Using smooth sheets to describe groundfish habitat in Alaskan waters, with specific application to two flatfishes

by

Mark Zimmermann[1]***,**

Jane A. Reid[2]**, and**

Nadine Golden[2]

*contact author

[1]National Marine Fisheries Service, NOAA
Alaska Fisheries Science Center
7600 Sand Point Way NE, Bldg. 4
Seattle, WA 98115-6349. USA.

[2]U.S. Geological Survey
Pacific Coastal and Marine Science Center
400 Natural Bridges Drive
Santa Cruz, CA 95060. USA.

Voice (206) 526-4119

email: mark.zimmermann@noaa.gov

Keywords: USA, Alaska, Gulf of Alaska, Fish, Habitat, Bathymetry, Grain size.

Abstract

In this analysis we demonstrate how preferred fish habitat can be predicted and mapped for juveniles of two Alaskan groundfish species - Pacific halibut (*Hippoglossus stenolepis*) and flathead sole (*Hippoglossoides elassodon*) - at five sites (Kiliuda Bay, Izhut Bay, Port Dick, Aialik Bay, and the Barren Islands) in the central Gulf of Alaska. The method involves using geographic information system (GIS) software to extract appropriate information from National Ocean Service (NOS) smooth sheets that are available from NGDC (the National Geophysical Data Center). These smooth sheets are highly detailed charts that include more soundings, substrates, shoreline and feature information than the more commonly-known navigational charts. By bringing the information from smooth sheets into a GIS, a variety of surfaces, such as depth, slope, rugosity and mean grain size were interpolated into raster surfaces. Other measurements such as site openness, shoreline length, proportion of bay that is near shore, areas of rocky reefs and kelp beds, water volumes, surface areas and vertical cross-sections were also made in order to quantify differences between the study sites. Proper GIS processing also allows linking the smooth sheets to other data sets, such as orthographic satellite photographs, topographic maps and precipitation estimates from which watersheds and runoff can be derived. This same methodology can be applied to larger areas, taking advantage of these free data sets to describe predicted groundfish essential fish habitat (EFH) in Alaskan waters.

1. Introduction

The National Marine Fisheries Service (NMFS) is required to delineate essential fish habitats (EFH, defined as "those waters and substrate necessary to fish for spawning, breeding, feeding or growth to maturity", Section 3, U.S. Congress, 2006) for commercially managed species, along with the habitats of commercially impacted bycatch species such as corals and sponges (NMFS 2002; U.S. Congress, 2006), but the most appropriate method for fulfilling this mandate has not been identified. In the Gulf of Alaska (GOA), defining EFH is especially daunting due to the amount of detail required for describing the niches of different life stages of commercially managed species and the vast NMFS management area (320,000 km^2; von Szalay et al., 2010). High-resolution seafloor survey tools such as multibeam sonar, sidescan sonar, LIDAR and laser line scan, combined with seafloor groundtruthing methods such as underwater video and sediment sampling, can be integrated to provide the necessary details for these analyses. However, these tools are expensive and limited in availability, with intensive data-collection and processing periods. It would take many years, or perhaps many decades, to complete maps for the GOA NMFS management area, which are only incompletely described by small-scale National Ocean Service (NOS) navigational charts.

In addition to collecting fish habitat data, these data also need to be classified for use. Brown et al. (2011) provides a thorough review which contrasts two general classification methods for this type of data: unsupervised and supervised. The unsupervised classification system, such as that proposed by Greene et al. (1999 and 2008), where habitat divisions are based on geological divisions, has been the standard used in the eastern Pacific region (see Greene et al., 2011; O'Connell, 2007). Supervised methods, where the seafloor mapping information is viewed and organized through the known preferences of an organism, is much less common, in part, because the niche of an organism needs to be clearly defined (Brown et al., 2011).

It is hypothesized that demersally-oriented, juvenile fishes (here termed groundfishes) in the GOA are transported as larvae from offshore, deep water spawning areas into shallow, onshore waters (Bailey and Picquelle, 2002), where successful settlement as juveniles onto appropriate substrates can influence year-class strength. Little is known about this larval process. Staaterman et al. (2012) showed that oriented-swimming of larvae toward preferred habitat, perhaps in response to acoustic cues, may be important for successful settlement, while Paris et al. (2013) showed that olfactory cues may draw larvae toward preferred habitat. Regional environmental conditions (Mueter et al., 2007) may be more important than the number of spawners (Turnock and Wilderbuer, 2007; Hanselman et al., 2007; Dorn et al., 2008; Hanselman et al., 2008; Thompson et al., 2008), and is the topic of ongoing research, such as the North Pacific Research Board's (NPRB) Gulf of Alaska Integrated Ecosystems Research Project (GOA-IERP).

We seek to provide information about juvenile groundfish preferred settlement habitats, which could be termed predicted EFH for this specific life stage. Several field studies in the GOA have documented the important habitat elements for some juvenile groundfish species, such as: water column structure for walleye pollock (*Gadus chalcogrammus*) (Mueter and Norcross, 1994); location, depth, substrate, water temperature and salinity for rock soles (*Lepidopsetta* spp.), flathead sole (*Hippoglossoides elassodon*), Pacific halibut (*Hippoglossus stenolepis*) and yellowfin sole (*Pleuronectes asper*) (Norcross et al., 1995); depth and substrate type for flathead sole and rock soles (Abookire and Norcross, 1998); depth, substrate, location, water temperature and salinity for arrowtooth flounder (*Atheresthes stomias*), flathead sole, Pacific halibut, yellowfin sole and rock soles (Norcross et al., 1999); depth for rock soles, Pacific cod (*Gadus macrocephalus*) and 13 other groundfish species (Abookire et al., 2001); and depth, sea cucumber (*Paracaudina chilensis*) mounds and salinity for Pacific cod (Abookire et al., 2006). In addition, laboratory studies demonstrated substrate preferences for starry flounder (*Platichthys stellatus*), Pacific halibut, yellowfin sole, and rock soles (Moles and Norcross, 1995), substrate preferences for Pacific halibut (Stoner and Abookire, 2002), and substrate and demersal structure preferences for Pacific halibut and northern rock sole (*Lepidopsetta polyxystra*) (Stoner and Titgen, 2003). [Pacific halibut is not a federally managed species and therefore, technically, does not have EFH].

We propose that a supervised classification method can be made for juvenile groundfish using information from the literature and from existing data derived from NOS smooth sheets, which are lesser-known but detailed, larger-scale (often 1:20,000) bathymetric charts produced by the NOS in preparation for creating or updating the well-known, smaller-scale (often 1:300,000) navigational charts (Umbach, 1976). For example, a supervised classification in Alaskan waters used multibeam data and mini-submersible observations to predict the presence of corals from smooth sheet bathymetry (Woodby et al., 2009). Haeussler et al. (2007) analyzed change in bathymetry outside of Seward, Alaska before and after the great 1964 Alaskan earthquake by working with old smooth sheet bathymetry. Taylor et al. (2008) combined smooth sheet bathymetry with elevation data to produce a tsunami inundation grid for Dutch Harbor, Alaska. Researchers have also worked with smooth sheet bathymetry and extracted substrate information for fisheries habitat research off Oregon (Agapito, 2008; Amolo, 2010). Zimmermann et al. (2013) proofed, edited and digitized 2.1 million soundings, along with 25,000 sediment observations, from 290 contiguous smooth sheets in the Aleutian Islands, so that the most detailed description of that region produced to date could be used for coral and sponge predictive models (Rooper et al., 2014). Zimmermann and Prescott (2014) proofed, edited and digitized 1.4 million soundings, 18,000 cartographic features, 2,400 km of shoreline, and 9,000 sediment observations from 98 smooth sheets in Cook Inlet, along with 1.75 million soundings and 96,000 cartographic features from 225 smooth sheets in the central Gulf of Alaska (Zimmermann and Prescott, In review).

Smooth sheets have much more information than the navigational charts and, through a variety of GIS (Geographic Information System) processing steps, this information can be extracted and used to create groundfish benthic habitat maps. For example, the NOS navigational chart 16592 (Scale 1:80,728) for Kiliuda Bay on Kodiak Island, Alaska has only 255 soundings and 18 substrate observations (Fig. 1A), while the smooth sheet H05152 (Scale 1:20,000) has 7,531 soundings (about 30 times as many), and 313 sediment observations (about 17 times as many) (Fig. 1B).

As an illustration of converting smooth sheets into groundfish preferred habitat descriptions, we use GIS to process the smooth sheet data into a variety of groundfish habitat information layers (bathymetry and derivatives, substrates, shoreline and exposure, openness, water volumes) for five central GOA sites which were chosen as a focus of the NPRB’s GOA-IERP investigations: Kiliuda Bay, Izhut Bay, Port Dick, Aialik Bay, and the Barren Islands (Fig. 2). The study sites, four bays and an archipelago, are compared and contrasted based on the same metrics and literature information is used, in a simple conditional approach, to describe juvenile flatfish habitat for each site.

2. Materials and methods

2.1 Smooth sheet georegistration, Datum-shifting and Bathymetry editing

Smooth sheets and smooth sheet-derived bathymetry data used for this project are available from NGDC (National Geophysical Data Center: http://www.ngdc.noaa.gov). The smooth sheets do not have any associated datum or projection information and therefore were georeferenced and brought into a current datum (North American Datum of 1983 or NAD83) through GIS processing (Zimmermann and Benson, 2013). Once this step was accomplished, the smooth sheet-derived bathymetry data was plotted on top of the smooth sheet for comparison. In those cases where the bathymetry data and smooth sheet were misaligned, the bathymetry was corrected with a horizontal shift, to match the smooth sheet as projected in NAD83. In addition, each digital bathymetric data set was examined for completeness and correctness against the smooth sheet (Zimmermann and Benson, 2013).

Single, comprehensive, 1:20,000 scale, Valdez datum-era smooth sheets were available for three study sites; Kiliuda Bay (H05152, 1931 and 1933), Izhut Bay (H05257, 1932-33) and Port Dick (H05101, 1930). The smooth sheet-derived bathymetry data for these three sites all needed to be datum-shifted about 500 m to the northeast to align properly with NAD83. For the Barren Islands, most of the bathymetry came from two North American Datum of 1927 (NAD27) smooth sheets (H10137 and H10149 Scale 1:20,000, 1984), with some supplementary bathymetry along the eastern edge of the study site from a contemporary survey H10143 (Scale 1:40,000). The Barren Islands bathymetry had already been successfully datum-shifted to NAD83. Aialik Bay bathymetry came from three NAD83, Scale 1:20,000, multibeam surveys (H10968 and H11010, 2000; and H11075, 2001) which only needed to be combined into a single file.

Openness of a bay is an unknown but potentially important factor in juvenile groundfish entering and settling within the bay, and therefore we developed measures describing the linear openness (ratio of mouth of bay compared to length of bay shoreline), areal openness (ratio of cross-sectional area of mouth to surface area of the bay), and volumetric openness (ratio of tidal prism to volume of water within the bay) of the mouth of the bay. Since juvenile groundfish typically prefer shallower habitats, which are generally closer to shore, we also created measures describing the influence of shore on the ecology of the bay.

2.2 Digitizing the shoreline

The smooth sheet shoreline, which is defined as mean high water (MHW), was digitized and used to supplement the bathymetric soundings, which typically range only as shallow as the tidal depth of mean lower low water (MLLW), defined as zero depth. This helped cover a substantial horizontal gap, called "the white zone," between the soundings and the shoreline (Zimmermann and Benson, 2013).

The shoreline was digitized from single smooth sheets for Kiliuda, Izhut and Port Dick. For the Barren Islands, the shoreline from the eastern islands was digitized from a single NAD27 smooth sheet while the shoreline from the western islands was interpolated from a neighboring NAD27 smooth sheet (detailed bathymetry but incomplete shoreline data) and an older, presumably Valdez datum smooth sheet. For Aialik Bay, the shoreline was interpolated from NOS Chart 16682 and the smooth sheets and bathymetry from three, recent NAD83 multibeam surveys.

After shoreline digitization, a straight line was drawn from shore to shore across the mouth of each bay at the point where the shore trended outward toward the Gulf of Alaska. This enclosed the bay, provided a means of defining the bounds of each study site, and, when the length of the mouth of the bay was compared to the length of the total shoreline, provided a linear measure of bay openness. The Barren Islands study site does not have a mouth because the area is not enclosed by land - therefore the site was enclosed in a rectangular bounding box corresponding to the extent of the bathymetric surveys. While it might be self-evident that the Barren Islands are the most open study site, a similar openness calculation was made, dividing the bounding box length by the total shoreline length of the study site, so that the linear openness was quantified. "Mainland" shore length was taken from the three largest islands of the Barren Islands archipelago, accounting for about 94% of the land area.

Shore length is a notoriously unreliable measurement due to different abilities to measure every shore indentation and bulge with straight rulers of different lengths (Richardson, 1961; Mandelbrot, 1967). We bisected the MHW shoreline drawn on the smooth sheets with vectors of differing lengths (see Zimmermann and Benson, 2013). The shoreline of each study site was also buffered with radii of 100 and 1000 m to create nearshore polygons in order to measure how much area of the bay was near a shoreline. Islands and peninsulas scattered evenly throughout a study site will result in strong shore influence while large open areas will result in little shoreline influence.

2.3 Grid or Raster bathymetric surfaces

The digital point bathymetry file, containing the soundings along with the shoreline points, was processed using the spline function in ArcMap (v. 10.0, ESRI, Redlands, CA) for creating a continuous seafloor model raster surface (continuous series of 20 m or 10 m same-sized squares), so that area-weighted depth could be calculated. The spline method was used to create some smoothing as it allows interpolating beyond the input data values. The 20 m grid cell size was chosen for the four sites without multibeam data in order to maintain inshore bathymetric features, such as islets and inlets, while the 10 m grid for Aialik Bay was maintained from the input data. Bathymetry rasters were used to create the derivative surfaces of slope (defined as maximal change in depth, as measured in degrees, between any sounding and its immediate neighboring soundings) and rugosity (defined as ratio of true surface area to planimetric area; DEM Surface Tools, v. 2.1.305, Jenness Enterprises, Flagstaff, AZ; see Jenness, 2004). Thus gridded surfaces of the seafloor were characterized as deep or shallow, steep or flat (range 0° to 90°), and rough or smooth (range 1 to infinity). Rugosity results are included in the tables but were spatially so similar to the slope results that separate rugosity figures were not made.

Interpolated bathymetry surfaces (20 m horizontal resolution), extending from the MHW shoreline to the entrance of the bay, were created for each study site, except Aialik Bay, where the only real interpolation of the 10 m grid was between the shallowest soundings and the MHW shoreline. These surfaces included individual features such as rocks and islets that ranged higher than MHW. In Kiliuda Bay, Izhut Bay, and the Barren Islands (the shallowest sites), the relatively deeper soundings typically are sparser which created small, deep holes in the interpolated depth surface; but due to their limited extent, these artifacts had little impact on overall analyses.

