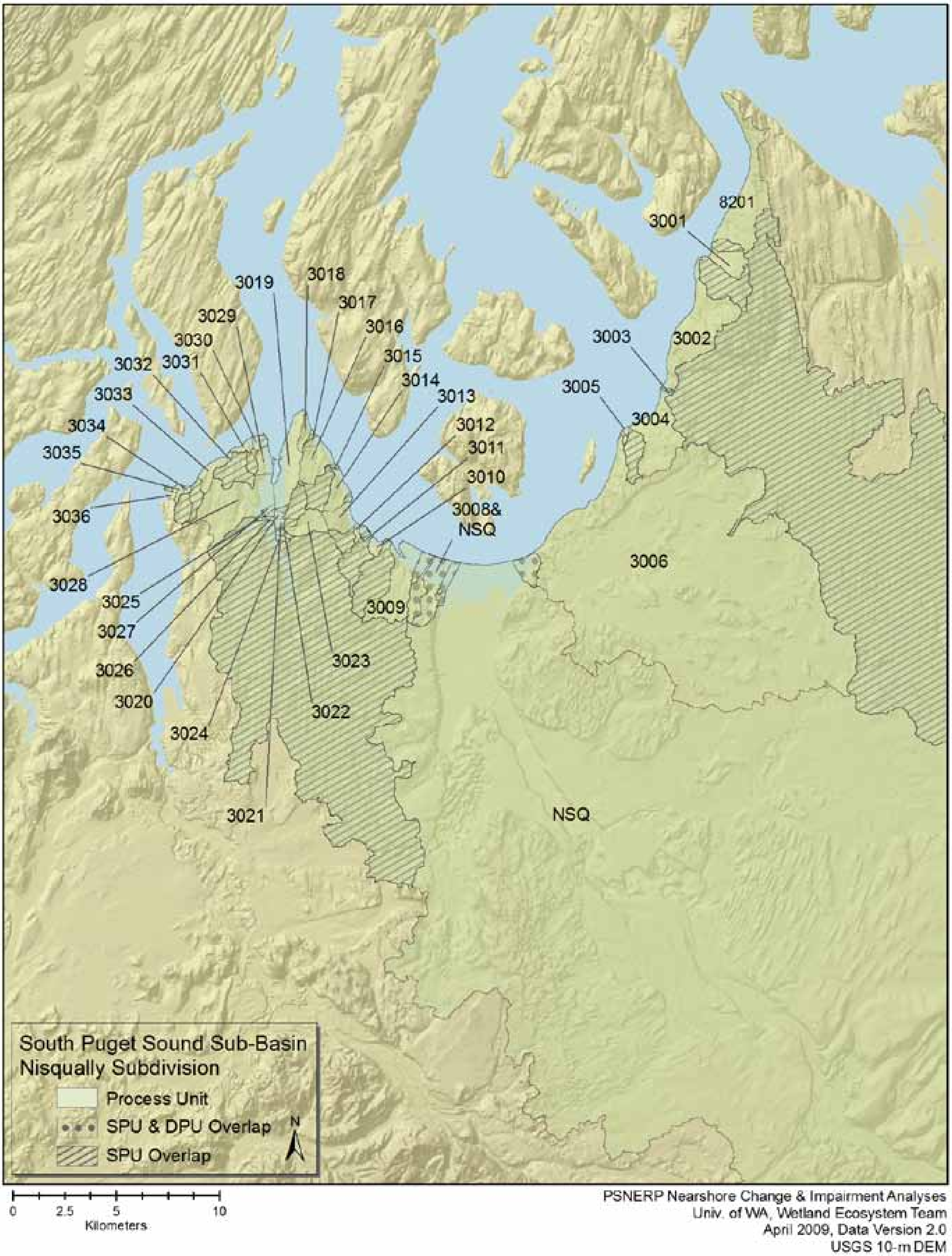

Figure E.16. Process units (PU) in Nisqually component of South Puget Sound Sub-Basin.