2.4 Water volumes and surface areas

The volume of water contained within each site, along with the surface area, was calculated from the bathymetry grid and the boundaries of the site. In addition, the volume of water and surface area at several horizontal or depth sections (e.g., MLLW, 10 m depth, 20 m depth) were also calculated from the bathymetry grid. Thus the sites were described in terms of volume of water exchanged during a tidal cycle (the tidal prism) as well as how much seafloor gets exposed at MLLW. The number of days it would take to refill an empty site, with tides alone, assuming two high tides at MHW per day, was calculated as a hypothetical but potentially useful metric to demonstrate impact of tides.

2.5 Cross-sections

The area of a vertical cross-section spanning across a body of water, from shoreline to shoreline, was also calculated from the bathymetry grid. This provided an areal measurement of the opening of the mouth of the bay, which is a constriction that prohibits water flow between the open ocean and the bay. Additionally this method was used to estimate the amount of constriction at selected locations within the bay (due to peninsular pinching, significant bottom deposits, faults, relict glacial moraines, or ebb-tidal deltas), or at the mouth of smaller bays nested within the main bay. For the Barren Islands, the comparable cross-section followed the arbitrary bounding box around the island group.

2.6 Exposure

The amount of bay shoreline exposure to oceanic waters was determined by radiating thousands of lines into the bay, one line for each segment of shore length, from each of 10 equally spaced loci or nodes across the mouth of each bay. Exposure was calculated for each shoreline segment as the number of radiating lines intersecting the segment, with 10 being full exposure (all 10 loci or nodes), 1 to 9 being partial exposure, and 0 being no exposure. For each study site, a length-weighted average of exposure was produced to mimic the natural vulnerability of each bay due to the spatial orientation and size of the mouth of the bay, along with any peninsulas and islands that might block the path of currents, storms, winds, seas, and swells heading into the bay. No effort was made here to investigate wind waves created within each bay itself. For the Barren Islands, 10 equally spaced loci were placed along each of the four sides of the bounding box, since there was no mouth for this site, like for the bays. For Aialik Bay, where a large island partially blocks the mouth, 11 nodes were used so that one of them could fall on the island and be eliminated from the analysis, while 10 nodes could fall on water and be used for the analysis.

2.7 Watershed

The watershed for each study site was determined through visual inspection of USGS (United States Geological Survey) topographic sheets and orthographic imagery (both available from within ArcMap v. 10.0, ESRI, Redlands, CA; satellite imagery supplied to ESRI courtesy of Bing Map Imagery© Microsoft Corporation and its data suppliers). This process was aided by adding a digitized file of the streams and rivers (*ftp://ftp.dnr.state.ak.us/asgdc/adnr/hydro_63360.zip*). Once the watershed was estimated, the intersection of the watershed with an annual precipitation layer (*http://agdc.usgs.gov/data/usgs/water*; Jones and Fahl, 1994) provided an estimate of the volume of freshwater input at each site. Additionally, the watershed and volume of water draining from each stream or river into the bay can be estimated, providing local salinity estimates within the bay. The number of years it would take to refill each site with runoff alone was calculated as another hypothetical but potentially useful metric to demonstrate the impact of freshwater input.

2.8 Features

Significant cartographic features within the bay, such as rocks, islets, floating or emergent kelp patches, and subsurface rocky reefs were often noted by hydrographers and depicted with symbols on the smooth sheets. These cartographic features were digitized and quantified using GIS. The rocks and islets were digitized as points for inclusion with the substrate. Islet shores were digitized as lines for inclusion in shore length calculations as well as polygons for inclusion in land area calculations. The smallest floating kelp patches (symbolized as wavy, forked lines) were digitized as single points while larger patches were digitized as multiple points to indicate their spatial extent for inclusion as rock with the substrates. Rocky reefs were digitized as a perimeter of points. Both rocky reefs and kelp patches were also digitized as polygons to calculate their areas as additional groundfish habitat measures that characterize a bay. Rocks, islets and reefs sometimes have elevation or depths and these point observations were added to the bathymetry.

2.9 Substrates

Seafloor characterization data are from a sediment sample in the small cup at the end of the sounding lead in the older surveys, or from dedicated sediment sampling with equipment such as a Van Veen grab in the Aialik Bay multibeam surveys. These sediments are depicted as text abbreviations on the smooth sheets, such as "S" for sand, “G” for gravel, etc., and were digitized into a point file.

By using fuzzy logic software that follows established guidelines (Jenkins, 1997), these verbal sediment notations were converted into simplistic estimates of sediment-size distributions and mean grain size (Wentworth, 1922). For example, “S” is estimated as 100% sand, with no gravel and no mud, with an associated estimated mean grain size of 1 phi (where phi = -$\log_2$ diameter in mm; Krumbein, 1934). Bimodal size distributions are given a grain-size mean between the two end points: for example “SM” is assumed to be a 50/50 sand and mud mix, with a mean diameter of 3 phi.

Smooth sheet seafloor data include information other than grain size, such as "sticky", "soft", "hard", and "rocky" which are not converted into estimated phi diameters by Jenkins' (1997) method. To expand the data available for inclusion in a single substrate surface, "sticky" was forced to equal clay (phi = 9), “soft” was forced equal to mud (phi = 6), “hard” was forced to equal sand/gravel (phi = 0), and "rocky" was forced to equal -9 phi. Rock (point), islet (point), kelp (single or multiple points, depending on extent) and rocky reef (perimeter of points) cartographic features were treated as the sediment equivalent of "rocky" and forced to equal the numerical sediment value for "rocky" (-9 phi), even though bedrock technically does not have a grain size diameter. Combining the cartographic features which indicated rock with the sediment data served two purposes: 1) increasing the number of sediment data points, and 2) expanding the nearshore coverage. The rock, islet, kelp and rocky reef cartographic features added approximately 100 to 1000 sediment observations, increasing total sediment observations to about 700 to 1800 at each site. We interpolated forced mean phi in ArcMap to create 20 m raster surfaces by using Inverse Distance Weighting (IDW) so that the input data range would be maintained, even though IDW tends to create "bulls eye" artifacts when individual sediment samples differ greatly from their neighbors in terms of grain size diameter.

2.10 Groundfish preferred habitat

We used the preferred depth and substrate results for flathead sole (80-120 m, mud) and Pacific halibut (10-70 m, sand, within 7 km of mouth of bay) from Norcross et al. (1997) in a very simplistic, conditional approach to demonstrate how some of the GIS layers can be used to map preferred habitat. While EFH is likely to contain other components such as salinity, temperature, water flow, openness or protection from the ocean, and prey and predator abundance, these factors were not included in this analysis but can be added in future analyses, such as the ongoing work at GOA-IERP.

3. Results

Kiliuda Bay, Izhut Bay, and Port Dick are the three smallest study sites and are similar in many measures, such as mainland and island shoreline lengths (Table 1), depths (Table 2), water surface area (Table 3), volume (Table 4), and features and substrates (Table 5). Therefore these three bays are generally compared to each other in the results. Aialik Bay is significantly larger than the other bays, with notably greater mean depth, a surface area roughly equivalent to the three smaller bays combined, and a volume roughly double the three smaller bays combined. The Barren Islands results are different due to their physiography and setting in the open ocean. Despite basic differences between the three small bays, the large bay, and the island archipelago, all measures were created and presented for all five sites.

3.1 Kiliuda Bay

Kiliuda Bay, located on the southern shore of Kodiak Island (Fig. 2), opens toward the southwest, with a relatively narrow and shallow mouth that is oriented at a slight angle to a direct east-west line (Fig. 3A). Kiliuda Bay has the largest overall percent area of smooth and flat seafloor of all bays studied (Table 2) due to two large well-defined basins with a classic fjord shape – flat floors surrounded by narrow steep sides (slopes generally between 10 and 20%; Fig. 4A) which are divided by a relatively high, broad (3.5 km), shallow (40 m depth) sill (Fig. 3A) with coarser sediment.

Kiliuda Bay has intermediate amounts of area and percentages of area within 100 m and 1000 m of shoreline among the three smaller bays (Table 1). The most exposed shorelines are nearest the entrance of the bay or directly opposite to it (Fig.5A). The south side of the western basin and the upper reaches of Shearwater Bay are protected from direct wind, waves, and currents coming in from the Gulf of Alaska.

Tides and runoff are important in the bay. The effect of the largest watershed of the three smaller bays and high precipitation runoff (0.97 km^3), combined with its shallow depth and low water volume, gives it the highest runoff to saltwater volume ratio and fewest years predicted to refill the bay with runoff alone (Table 4, Fig. 6A). This, combined with the smallest mouth (0.3 km^2) among all study sites (Table 3), translates into the lowest predicted salinity, although this would be counteracted by the highest ratio of tidal prism to MHW (Table 4). The amount of seafloor exposed at MLLW is intermediate among the three smaller bays, and the percentage of seafloor exposed at MLLW is lowest (5.5%) among the three smaller bays (Table 3).

Hard seafloor, coarse sediment, or rocky areas generally line the shoreline of Kiliuda Bay; however, the two small westernmost bays, plus Shearwater Bay and a north-facing portion of the main bay itself show finer or softer sediment (Fig. 7A). It has the lowest amount and percentage of area covered by kelp (0.346 km^2 and 0.39%) and the highest amount and percentage of rocky reef areas (0.157 km^2 and 0.18%) among the three smaller bays (Table 5). Statistically, Kiliuda Bay has a median of forced-phi of 0.4 and is about 20% covered by mud (Table 5).

While Kiliuda Bay was small by many measures (notably volume), about 23% of Kiliuda Bay was predicted to be preferred habitat for Pacific halibut and flathead sole combined, due to broad areas of overlap of appropriate depth and sediment type, which was by far the highest among all sites (all others <8% total predicted preferred habitat) (Table 6, Fig. 8A).

3.2 Port Dick

Port Dick is the smallest bay by water surface area, about two-thirds the size of Kiliuda Bay and about a quarter the size of Aialik Bay (Table 3). Located on the Kenai Peninsula (Fig. 2), there are two distinct internal bays within Port Dick, the narrow, linear West Arm that extends northwestward, and Taylor Bay, which is along the axis of the main bay with a diminishing width to the north (Fig. 3B).

The center of Port Dick is generally deep, with smooth steep sides and an elongated oval shape, cut by a northwestward-trending discontinuous elongate low rise that crosses the floor at about 150 m above bottom (Fig. 3B). The deepest part of the bay extends southeastward toward Gore Point and northwestward into the West Arm. A higher, steep and rugose area of seafloor divides Takoma Cove and Sunday Harbor from the bay’s deepest area and a short low rise runs northward near the eastern edge of the bay’s deepest basin (Fig. 4B). Average slope (10.9°) and rugosity (1.036) are highest among all five sites and maximum slope and rugosity are greater than all but Aialik Bay (Table 2).

Similar to Kiliuda and Izhut Bays, the lower reaches of Port Dick, along with the area directly opposite the entrance, are the most exposed, here to 3.5 km inside of the bay (Fig. 5B), and Port Dick has the greatest amount of shoreline with no exposure (68%, Table 1). Port Dick has the greatest percentage of water within 100 m and 1000 m of shore (14.7% and 79.5%, respectively) among all sites (Table 1) and intermediate amounts of watershed and runoff (Fig. 6B and Table 4).

Areas of finer or soft sediment dominate the deeper areas of the bay, with wide coarser, hard, or rocky areas along the edges (Fig. 7B). A somewhat unusual area of coarser material appears at relatively shallow depths far from shore outside Takoma Cove and Sunday Harbor. The uppermost reaches of Taylor Bay, West Arm, and the southern shores of Sunday Harbor and Takoma Cove do not have coarser materials near the shore, but appear to have a significantly finer or softer substrate cover. An interpolated bridge of coarser material crosses West Arm at approximately the center of its length due to an artifact of the gridding process - the Arm is so narrow that inshore "rock" and "rocky" samples exert influence in a deep area of sparse "mud" and "sticky" sediments.

Port Dick and Izhut Bay have similar water volumes at MHW and MLLW, however, Port Dick has greater volumes remaining in the bay below 50 m and 100 m in depth than the other two smaller bays (Table 4). Port Dick’s mouth is deep and narrow (Fig. 3B) yielding a cross-section double that of Kiliuda but roughly equal to Izhut Bay (Table 3).

Despite equivalent tidal prisms among the three smaller bays, Port Dick has the lowest percentage of water exchanged during a tidal cycle (3.0%; Table 4), and the highest MHW at -3.45 m (Table 2). Low slope values in Taylor Bay, Sunday Harbor and Takoma Cove areas (Fig. 4B) may be the cause of the highest seafloor exposure value during MLLW (5.7 km^2 or 8.9% of bay area) (Table 3).

Port Dick had the least amount of predicted preferred habitat for Pacific halibut and flathead sole among the three smaller bays by several measures (Table 6, Fig. 8B).

3.3 Izhut Bay

Izhut Bay is located on the southern shore of Afognak Island, off of Marmot Bay (Fig. 2), with its entrance oriented nearly east west (Fig. 3C). In mean and maximum depth, water surface area, and water volume measures, it is in the middle of the three smaller bays (Tables 2-4).

The seafloor along the axis appears generally continuous from mouth through most of Izhut Bay; however, the basin area shows several discontinuous narrow slopes that divide the seafloor into a complex web of small basins separated by short, narrow 10-20% slopes (Fig. 4C), distinguishing it from flat-bottomed Kiliuda Bay. The outer slopes along the main basin are more continuous than in Kiliuda Bay, and the combined flat-seafloor area is small, second only to Port Dick. A sill appears at the deepest depths of the Kitoi Bay mouth; no other obvious constriction points are evident.

Maximum shoreline exposure is within 4 km of the entrance on the east side, and other than a small, highly embayed cove on the western side, extends only about half way down the bay (Fig. 5C).

Izhut Bay has the widest entrance of the three smaller bays with a maximum depth nearly twice that of Kiliuda Bay, but about 70 m less than Port Dick (Tables 1 and 2). Despite the difference in depths, Izhut Bay and Port Dick have similar mouth cross-sectional areas (Table 3) and tidal prisms (Table 4); the ratio of mouth cross-sectional area to bay surface area of Izhut Bay is similar to that of Port Dick and Aialik Bay, but is nearly triple that of Kiliuda Bay (Table 3).

Among the three smaller bays, Izhut has the smallest watershed in area and the lowest precipitation rate of 178 cm/year (Jones and Fahl, 1994), hence the lowest runoff volume and highest predicted salinity – freshwater refill time is nearly 24 years (Fig. 6C,Table 4). Ratio of Izhut Bay tidal prism to MHW bay volume is intermediate among the three smaller bays. The substrate is the rockiest (forced mean phi of -4.3) of all the bays (Table 5, Fig. 7C). It has the largest kelp area both in size and relative amount of any site save the Barren Islands (Table 5). The amount of total predicted preferred habitat for Pacific halibut and flathead sole was second to that of Kiliuda Bay, both in terms of area and percent of area (Table 6, Fig. 8C).

3.4 Aialik Bay

Aialik Bay, located on the Kenai Peninsula (Fig. 2), dwarfs all other bays in depth, all boundary dimensions, and watershed size (Table 1-3). The Chiswell Islands are in the center of the entrance to Aialik Bay; the largest, Harbor Island, is oriented along the bay’s axis (Fig. 3D).

Bathymetrically, Aialik Bay proper has a classic fjord shape, with a nearly flat center bottom that represents nearly 20% of the seafloor - a large, very deep area (Fig. 3D). Aialik Bay is so deep that below 50 m it contains a volume of water equal to that of the volume of water below 50 m in the much larger Barren Islands (Table 4). Similarly, below 100 m, Aialik Bay contains a volume of water greater than the volume of water below 100 m in all other sites combined (Table 4). Sides of Aialik Bay’s basin are confined, continuous, and steep with the second highest mean slope (Fig. 4D, Table 2). Two significant sills define higher basins in the northernmost Aialik Bay and at the entrance to Holgate Arm while a third, thin, sill that extends northward from an island provides the western edge to the northern bay's basin.

To the east of Harbor Island, the seafloor is flat (Fig. 4D) and deep as an extension of the center deep basin. However, to the west, the seafloor is shallower, more steep and rugose (Fig. 4D) with a narrow central channel. Overall, the maximum rugosity of Aialik Bay is about 2.5 times higher than any other bay (Table 2), although due to its large flat basin, the mean is lower than the narrower Port Dick.

The Chiswell Islands in the entrance to Aialik Bay have a significant impact on shoreline exposure (Fig. 5D). None of the bay is exposed under all weather tracks and 57% of the shorelines are fully protected (Table 1). This occlusion of the bay is also shown in the substrate cover, where the southern, deeper half of the bay is covered in finer or soft sediment, and the upper half, including Holgate Arm, both at depths and along slopes, is covered in medium-sized sediment (Fig. 7D). This is somewhat unusual of the bays studied, where finer or softer sediment is found farther from the mouth and may be a function of depth, although the sills at the mouths of Holgate Arm and upper Aialik Bay appear to contain coarser material. Aialik Bay has the least area covered in kelp (0.32 km^2), no rocky reefs, the smallest median grain size (forced-phi of 1.8) and most area covered by mud (37.5%; Table 5).

The mouth of Aialik Bay has the greatest cross-section among the bays (Table 3), although the main body of the bay has a maximum sounding that is only slightly deeper than Port Dick (Table 2). This gives the largest overall tidal prism volume among all bays, but on a percentage basis, the water volume exchanged during a tidal cycle is the least among all sites (Table 4). Aialik Bay has less raw area (3.1 km^2) exposed during MLLW of any of the sites studied, and less percent seafloor (1.3%) area exposed at all sites except for the Barren Islands

(Table 3). This is likely due to the fjord shape of the main basin and the numerous small embayments that have relatively narrow nearshore regions, particularly on the eastern shore (Fig. 3D).

Aialik Bay has the biggest watershed area and highest runoff volume, but the lowest watershed-to-basin ratio and runoff-to-bay volume ratios among all bays (Fig. 6D, Table 4). The tidal prism ratio to bay volume ratio (2.0%) is also the smallest. These values give the longest freshwater refill time of nearly 30.6 years, the highest predicted bulk salinity value, and the highest tidal-fill time of 24.6 days of any of the four bays. Nearly one third of the Aialik Bay watershed is covered by glaciers - more than all the other sites combined, (Table 4; Fig. 6), - probably having a significant impact on the marine ecology of the bay.

Despite its vast area, Aialik Bay is too deep and therefore has less total predicted preferred habitat for Pacific halibut than Kiliuda Bay and far less for both species than Kiliuda Bay in terms of percentage of area (Table 6, Fig. 8D). Aialik Bay has approximately the same amount of Pacific halibut preferred habitat as the much smaller Izhut Bay and Port Dick because preferred sediment/depth areas were farther away from the mouth of Aialik Bay than 7 km (Norcross et al., 1997).

3.5 Barren Islands

The Barren Islands, located in the entrance to Cook Inlet, consist of several islands; the western Ushagat group that includes Sud Island, and the eastern Amatuli group that includes the smaller Nord and Sugarloaf Islands (Fig. 2). The seafloor surrounding each of these groups is relatively shallow and is rather smooth between the individual islands of each group (Fig. 3E).

A channel between 80 and 120 m deep separates the two island groups. Several elongate basins and ridges are evident within this channel, and the two most prominent basins are sequential and are oriented nearly perpendicular to each other. Straight narrow slopes define the east and west edges of the channel. Another relatively deep area within the island groups is evident in an elongate basin to the south of Sugarloaf Island before another shoal area.

Even when including portions of the deep Kennedy and Stevenson Entrances, the Barren Islands study site's maximum depth is 70 m and 82 m shallower than the deepest parts of Port Dick and Aialik Bay, respectively; the average depth is only 86 m (Table 2). Not surprisingly, the highest slopes in the Barren Islands are at the edges of the exposed islands and submerged shoals (Fig. 4E), and due to the presence of Kennedy Entrance in the bounding box. The Barren Islands study site has the lowest average slope (2.4°), largest area of flat seafloor (33.4%), the lowest average rugosity (1.001), and the largest percent smooth area (64.0%, Table 2).

Precipitation rates are not available for the Barren Islands. However, using a rate from the nearby Kenai Peninsula (Jones and Fahl, 1994), and the low ratio of watershed (Fig. 6E) to the arbitrarily defined sea surface area (Table 4), the Barren Islands has the highest predicted salinity. The relative tidal-volume variation in the bounding-box area of Barren Islands is nearly as high as the confined Kiliuda Bay (4.3 versus 4.7%, Table 4).

Mean shoreline exposure (6.0 out of 10 nodes), amount of shoreline with partial exposure (85%) to the ocean, and full shoreline exposure (12%) was highest among all sites (Table 1). Shorelines with less exposed shoreline in the Barren Islands are primarily in the leeward sides of other islands or significant peninsulas (Fig. 5E). On the easternmost shore of Ushagat Island, however, the shore appears to be exposed even in the lee of West Amatuli Island; this may be from tracks that nearly parallel the shore.

Very little variation in substrate character exists in the Barren Islands (Fig. 7E). The floor is covered primarily in coarse sediment, hard bottom, or rocks, with the highest mean and median phi among all sites (Table 5). Rocky reefs (0.549 km^2) and kelp (5.704 km^2) cover the most area of any study site. Mud or soft sediment, covering only 0.1% of the area, is confined to small patches between the islands.

The Barren Islands had the largest predicted preferred habitat area for Pacific halibut, roughly equivalent to that of all other areas combined, partially because this study site was so large and so shallow, and partially because the 7 km rule (Norcross et al., 1997) was not applied here (Table 6, Fig. 8E). Due to nearly complete lack of mud substrate, the Barren Islands had no flathead sole predicted preferred habitat at all.

4. Discussion

4.1 GIS data extraction

We demonstrated how detailed surfaces (20 m resolution) of important habitat variables for juvenile groundfish, such as depth and substrate type, could be made from smooth sheets for four central GOA bays and one archipelago site. Each of our study sites was quantitatively compared to the other sites in terms of variables that might make each site a productive groundfish nursery area. Arguably, Kiliuda Bay had the most predicted preferred habitat for the two species of study. Such detailed, continuous surfaces have never been presented or compared for these sites, except for the multibeam (depth) raster layers created by NOS for Aialik Bay. By digitizing the MHW-defined shoreline, we provided the first detailed measure of shore length for these sites, which enabled better bathymetry analysis, water surface area calculations, and water volume calculations such as tidal prism. Accurate georegistration and custom datum-shifting of the smooth sheets facilitated merging these smooth sheet data layers to other data layers such as USGS topographic sheets and orthographic imagery for linkages to the streams, rivers, and precipitation of surrounding watersheds for additional calculations. Bay openness measures (length of bay mouth versus length of shoreline, vertical cross-sectional area of bay mouth versus bay surface area, and tidal prism versus bay volume), along with bay shoreline influence measures (100 and 1000 m buffers of shoreline), percent bay coverage by kelp and rocky reefs, and shoreline exposure quantification are all metrics that can be used for comparing different study sites.

4.2 Cost consideration

In total, our maps at the five study sites only covered about 1,046 km^2 - just a small fraction (0.3%) of the GOA management area - but demonstrated the means of accomplishing the task of describing EFH by using existing, available groundfish habitat data. Our method only involves computer time, GIS software, and the roughly 1000 smooth sheets which cover much of the Alaska coastline. New multibeam data collection can cost over US$30,000 per day (Reynolds et al., 2008) and take months of processing time, so we suggest that our methods be applied as an alternative to any location under consideration for groundfish habitat mapping. There are thousands of additional smooth sheets covering the US West Coast, the Hawaiian Islands, the Gulf Coast, Puerto Rico, the US East Coast, and the Great Lakes, so the same methods can also be applied in many other areas of the United States.

4.3 Smooth sheet validity

Several studies have already utilized some of the information from these smooth sheets. First and foremost, these smooth sheets remain the authoritative account of obstacles to safe navigation which are presented on the less-detailed NOS navigation charts. Field researchers who successfully navigate through their study areas by using NOS charts are often validating the input data from the smooth sheets, even though most mariners have never heard of the smooth sheets. There are various unpublished bathymetry compilations in progress which offer different resolutions of the original data.

Most of the smooth sheets used for this analysis are old and therefore might be suspect for accuracy. In every instance we used the most modern data available and supplemented it with older data when needed. When Alaskan locations get resurveyed after several years it is possible to quantify shore, substrate and bathymetric (Haeussler et al., 2007) changes over time. Obviously it would be preferable to use only recent data but most Alaskan smooth sheets are between 50 and 100 years old, while some Alaskan locations, such as the Sandman Reefs in the western Gulf of Alaska and Amlia Island, in the Aleutian Islands (Zimmermann et al., 2013), have never been surveyed.

There is bound to be a difference in the smooth sheet lead-line sediment sampling, which is probably more of a surface sample, and core or grab sampling, which probably penetrates deeper into the sediment. Without dedicated groundtruthing, it is difficult to correct for possible differences in grain size that might exist between historical surface samples and present-day sub-surface samples, or to provide a more detailed substrate cover similar to modern maps.

While the substrate interpretation and habitat predictability would be improved by backscatter imagery and more groundtruthing information (e.g., samples or photos), this work was focused as a desk exercise to test the worthiness of free, older, and existing data to provide insights into EFH predictions. Sediment surfaces here are created by translating an extended range of verbal classes into numbers (rocks added as -9 phi and ‘sticky’ as 9 phi, equivalent to clay) with an IDW interpolation that results in surfaces with isolated peaks and valleys, or "bulls eyes". The use of such a large range of grain-size values enhances the variability of the seafloor surface to emphasize the possible range of apparent habitat types. By using an exact interpolator that gives steep transitions between neighboring sediments of dissimilar sizes, the input data structure is preserved and translated into a numerical surface. Zimmermann and Benson (2013; see Fig. 37) show details of the input sediment points and the resulting IDW sediment surface of Shearwater Bay, within Kiliuda Bay, as an example of these decisions. Interpolation by smoothing on a restricted range of grain sizes would result in a more generalized surface - there would be no inshore areas of rock (-9 phi), no central area of sticky (9 phi) clay, and the entire bay would range only from gravel (-2 phi) to mud (6 phi). An alternative method of drawing sediment polygons is moving downwards on the data quality scale (Robinson et al., 1995), from ordinal to nominal, rather than upwards from ordinal to interval, as Jenkins' (1997) method attempts.

4.4 Groundfish habitat classification

One of the purposes in conducting this project was to provide the necessary GIS layers so that groundfish habitats could be defined by the preferences of the animal (supervised classification), rather than by the preferences of the scientist conducting the analysis (unsupervised classification) (Brown et al., 2011). Preferences for depth, slope, substrate and other measures will most likely differ between species, between life-stages within each species, between seasons, and perhaps also between night and day cycles. Therefore we suggest that it is better to provide the data layers so that boundaries can be drawn on the basis of specific preferences rather than to provide a single set of boundaries that are supposed to suit all species. We hope that our detailed maps will be tested with comprehensive sampling of groundfish species so that errors in our maps and predictive models can be detected and repaired, and also so that new variables can be mapped.

4.5 Additional groundfish habitat factors

Despite our efforts to maximize the extraction of all the information from the smooth sheets, there are likely several important groundfish habitat variables which are beyond the scope of this analysis. Current strength and direction probably have a strong influence on the successful settlement of juvenile groundfish at nursery areas, and it may be possible, in the future, to convert our bathymetry and water volume calculations into water flow. The addition of estimated annual freshwater runoff at each individual stream and river would provide an estimate of salinity variability in different portions of a bay. Water temperature is an important factor in groundfish growth and survival but this is a temporal variable that is quite dependent on season and weather, and probably best estimated by measurements in the field. Drawing a line across the mouth of the bays and drawing the watershed boundary based on topography seemed like a reasonable method of defining each bay study site for analysis, but these methods served to simplify each study site. For example, at Aialik Bay about one-third of the watershed is glacier, which was a minor concern in other watersheds, and Aialik is undergoing rapid changes due to glacial retreat. Immediately outside of Aialik Bay, the Chiswell Islands block some of the exposure to the ocean, and the islands are surrounded by two deep channels which probably have some influence on bay connectivity to the ocean.

The Barren Islands were included in this study to test the methodology in open waters and many statistics are largely dependent on the bounding box that was arbitrarily set at the limits of the bathymetric data for the two main smooth sheets used – enclosing approximately 600 km^2. Comparing the relatively open waters of the Barren Islands site to the relatively closed waters of the four bay sites obviously has some caveats. Our purpose was not to declare that bays and archipelagos were equivalent, but rather to demonstrate that the groundfish habitat description methods have some flexibility in application. While each study site will have some combination of groundfish habitat characteristics that make it unique, we felt that it was more useful to provide the actual metrics on factors that can be measured so that formal comparisons can be made.