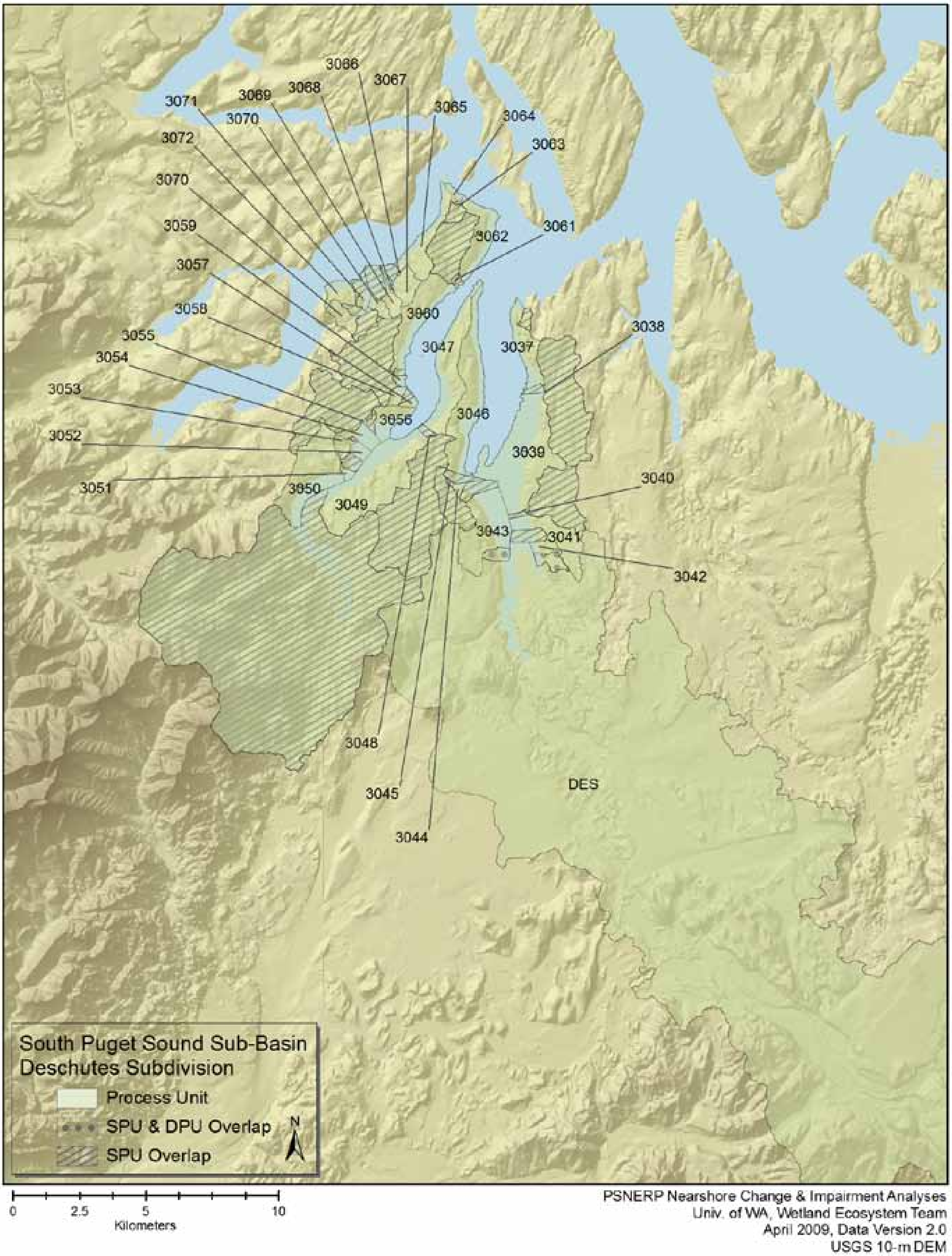

Figure E.17. Process units (PU) in the Deschutes component of the South Puget Sound Sub-Basin.