5. Conclusions

We created predictive preferred habitat maps for two juvenile groundfish species and compared five study sites - four bays and one archipelago - by a wide variety of metrics, all of which were derived from NOS smooth sheets or geographically compatible, free data sets. This same method can be expanded to broader areas in Alaska, providing the first detailed EFH maps for a variety of species. Byproducts, such as a more detailed bathymetric map would be useful for a wide-variety of research topics, such as estimating trawlable and untrawlable areas, and ocean current circulation. The validity of the groundfish habitat measurements presented here, such as openness and exposure, along with the predicted EFH maps, need to be tested with extensive groundtruthing. Other focused research on these groundfish habitats is underway and corrections will be incorporated to the smooth sheet data sets where possible. In general though, it will be very difficult, both financially and logistically, to collect data sets comparable to those provided by the smooth sheets. The specific predicted preferred habitat maps generated for this project were only intended as an illustration demonstrating the utility of our methods, rather than as a definitive statement for the habitat requirements of juvenile Pacific halibut and flathead sole.

Acknowledgments

Thanks to J. Benson for extensive help with ArcMap software and to C. Paternostro for help with cross sections. B. McMahon, G. Nelson (retired) and especially C. Barry (Pacific Hydrographic Branch) provided assistance with interpreting smooth sheets, bathymetric sounding files, and descriptive reports. D. Doyle (retired) from the National Geodetic Survey provided invaluable assistance with triangulation stations and datum shifts. D. Fischman, G. Glover, J.A. Bunn, J. Campagnoli, M. Frydrych, and M. Cole from the National Geophysical Data Center helped with accessing smooth sheets on the NGDC web page. Thanks to Alaska Department of Natural Resources for supplying digitized streams and rivers, and thanks to T. Brabets for the digital version of the annual precipitation map. Thank you to W. Palsson, D. Somerton, G. Cochrane, F. Mueter, E. Edinger and two anonymous reviewers for constructive criticism.

The findings and conclusions in the paper are those of the author(s) and do not necessarily represent the views of the National Marine Fisheries Service, NOAA or the USGS. Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA or the USGS.

References

Abookire, A. A., and B. L. Norcross. 1998. Depth and substrate as determinants of distribution of juvenile flathead sole (*Hippoglossoides elassodon*) and rock sole (*Pleuronectes bilineatus*), in Kachmak Bay, Alaska. J. Sea Res. 39:113-123.

Abookire, A. A., J. F. Piatt, and B. L. Norcross. 2001. Juvenile groundfish habitat in Kachemak Bay, Alaska, during late summer. Alaska Fish. Res. Bull. 8(1):45-56.

Abookire, A. A., J. T. Duffy-Anderson, and C. M. Jump. 2006. Habitat associations and diet of young-of-the-year Pacific cod (*Gadus macrocephalus*) near Kodiak, Alaska. Mar. Biol. 150:713-726.

Agapito, M. T. 2008. Mapping and lithologic interpretation of the territorial sea, Oregon. M.S. thesis, 92 p. Corvallis, Oregon State University, OR.

Amolo, R. C. 2010. Habitat mapping and identifying suitable habitat of Redfish Rocks Pilot Marine Reserve, Port Orford, Oregon. M.S. thesis, 106 p. Corvallis, Oregon State University, OR.

Bailey, K. M., and S. J. Picquelle. 2002. Larval distribution of offshore spawning flatfish in the Gulf of Alaska: potential transport pathways and enhanced onshore transport during ENSO events. Mar. Ecol. Prog. Ser. 236:205-217.

Brown, C. J., S. J. Smith, P. Lawton, and J. T. Anderson. 2011. Benthic habitat mapping: a review of progress towards improved understanding of the spatial ecology of the seafloor using acoustic techniques. Estuar. Coast. Shelf Sci. 92:502-520.

Dorn, M. W., K. Aydin, S. Barbeaux, M. Guttormsen, B. Megrey, K. Spalinger, and M. Wilkins. 2008. Assessment of the walleye pollock stock in the Gulf of Alaska. *In* Stock assessment and fishery evaluation report for the groundfish fisheries of the Gulf of Alaska as projected for 2009. [Available from North Pacific Fishery Management Council, 605 W 4th Avenue, Suite 306, Anchorage, AK 99510.]

Greene, H. G., M. M. Yoklavich, R. M. Starr, V. M. O'Connell, W. W. Wakefield, D. E. Sullivan, J. E. McRea, and G. M. Cailliet. 1999. A classification scheme for deep seafloor habitats. Oceanol. Acta 22 (6):663-678.

Greene, H. G., V. O'Connell, C. K. Brylinsky, and J. R. Reynolds. 2008. Marine benthic habitat classification: what's best for Alaska? *In* Marine habitat mapping technology for Alaska, (J. R. Reynolds and H. G. Greene, eds). Chapter 12, p. 169-184. Alaska Sea Grant Program, Univ. Alaska, Fairbanks.

Greene, H. G., V. O'Connell, and C. K. Brylinsky. 2011. Tectonic and glacial related seafloor geomorphology as possible demersal shelf rockfish habitat surrogates—Examples along the Alaskan convergent transform plate boundary. Cont. Shelf Res. 31:539-553.

Haeussler, P. J., H. J. Lee, H. F. Ryan, R. E. Kayen, M. A. Hampton, and E. Suleimani, 2007. Submarine slope failures near Seward, Alaska, during the M9.2 1964 earthquake. *In* Submarine mass movements and their consequences (V. Lykousis, S. Dimitris, and J. Locat, eds.), p. 269-278. Springer, Netherlands.

Hanselman, D. H., J. Heifetz, J. T. Fujioka, S. K. Shotwell, and J. N. Ianelli. 2007. Gulf of Alaska Pacific ocean perch. *In* Stock assessment and fishery evaluation report for the groundfish resources of the Gulf of Alaska as projected for 2008. [Available from North Pacific Fishery Management Council, 605 W 4th Ave, Suite 306 Anchorage, AK 99501.]

Hanselman, D. H., C. R. Lunsford, J. T. Fujioka, and C. J. Rodgveller. 2008. Assessment of sablefish stock in Alaska. *In* Stock assessment and fishery evaluation report for the groundfish fisheries of the Gulf of Alaska as projected for 2009. [Available from North

Pacific Fishery Management Council, 605 W 4th Avenue, Suite 306, Anchorage, AK 99510.]

Jenkins, C. J. 1997. Building offshore soils databases. Sea Tech. 38(12):25-28.

Jenness, J.S. 2004. Calculating landscape surface area from digital elevation models. Wildlife Society Bulletin. 32(3): 829-839.

Jones, S. H., and C. B. Fahl. 1994. Magnitude and frequency of floods in Alaska and conterminous basins of Canada: U.S. Geol. Surv. Water-resources Inv. Rep. 93-4179.

Krumbein, W.C. 1934. Size frequency distributions of sediment, Journal of Sedimentary Petrology, v. 4, p. 65-77.

Mandelbrot, B. 1967. How long is the coast of Britain? Statistical self-similarity and fractional dimension. Science 156(3775):636-638.

Moles, A., and B. L. Norcross. 1995. Sediment preferences in juvenile Pacific flatfishes. Neth. J. Sea Res. 34(1-3):177-182.

Mueter, F-J., and B. L. Norcross. 1994. Distribution, abundance, and growth of larval walleye pollock, *Theragra chalcogramma*, in an Alaskan fjord. Fish. Bull. 92:579-590.

Mueter, F. J., J. L. Boldt, B. A. Megrey, and R. M. Peterman. 2007. Recruitment and survival of northeast Pacific Ocean fish stocks: temporal trends, covariation, and regime shifts. Can. J. Fish. Aquat. Sci. 64: 911-927.

NMFS (National Marine Fisheries Service). 2002. Final rule implementing the Magnuson-Stevens Act Essential Fish Habitat provisions. National Marine Fisheries Service, 67 Federal Register 2343, 1/17/02 (codified at 50 CFR Part 600, subparts J and K).

Norcross, B. L., B. A. Holladay, and F-J. Muter. 1995. Nursery area characteristics of pleuronectids in coastal Alaska, USA. Neth. J. Sea Res. 34(1-3):161-175.

Norcross, B., F-J. Muter, and B. A. Holladay. 1997. Habitat models for juvenile pleuronectids around Kodiak Island, Alaska. Fish. Bull. 95:504-520.

Norcross, B. L., A. Blanchard, and B. A. Holladay. 1999. Comparison of models for determining nearshore flatfish nursery areas in Alaskan waters. Fish. Oceanogr. 8(1):50-67.

O'Connell, V. M., C. K. Brylinsky, and H. G. Greene. 2007. Special paper. The use of geophysical survey data in fisheries management: a case history from southeast Alaska. Geol. Assoc. Canada. 47: 319-328.

Paris, C. B., J. Atema, J.-O. Irisson, M. Kingsford, G. Gerlach, and C. M. Guigand. 2013. Reef odor: a wake up call for navigation in reef fish larvae. PloS ONE 8(8): e72808.

Reynolds, J. R., H. G. Greene, D. Woodby, J. Kurland, and B. Allee. 2008. Workshop report: Marine Habitat Mapping Technology Workshop for Alaska April 2-4, 2007 Anchorage, Alaska. *In* Marine Habitat Mapping Technology for Alaska, (J. R. Reynolds and H. G. Greene eds.) Chapter 17, p. 237-265, Alaska Sea Grant Program, University of Alaska Fairbanks.

Richardson, L.F. 1961. The problem of contiguity: an appendix to statistic of deadly quarrels. *In* General systems: Yearb. Soc. Adv. General Systems Theory. 6(139):139-187, Soc. General Systems Research, Ann Arbor, MI.

Rooper, C. N., M. Zimmermann, M. M. Prescott, and A. J. Hermann. 2014. Predictive models of coral and sponge distribution, abundance and diversity in bottom trawl surveys of the Aleutian Islands, Alaska. Mar. Ecol. Prog. Ser. 503: 157-176.

Robinson, A.H., J.L. Morrison, P.C. Muehrcke, A.J. Kimerling, and S.C. Guptill. 1995. Elements of cartography. 6th edition, John Wiley and Sons, Inc., New York, USA.

Staaterman, E., C. B. Paris, and J. Helgers. 2012. Orientation behavior in fish larvae: a missing piece to Hjort's critical period hypothesis. J. Theor. Biol. 304:188-196.

Stoner, A. W., and A. A. Abookire. 2002. Sediment preferences and size-specific distribution of young-of-the-year Pacific halibut in an Alaskan nursery. J. Fish Biol. 61:540-559.

Stoner, A. W., and R. H. Titgen. 2003. Biological structures and bottom type influence habitat choices made by Alaska flatfishes. J. Exp. Mar. Biol. Ecol. 292:43-59.

Taylor, L. A., B. W. Eakins, K. S. Carignan, R. R. Warnken, D. C. Schoolcraft, T. Sazonova, and G. F. Sharman. 2008. Digital elevation model for Dutch Harbor, Alaska: procedures, data sources and analysis. U.S. Dep. of Commer., National Oceanic and Atmospheric Administration, National Environmental Satellite, Data, and Information Service, National Geophysical Data Center, 27 p.

Thompson, G., J. Ianelli, and M. Wilkins. 2008. Assessment of the Pacific cod stock in the Gulf of Alaska. *In* Stock assessment and fishery evaluation report for the groundfish fisheries of the Gulf of Alaska as projected for 2009. [Available from North Pacific Fishery Management Council, 605 W 4th Avenue, Suite 306, Anchorage, AK 99510.]

Turnock, B. J. and T. K. Wilderbuer. 2007. Gulf of Alaska arrowtooth flounder stock assessment. *In* Stock assessment and fishery evaluation report for the groundfish fisheries of the Gulf of Alaska as projected for 2008. [Available from North Pacific Fishery Management Council, 605 W 4th Avenue, Suite 306, Anchorage, AK 99510.]

Umbach, M. J. 1976. Hydrogaphic manual, fourth edition. U.S. Dep. Commer., National Ocean Service.

U. S. Congress. 2006. Magnuson-Stevens Fishery Conservation and Management Act. Public Law 94-265, as amended, 16 U.S.C. 1853, 1855.

von Szalay, P. G., N. W. Raring, F. R. Shaw, M. E. Wilkins, and M. H. Martin. 2010. Data report: 2009 Gulf of Alaska bottom trawl survey. NOAA Tech. Memo. NMFS-AFSC-208, 245 p.

Wentworth, C.K., 1922. A scale of grade and class terms for clastic sediments: Journal of Geology, v. 30, p. 377-392.

Woodby, D., D. Carlile, and L. Hulbert. 2009. Predictive modeling of coral distributions in the Central Aleutian Islands, USA. Mar. Ecol. Prog. Ser. 397:227-240.

Zimmermann, M. and J. Benson. 2013. Smooth sheets: How to work with them in a GIS to derive bathymetry, features and substrates. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-249, 52 p.

Zimmermann, M., M. M. Prescott, and C. N. Rooper. 2013. Smooth sheet bathymetry of the Aleutian Islands. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-AFSC-250, 43 p.

Zimmermann, M., and M. M. Prescott. 2014. Smooth sheet bathymetry of Cook Inlet, Alaska. U.S. Dep. Commer., NOAA Tech. Memo. NMFS AFSC-275, 32 p.

Zimmermann, M., and M. M. Prescott. In review. Smooth sheet bathymetry of the central Gulf of Alaska. U.S. Dep. Commer., NOAA Tech. Memo. NMFS AFSC-xxx, xx p.

Figures

Figure 1. Detail of Kiliuda Bay, Kodiak Island from National Ocean Service (NOS) navigation chart 16592 (Scale 1:80,728) depicting scarce soundings and substrates. NOS smooth sheet H05152 (Scale 1:20,000) has roughly 30 times as many soundings and 17 times as many substrates for the same location.

Figure 2. Location of five study sites in the Gulf of Alaska - Kiliuda Bay, Port Dick, Izhut Bay, Aialik Bay, and the Barren Islands - for developing geographic information system (GIS) layers to map groundfish essential fish habitat (EFH).

Figure 3. Interpolated bathymetric surfaces based on the smooth sheet data. Red is shallow and blue is deep. (A) Kiliuda Bay, (B) Port Dick, (C) Izhut Bay, (D) Aialik Bay, and (E) the Barren Islands.

Figure 4. Interpolated slope surfaces based on the smooth sheet bathymetric data. Red is steep and blue is flat. (A) Kiliuda Bay, (B) Port Dick, (C) Izhut Bay, (D) Aialik Bay, and (E) the Barren Islands.

Figure 5. Shore exposure to the Gulf of Alaska as determined by direct linear paths from each section of shoreline to ten equally spaced points along the mouth of the bay. Since this same calculation could not be made for the Barren Islands, we used ten equally spaced points along each side of the perimeter of the Barren Islands study site. (A) Kiliuda Bay, (B) Port Dick, (C) Izhut Bay, (D) Aialik Bay, and (E) the Barren Islands.