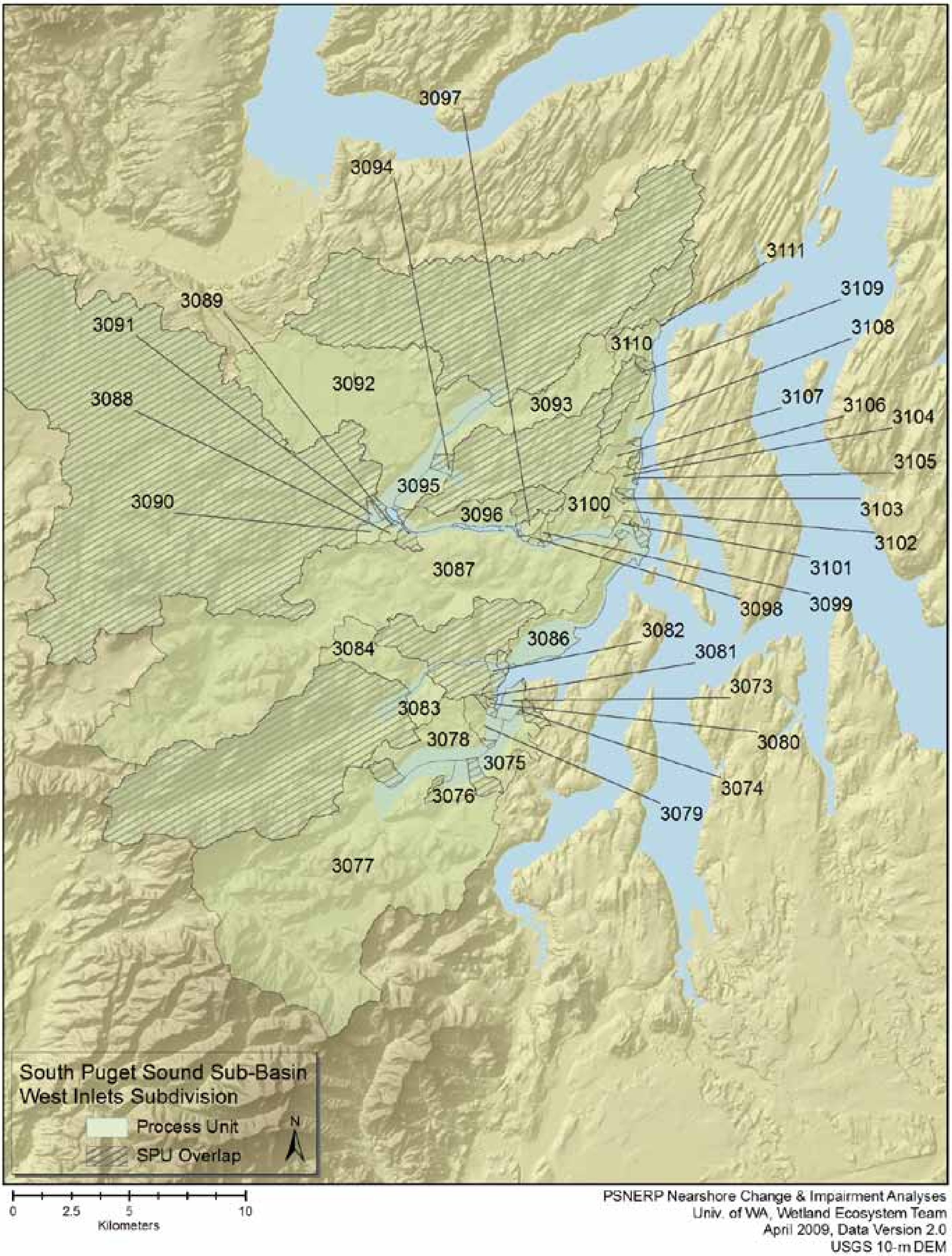

Figure E.18. Process units (PU) in West Inlets component of the South Puget Sound Sub-Basin.

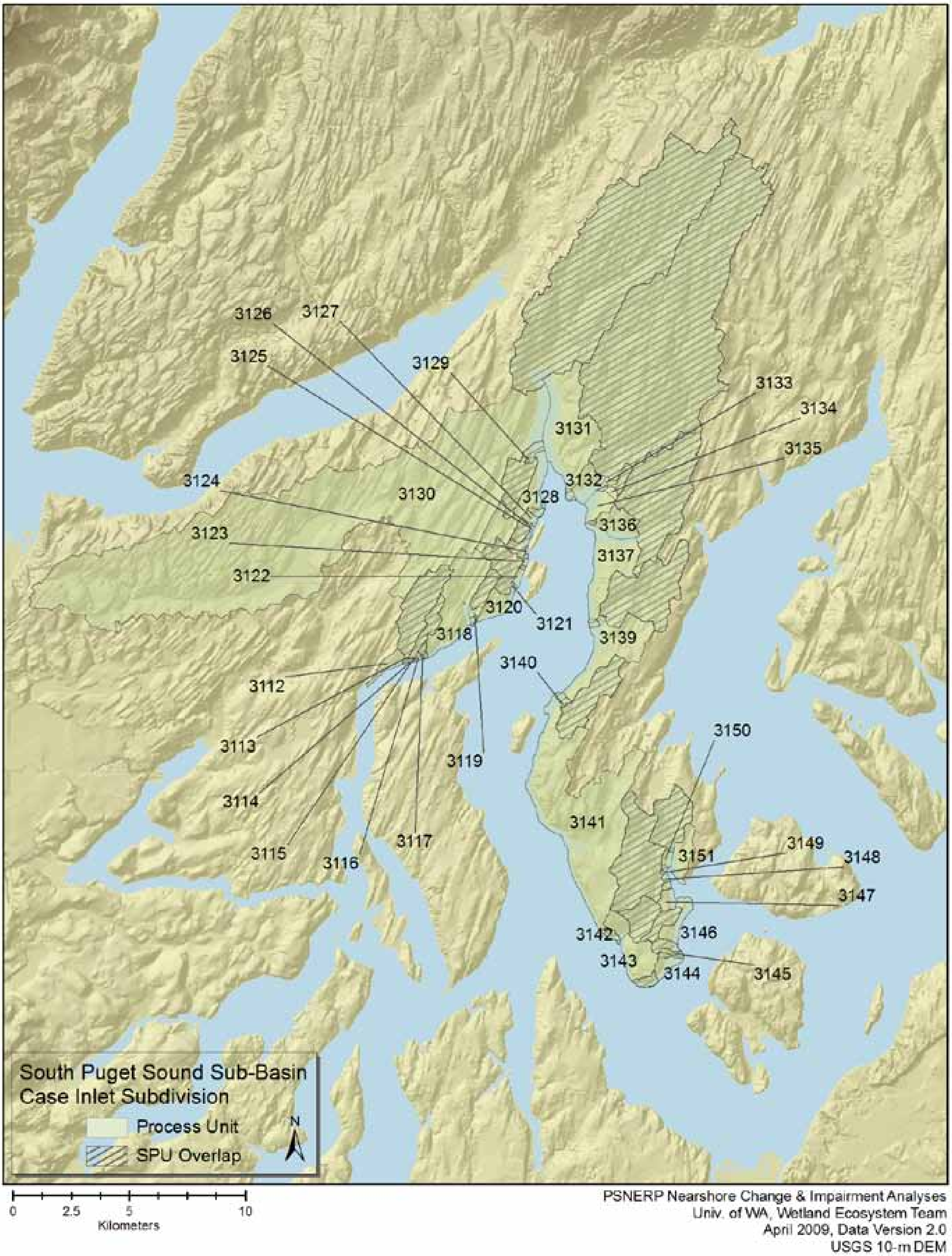

Figure E.19. Process units (PU) in Case Inlet component of South Puget Sound Sub-Basin.