Figure 6. Alignment of each interpolated bathymetric surface with seamless topographic layer (ArcMap v. 10.0, ESRI, Redlands, CA) showing digitized streams and rivers (courtesy Alaska Dept. Nat. Res.) and interpreted watershed for intersecting with annual estimated precipitation

(courtesy Alaska Geospatial Data Clearinghouse) in order to calculate freshwater runoff. Glaciers occurred in only the Kiliuda Bay, Port Dick and Aialik Bay watersheds. (A) Kiliuda Bay, (B) Port Dick, (C) Izhut Bay, (D) Aialik Bay, and (E) the Barren Islands.

Figure 7. Interpolated mean grain size layers based on substrates (mud, sand, gravel) and features (kelp, reef, rocks and islets) digitized from the smooth sheets. Darker green areas are mud (smaller grain size) and redder areas are rock (larger grain size). (A) Kiliuda Bay, (B) Port Dick, (C) Izhut Bay, (D) Aialik Bay, and (E) the Barren Islands.

Figure 8. Predicted essential fish habitat (EFH) for juvenile flathead sole and Pacific halibut (Norcross et al., 1997), with red areas for flathead sole (mud, 80-120 m) and blue areas for Pacific halibut (10-70 m, sand, within 7 km mouth of bay).

Figure1A

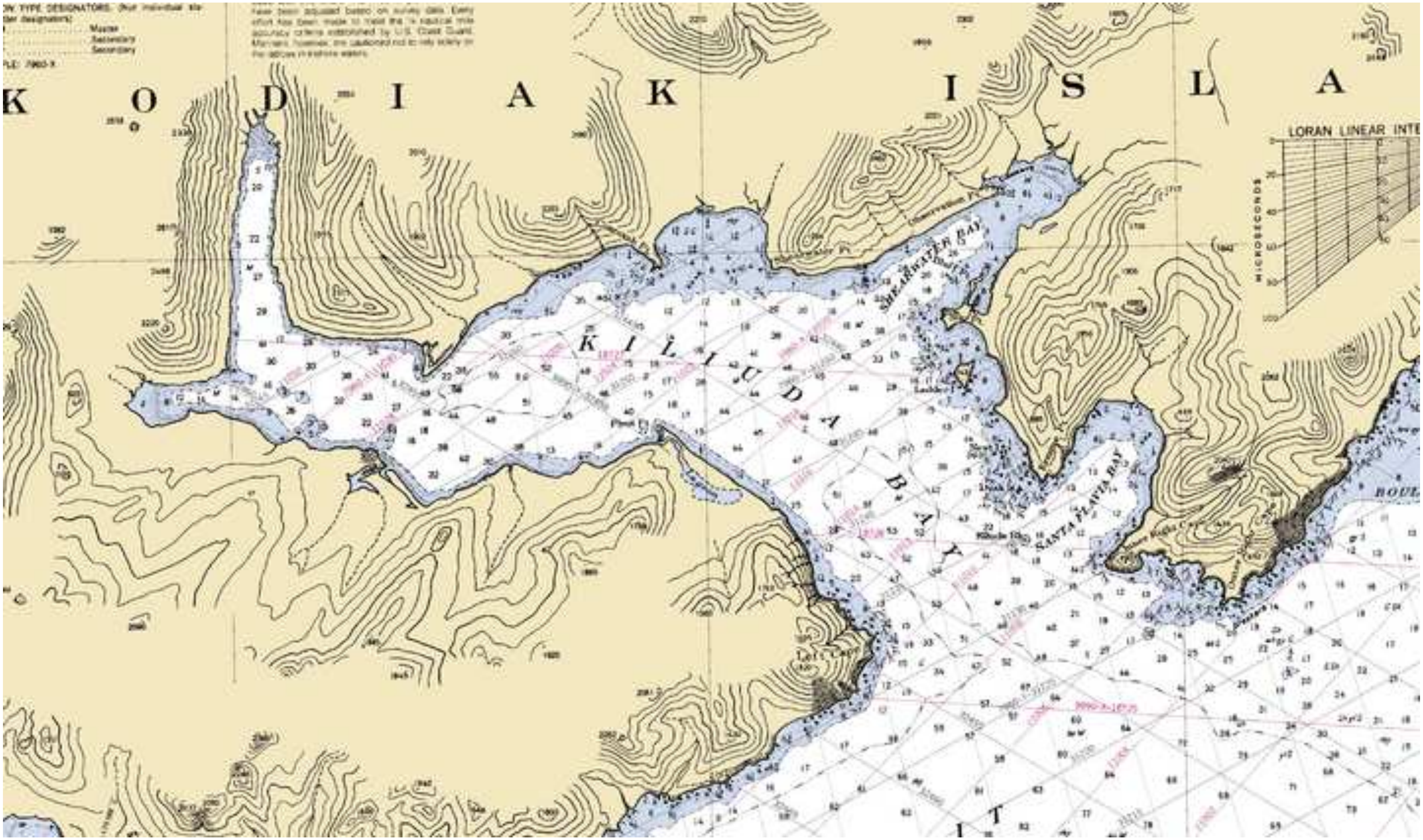

K O D I A K I S L A
KILIUDA BAY
SHEARWATER BAY
SANTA FLAVIA BAY
LORAN LINEAR INTE
MICROSECONDS

Figure1B

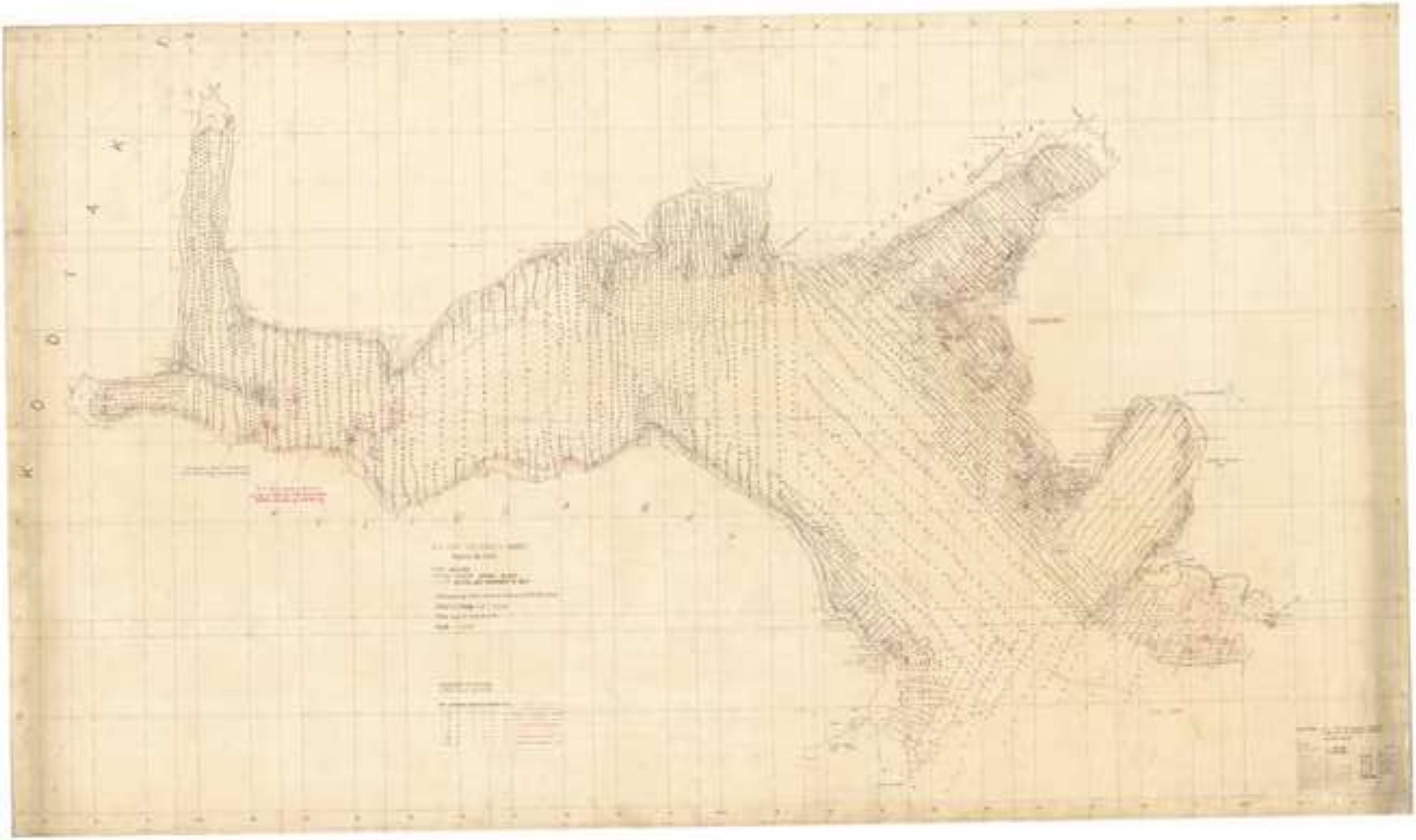
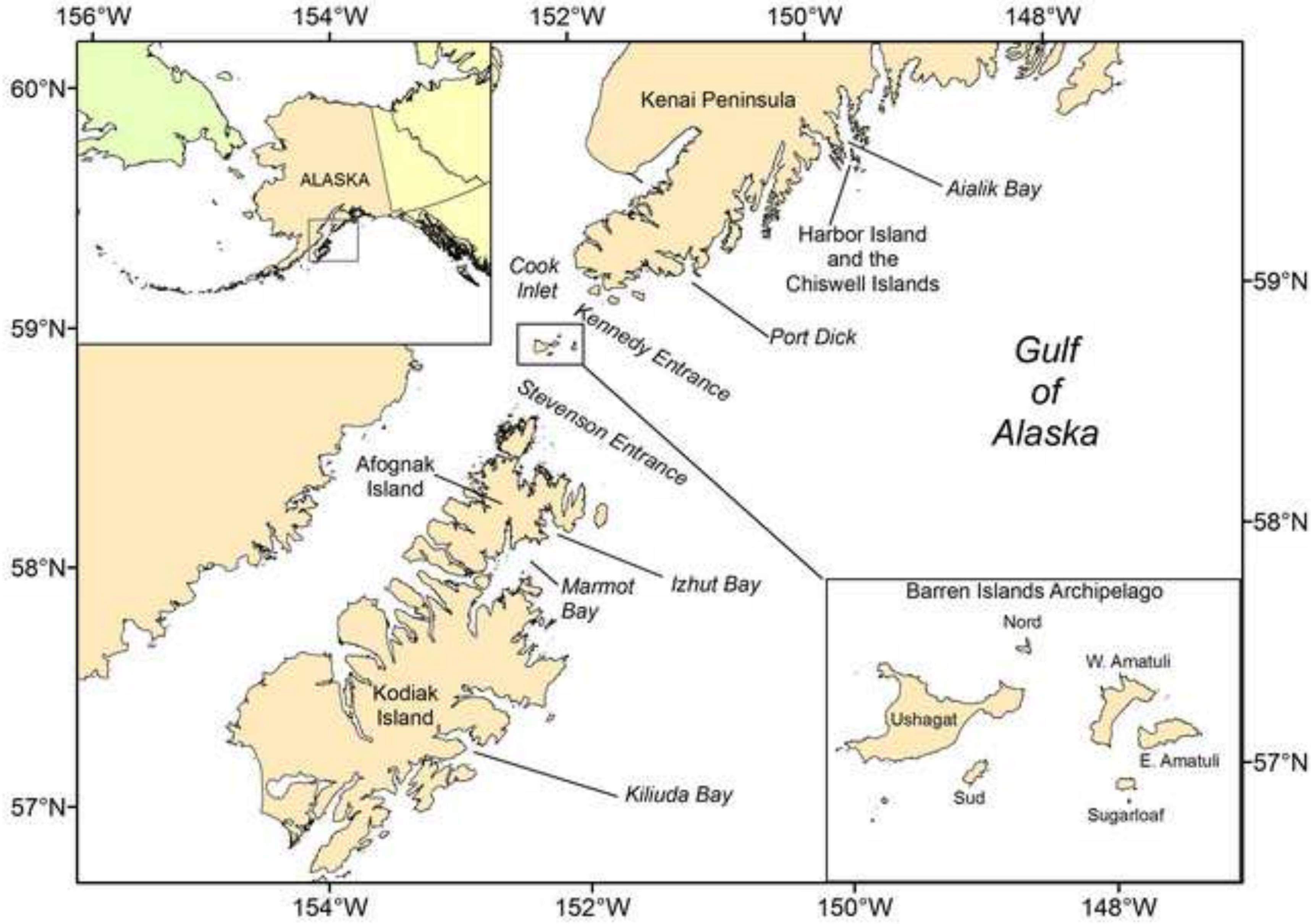
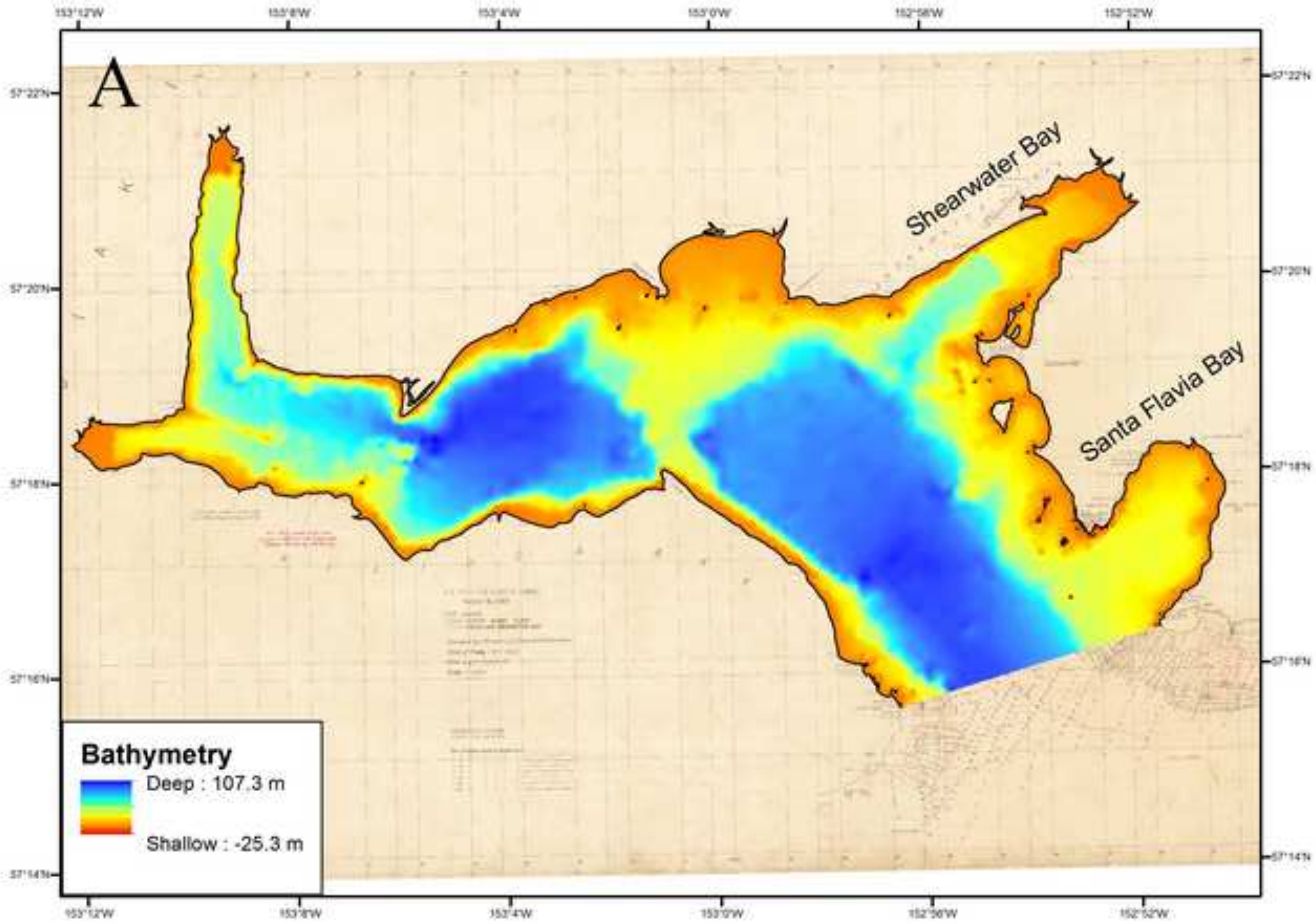