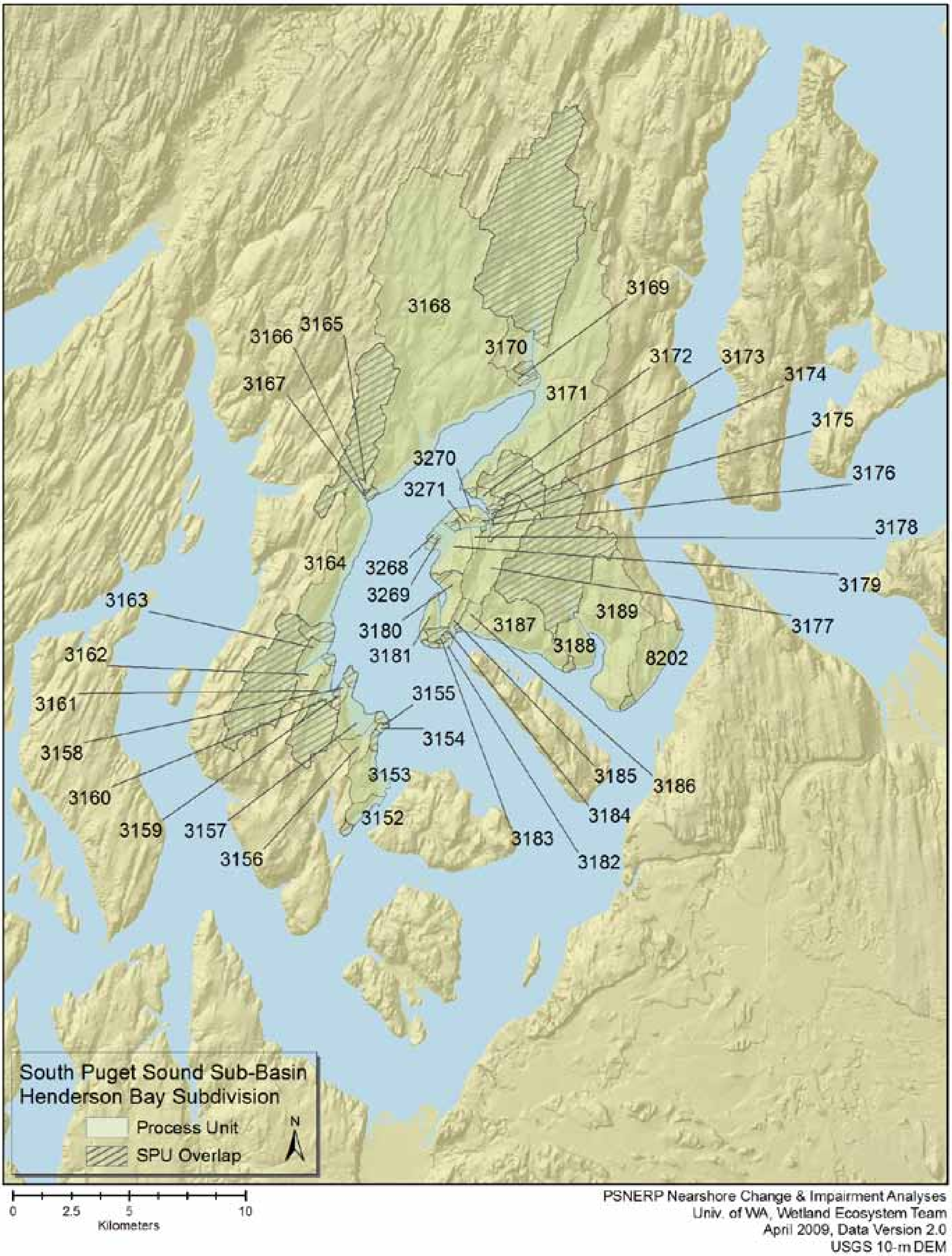

Figure E.20. Process units (PU) in the Henderson Bay component of the South Puget Sound Sub-Basin.

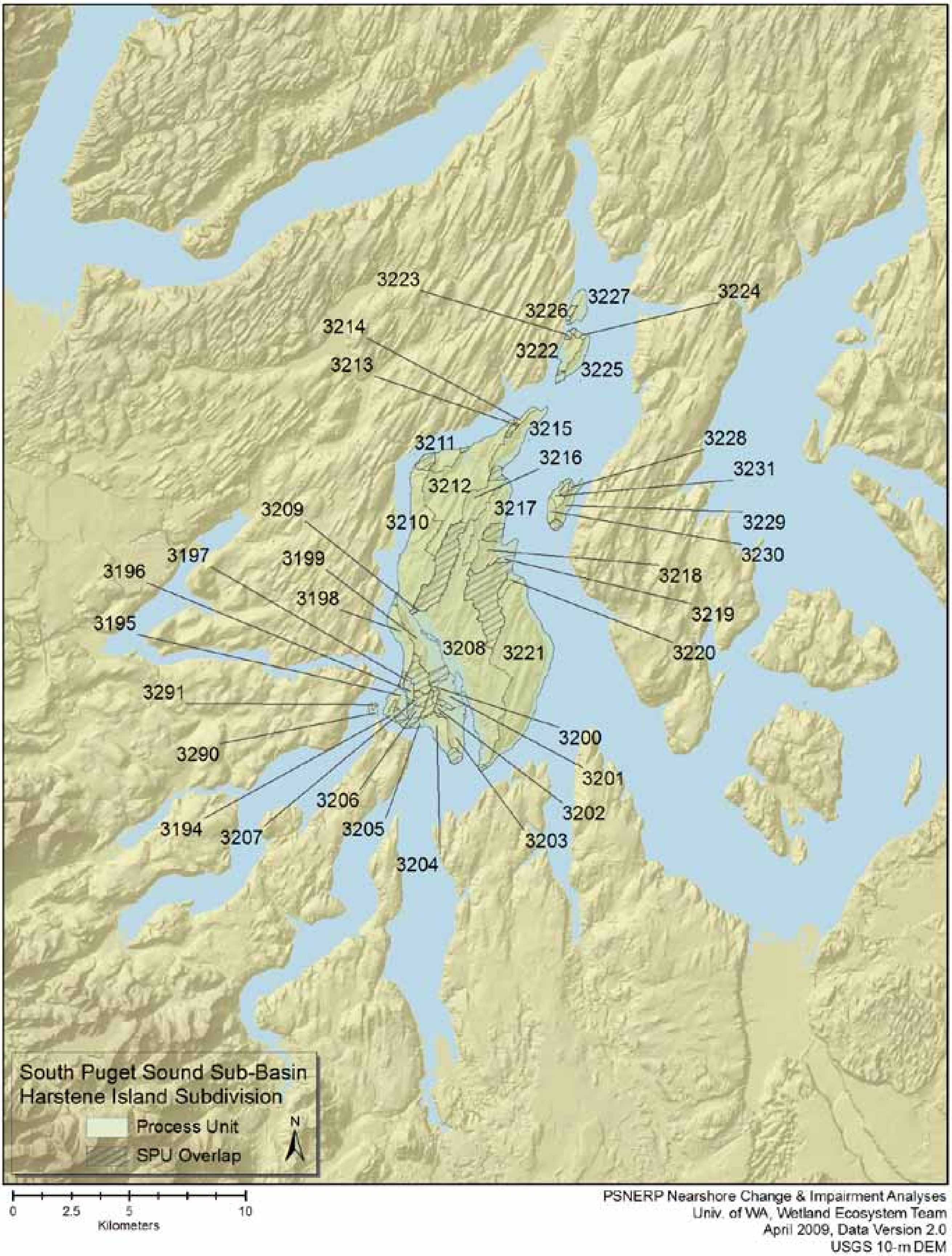

Figure E.21. Process units (PU) in Harstlne component of the South Puget Sound Sub-Basin.