Figure2



156°W
154°W
152°W
150°W
148°W
60°N
59°N
58°N
57°N
ALASKA
Kenai Peninsula
Aialik Bay
Harbor Island and the Chiswell Islands
Cook Inlet
Port Dick
Kennedy Entrance
Stevenson Entrance
Gulf of Alaska
Afognak Island
Izhut Bay
Marmot Bay
Kodiak Island
Kiliuda Bay
Barren Islands Archipelago
Nord
W. Amatuli
Ushagat
E. Amatuli
Sud
Sugarloaf
154°W
152°W
150°W
148°W
59°N
58°N
57°N

Figure3A



A
Shearwater Bay
Santa Flavia Bay
Bathymetry
Deep : 107.3 m
Shallow : -25.3 m
153°12'W
153°8'W
153°4'W
153°0'W
152°56'W
152°52'W
57°22'N
57°20'N
57°18'N
57°16'N
57°14'N

Figure3B

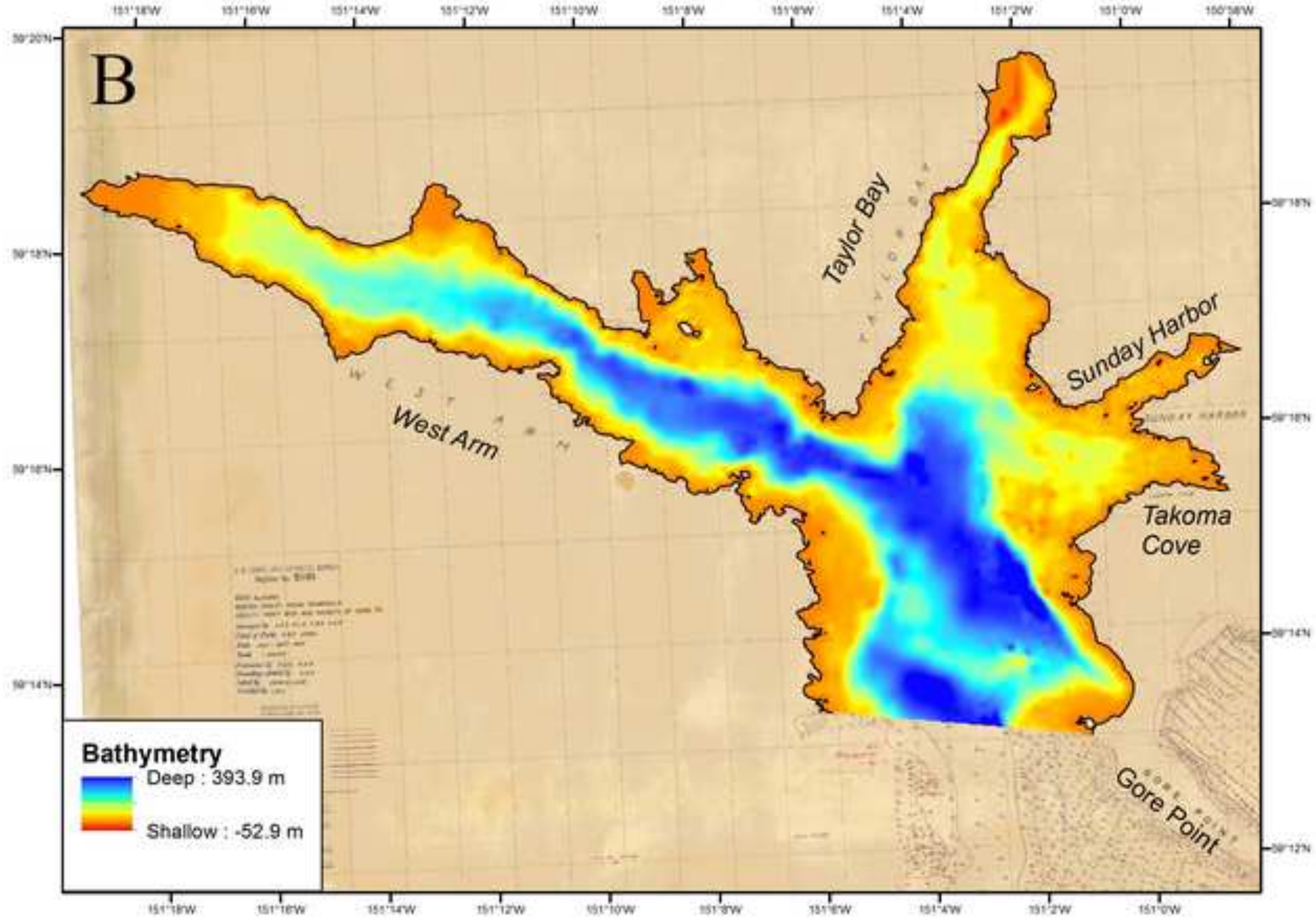

B
151°18'W
151°16'W
151°14'W
151°12'W
151°10'W
151°8'W
151°6'W
151°4'W
151°2'W
151°0'W
150°58'W
59°20'N
59°18'N
59°16'N
59°14'N
59°12'N
Taylor Bay
Sunday Harbor
West Arm
Takoma Cove
Gore Point
Bathymetry
Deep : 393.9 m
Shallow : -52.9 m

Figure3C

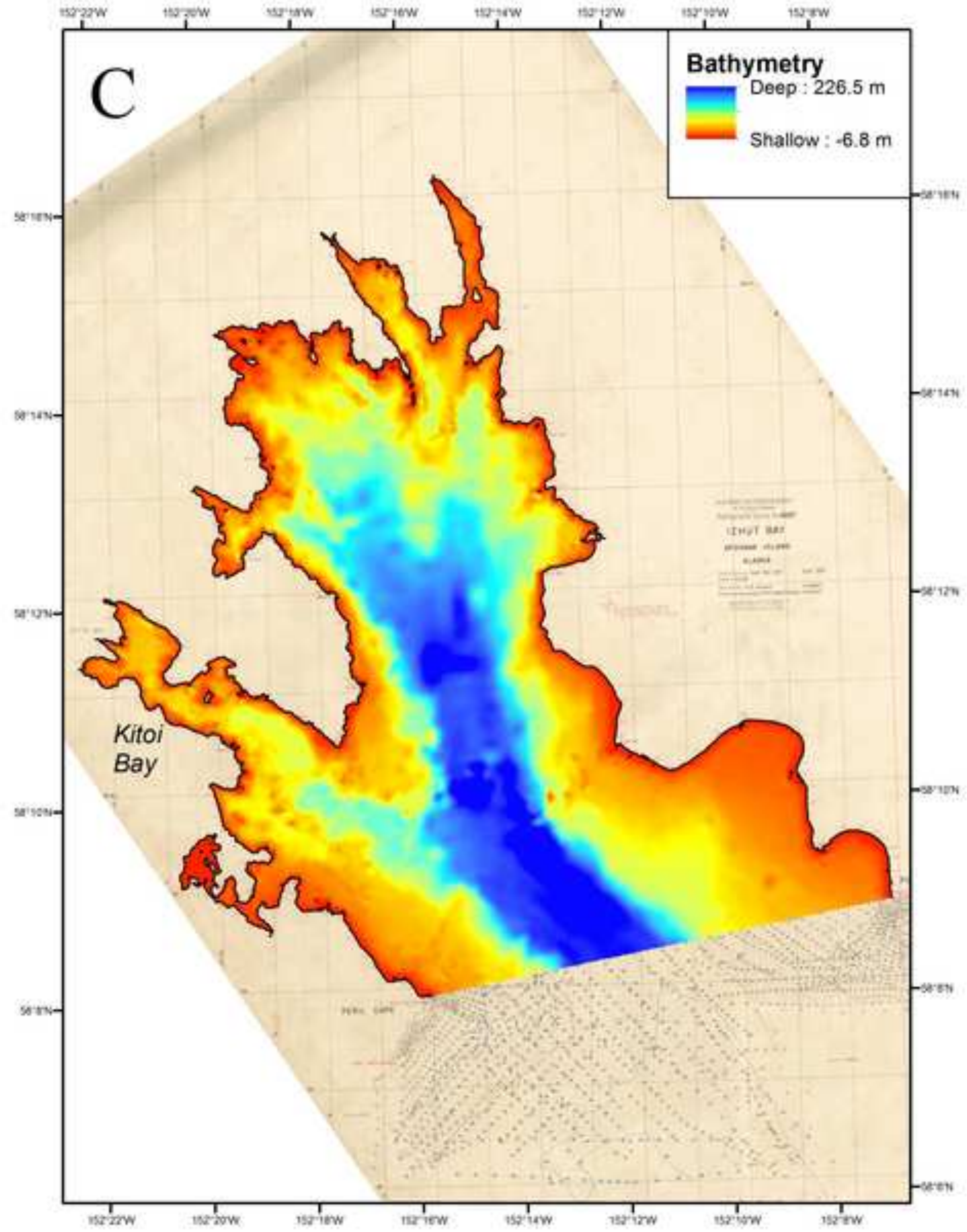

C
Bathymetry
Deep : 226.5 m
Shallow : -6.8 m
Kitoi Bay
IZHUT BAY
152°22'W
152°20'W
152°18'W
152°16'W
152°14'W
152°12'W
152°10'W
152°8'W
58°16'N
58°14'N
58°12'N
58°10'N
58°8'N
58°6'N

Figure3D

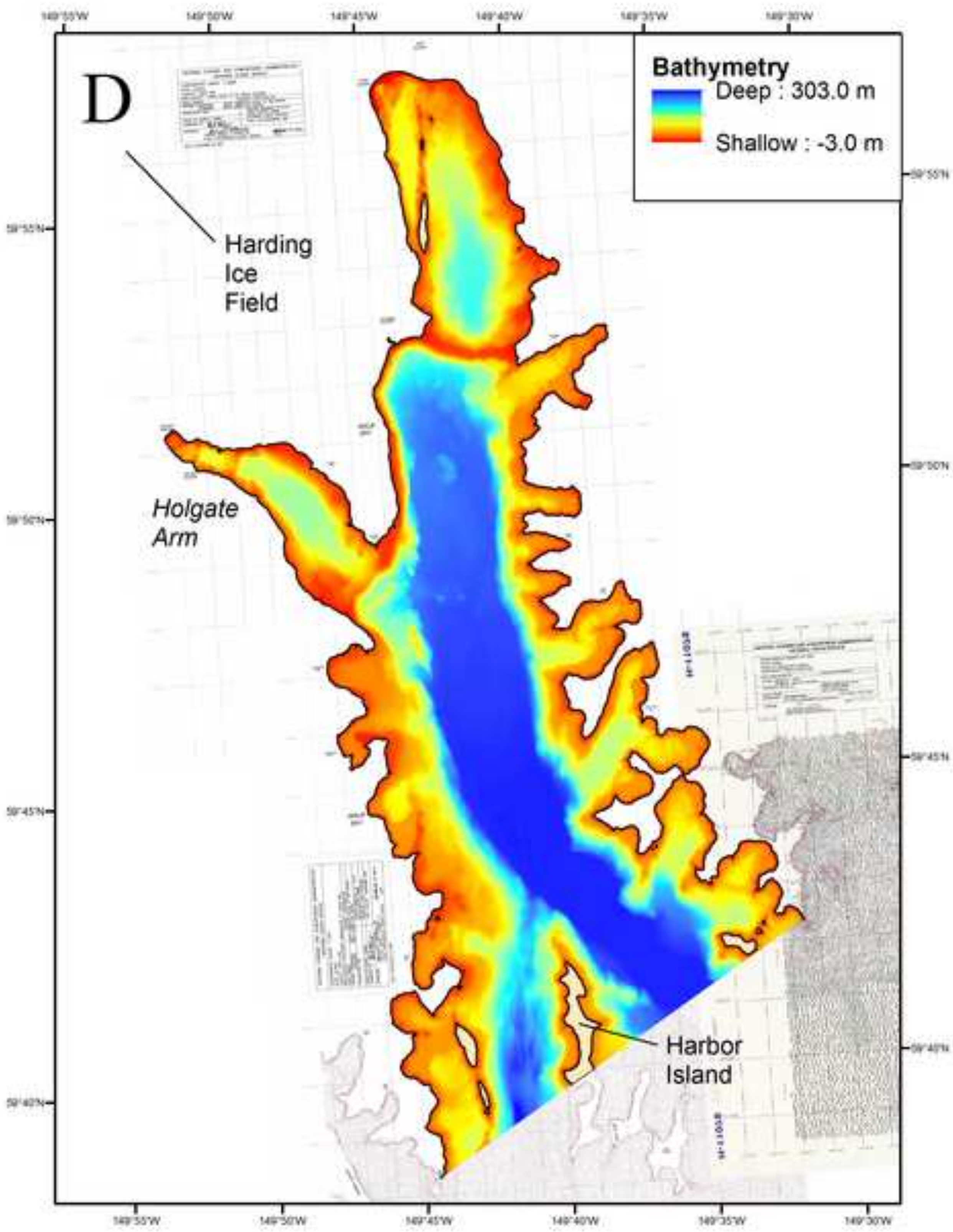

D
Bathymetry
Deep : 303.0 m
Shallow : -3.0 m
Harding Ice Field
Holgate Arm
Harbor Island
149°55'W
149°50'W
149°45'W
149°40'W
149°35'W
149°30'W
59°55'N
59°50'N
59°45'N
59°40'N