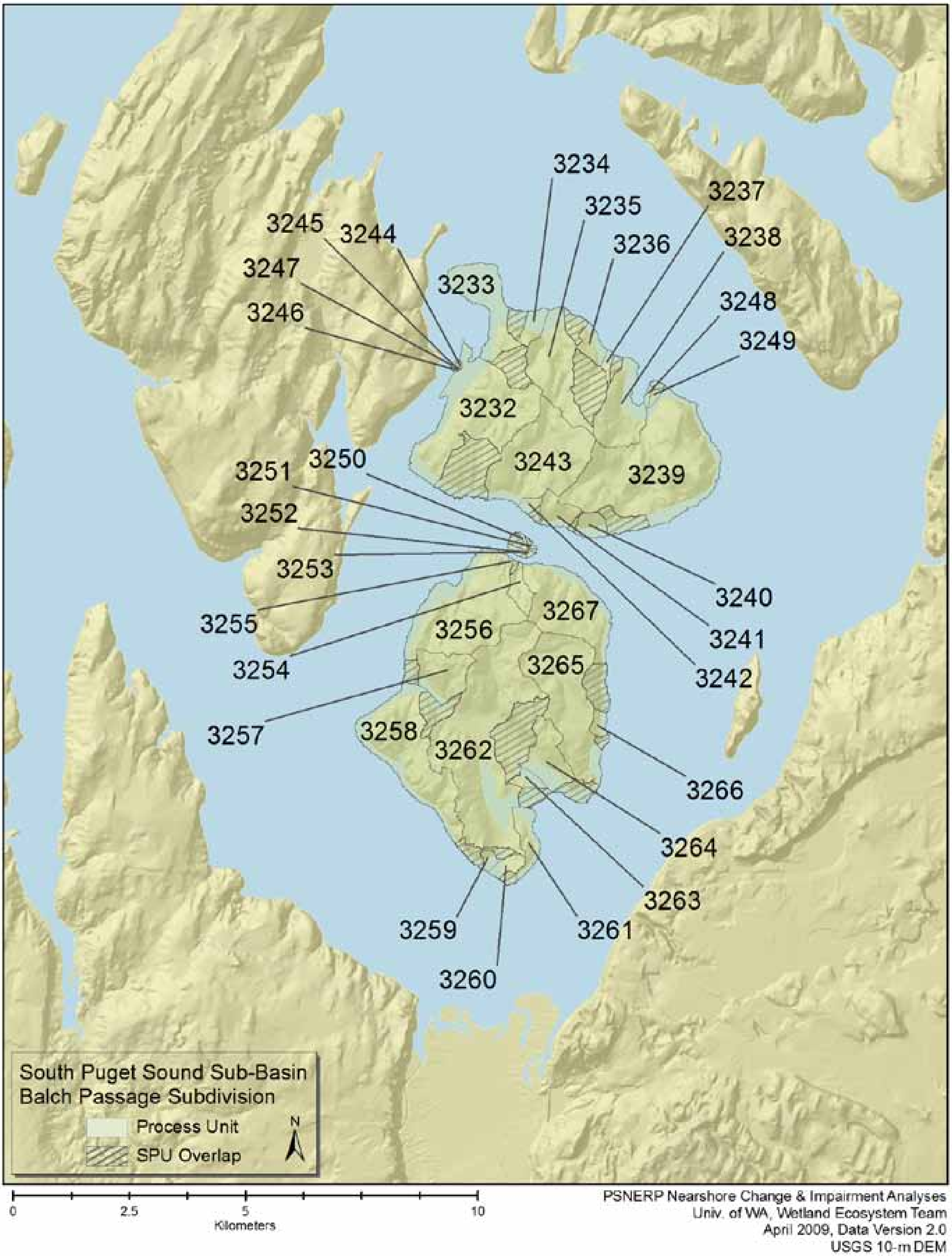

Figure E.22. Process units (PU) in the Balch Passage component of the South Puget Sound Sub-Basin.