Figure3E

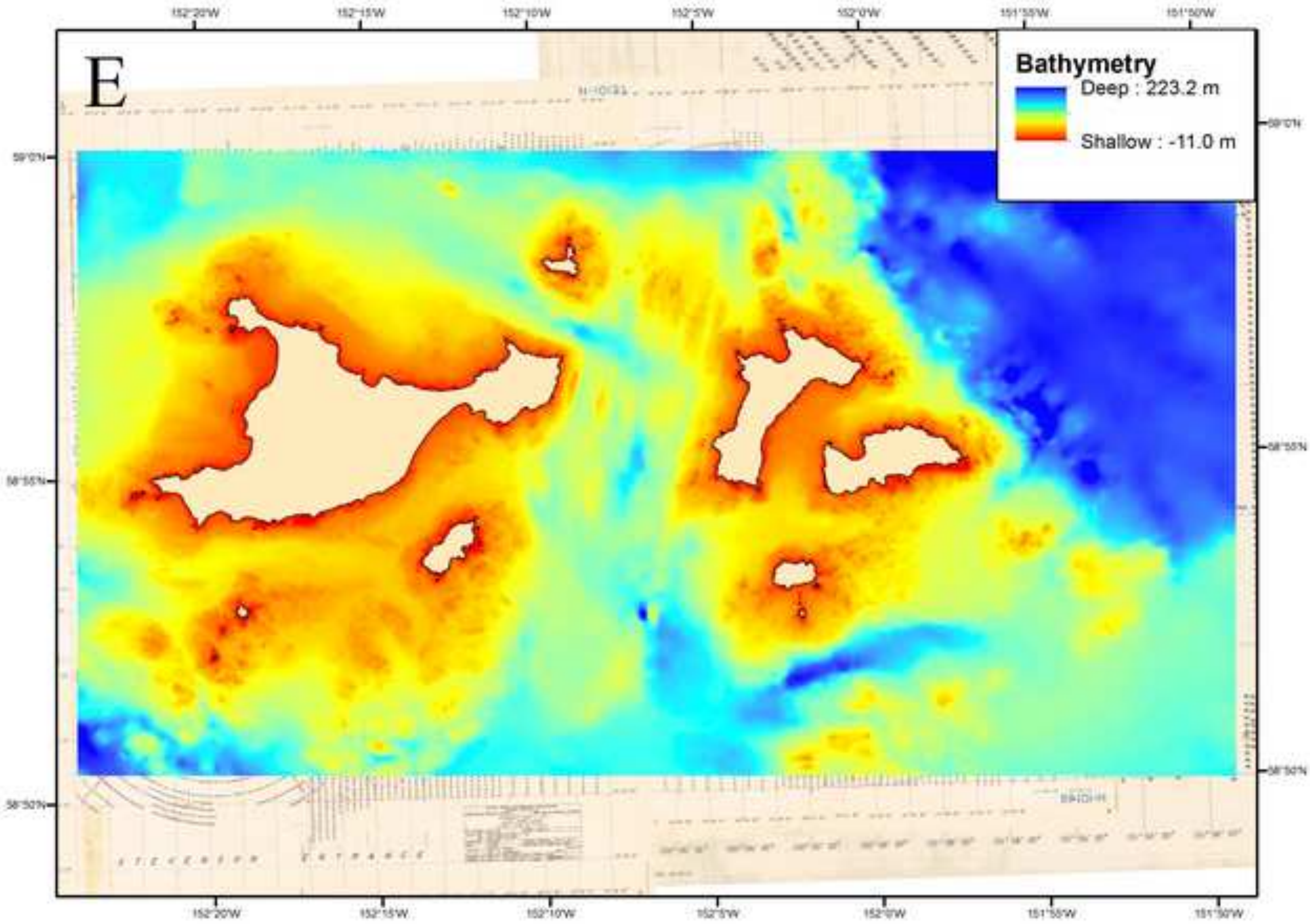

E
Bathymetry
Deep : 223.2 m
Shallow : -11.0 m
152°20'W
152°15'W
152°10'W
152°5'W
152°0'W
151°55'W
151°50'W
59°0'N
58°55'N
58°50'N

Figure4A

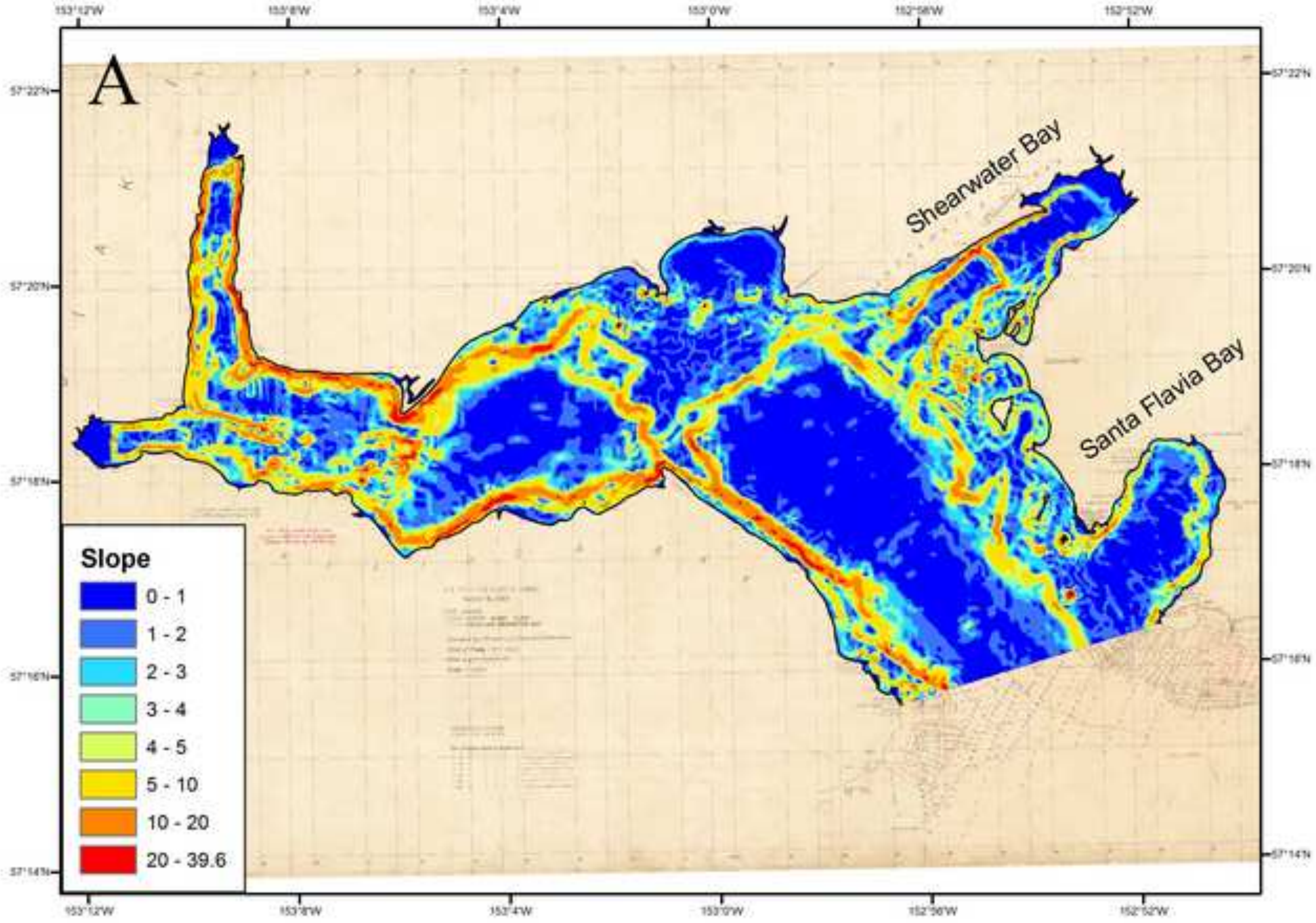

A
Shearwater Bay
Santa Flavia Bay
Slope
0 - 1
1 - 2
2 - 3
3 - 4
4 - 5
5 - 10
10 - 20
20 - 39.6
153°12'W
153°8'W
153°4'W
153°0'W
152°56'W
152°52'W
57°22'N
57°20'N
57°18'N
57°16'N
57°14'N

Figure4B

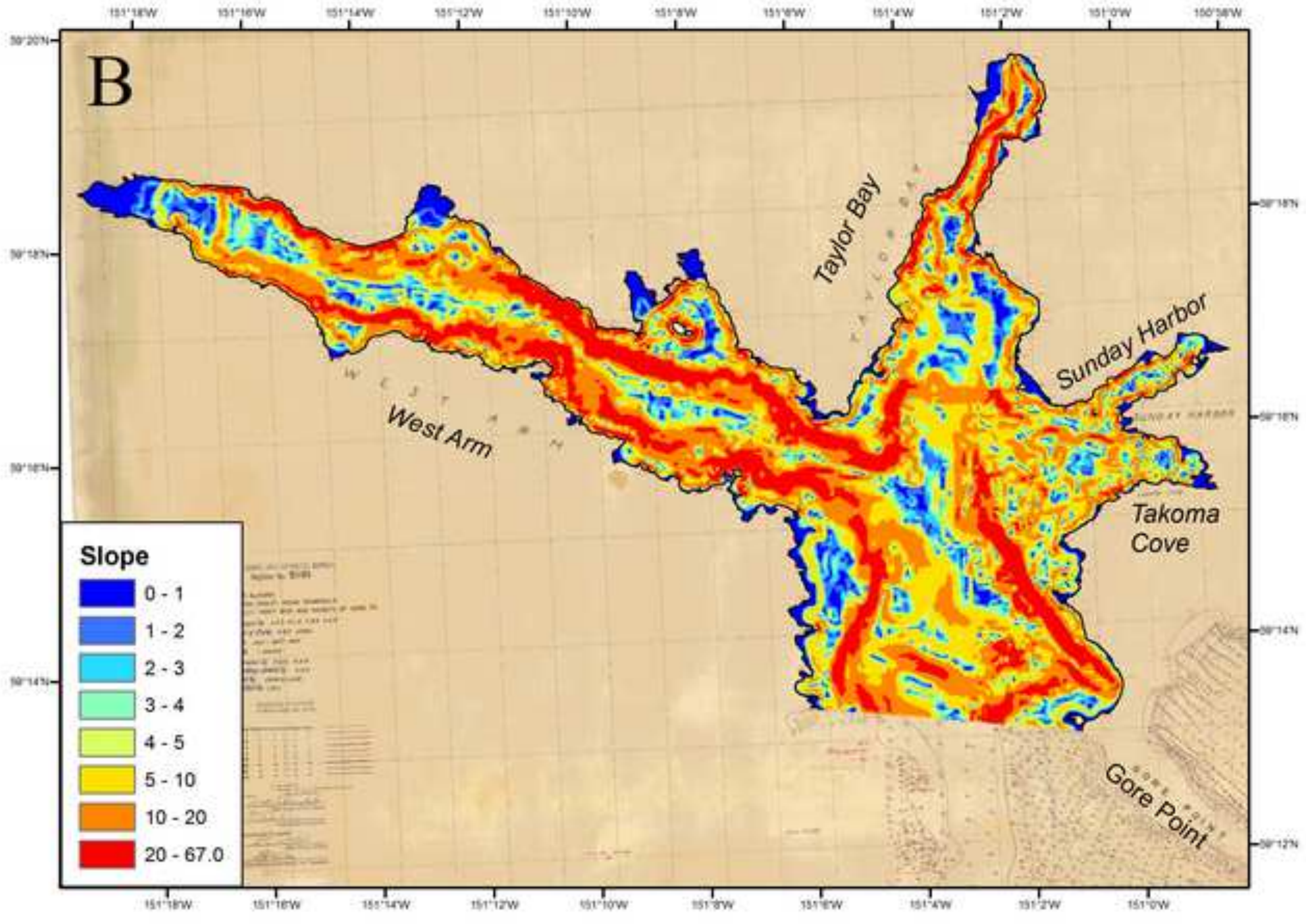

B
Slope
0 - 1
1 - 2
2 - 3
3 - 4
4 - 5
5 - 10
10 - 20
20 - 67.0
Taylor Bay
Sunday Harbor
West Arm
Takoma
Cove
Gore Point
151°18'W
151°16'W
151°14'W
151°12'W
151°10'W
151°8'W
151°6'W
151°4'W
151°2'W
151°0'W
150°58'W
59°20'N
59°18'N
59°16'N
59°14'N
59°12'N