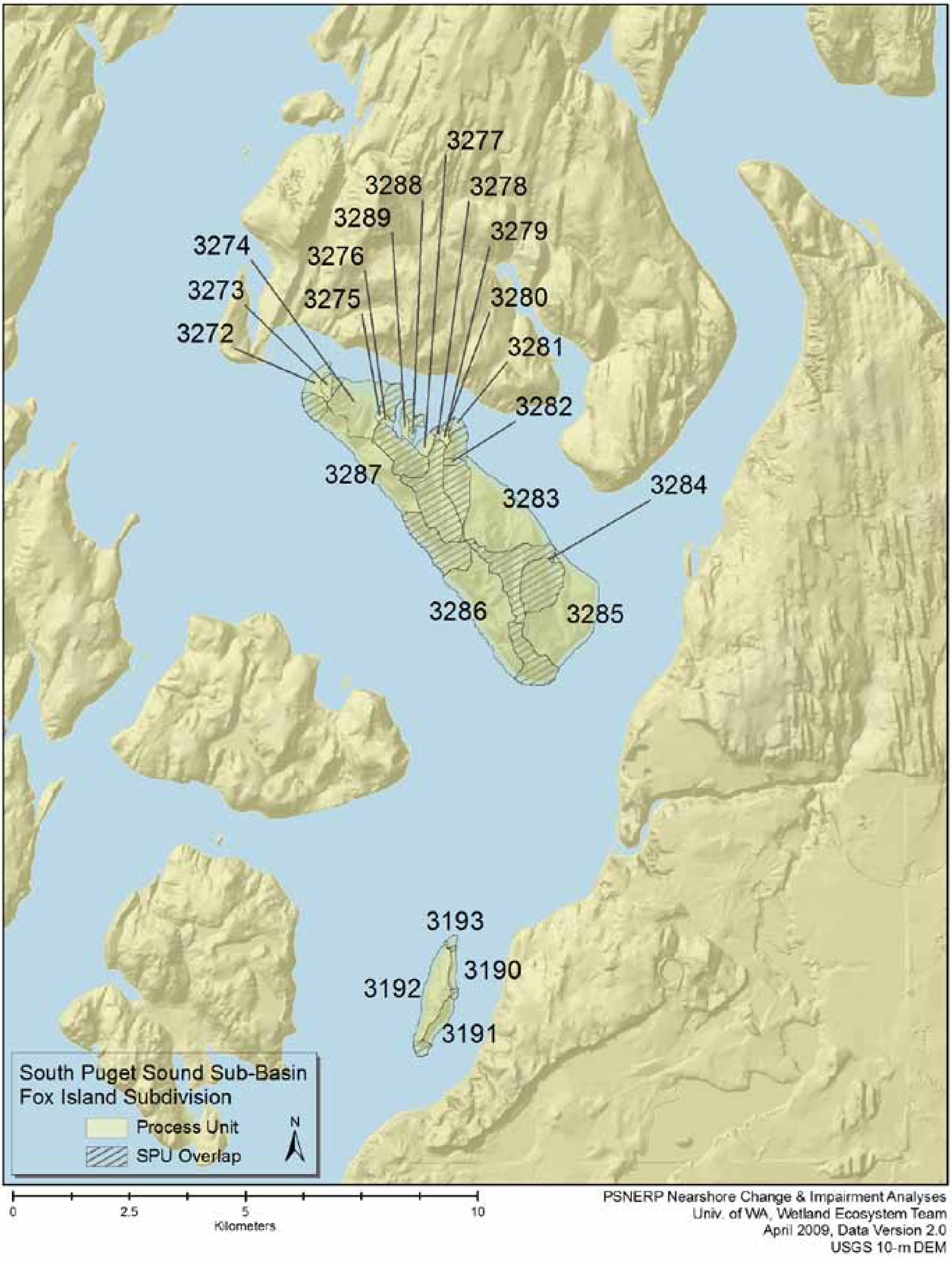

Figure E.23. Process units (PU) in the Fox Island component of the South Puget Sound Sub-Basin.

PUGET SOUND
NEARSHORE
ECOSYSTEM RESTORATION PROJECT

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