Figure4C

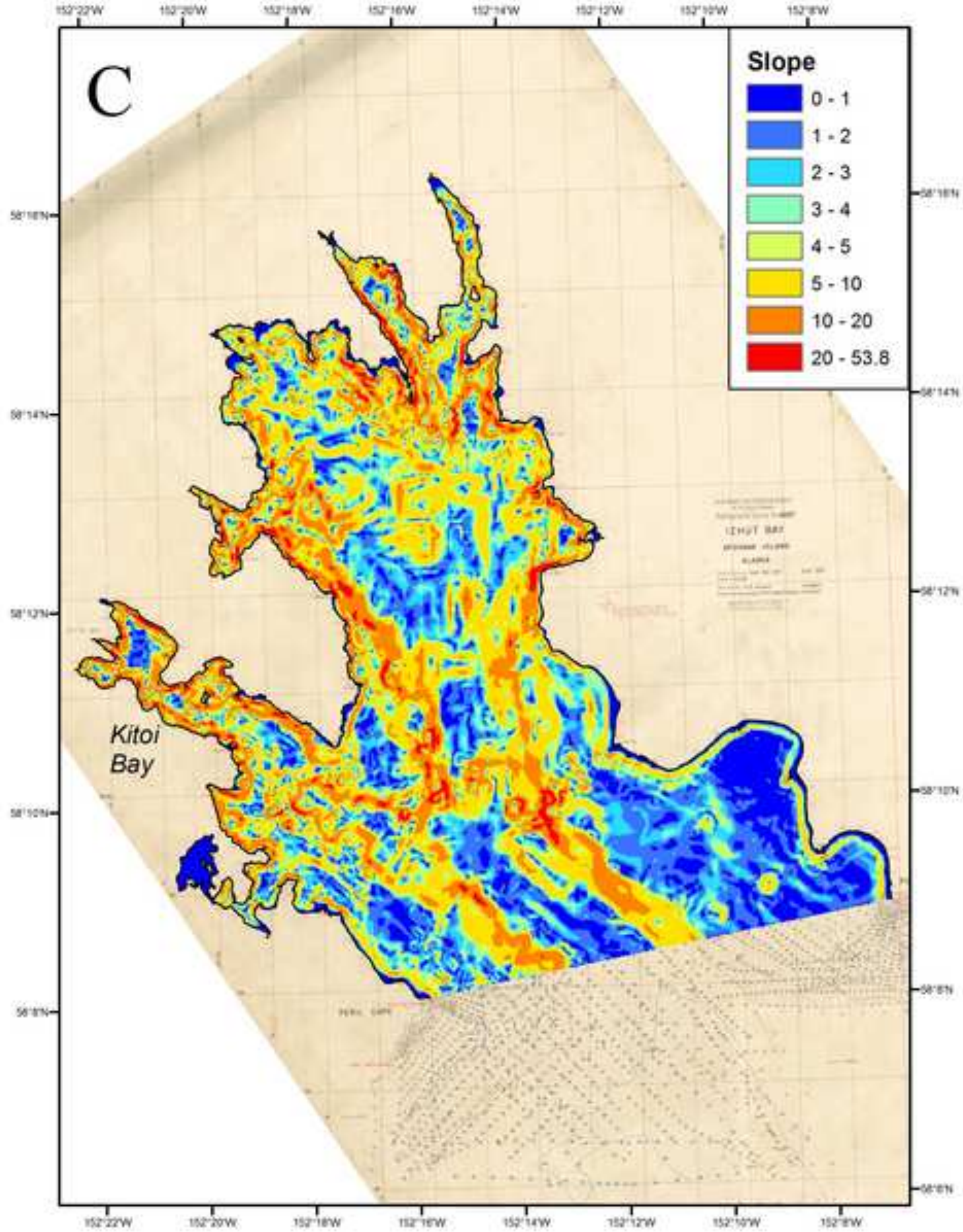

C
Slope
0 - 1
1 - 2
2 - 3
3 - 4
4 - 5
5 - 10
10 - 20
20 - 53.8
Kitoi Bay
IZHUT BAY
152°22'W
152°20'W
152°18'W
152°16'W
152°14'W
152°12'W
152°10'W
152°8'W
58°16'N
58°14'N
58°12'N
58°10'N
58°8'N
58°6'N

Figure4D

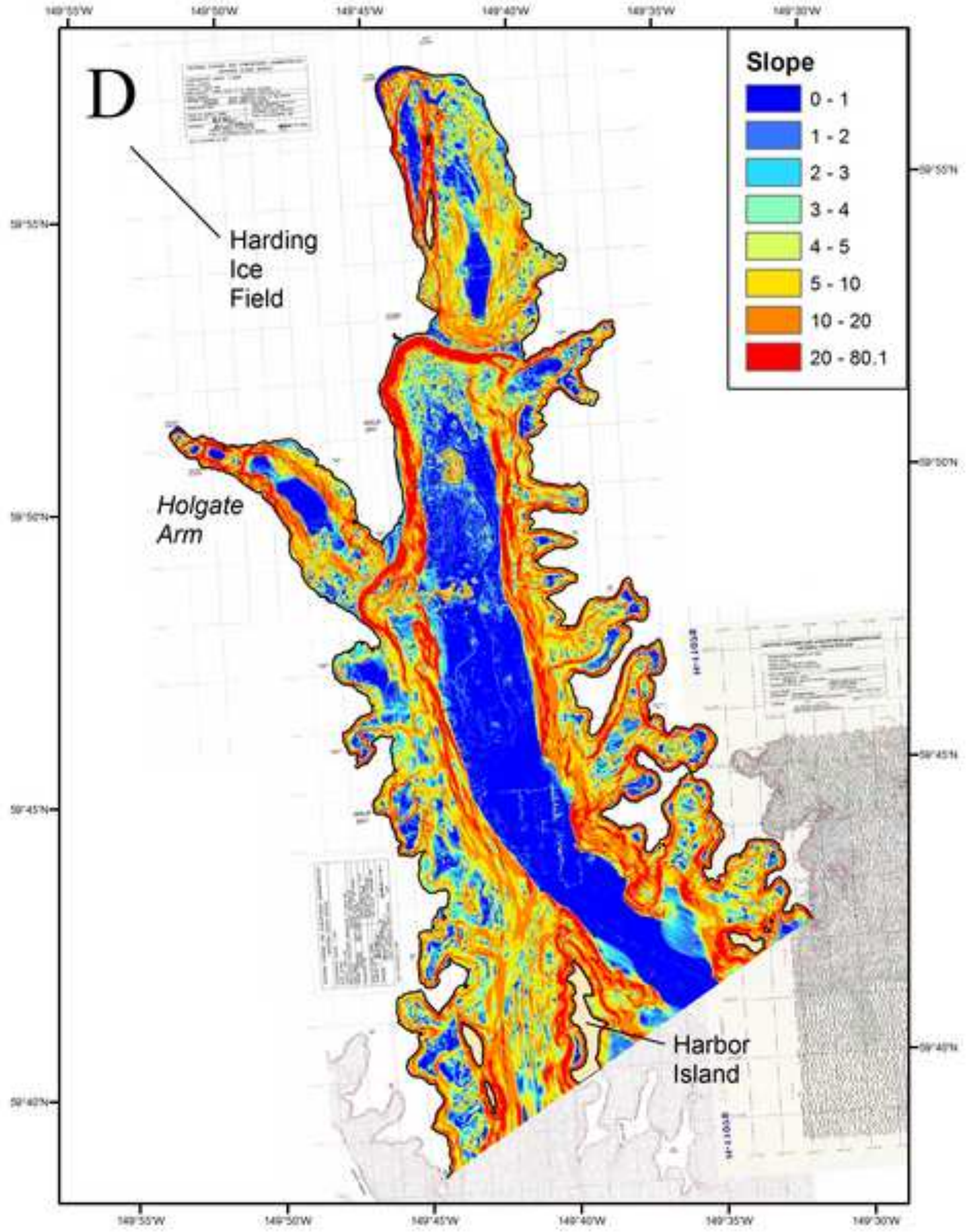

D
Harding Ice Field
Holgate Arm
Harbor Island
Slope
0 - 1
1 - 2
2 - 3
3 - 4
4 - 5
5 - 10
10 - 20
20 - 80.1
149°55'W
149°50'W
149°45'W
149°40'W
149°35'W
149°30'W
59°55'N
59°50'N
59°45'N
59°40'N

Figure4E

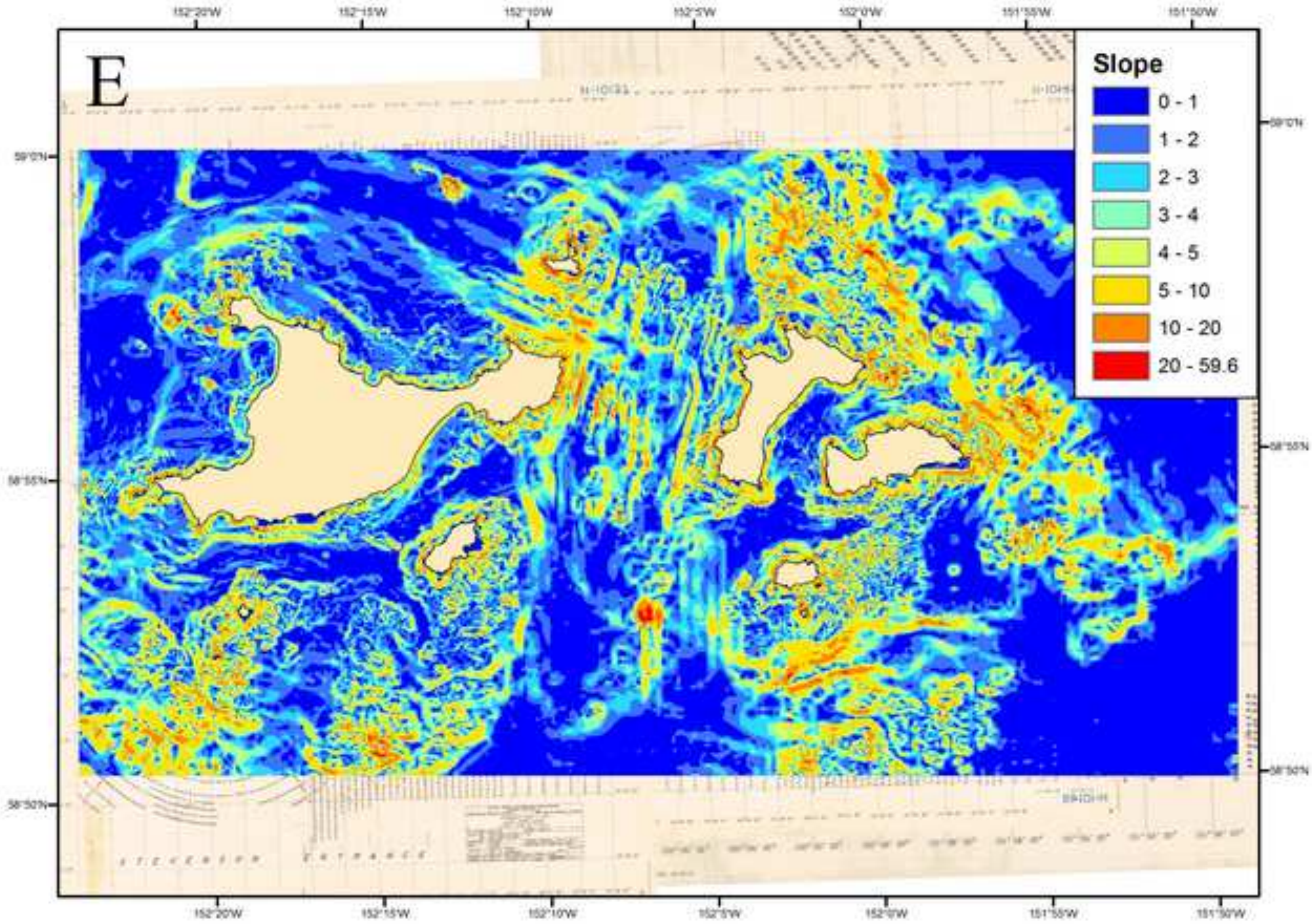

E
Slope
0 - 1
1 - 2
2 - 3
3 - 4
4 - 5
5 - 10
10 - 20
20 - 59.6
152°20'W
152°15'W
152°10'W
152°5'W
152°0'W
151°55'W
151°50'W
59°0'N
58°55'N
58°50'N

Figure5A

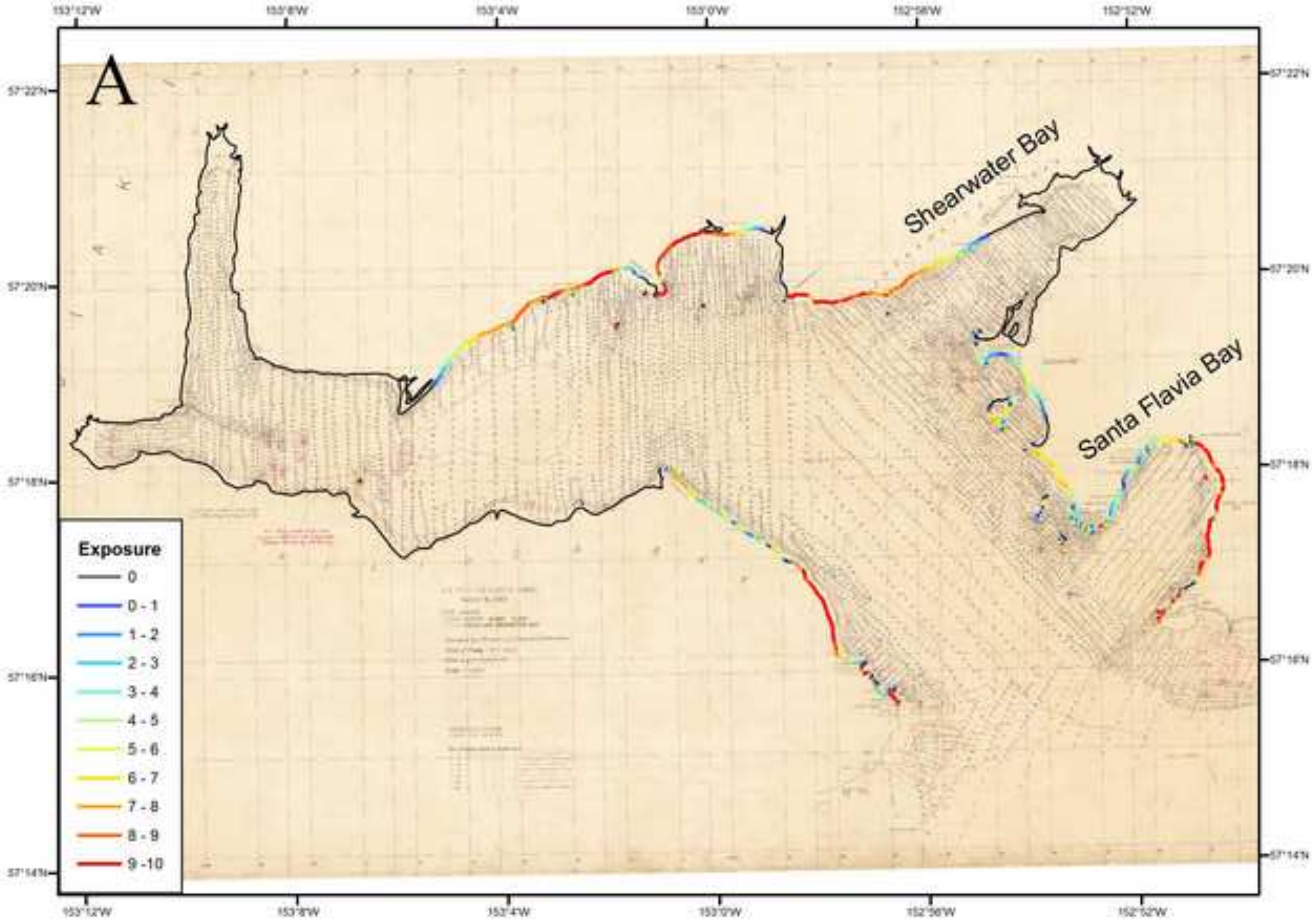

A
Shearwater Bay
Santa Flavia Bay
Exposure
0
0 - 1
1 - 2
2 - 3
3 - 4
4 - 5
5 - 6
6 - 7
7 - 8
8 - 9
9 -10
153°12'W
153°8'W
153°4'W
153°0'W
152°56'W
152°52'W
57°22'N
57°20'N
57°18'N
57°16'N
57°14'N

Figure5B

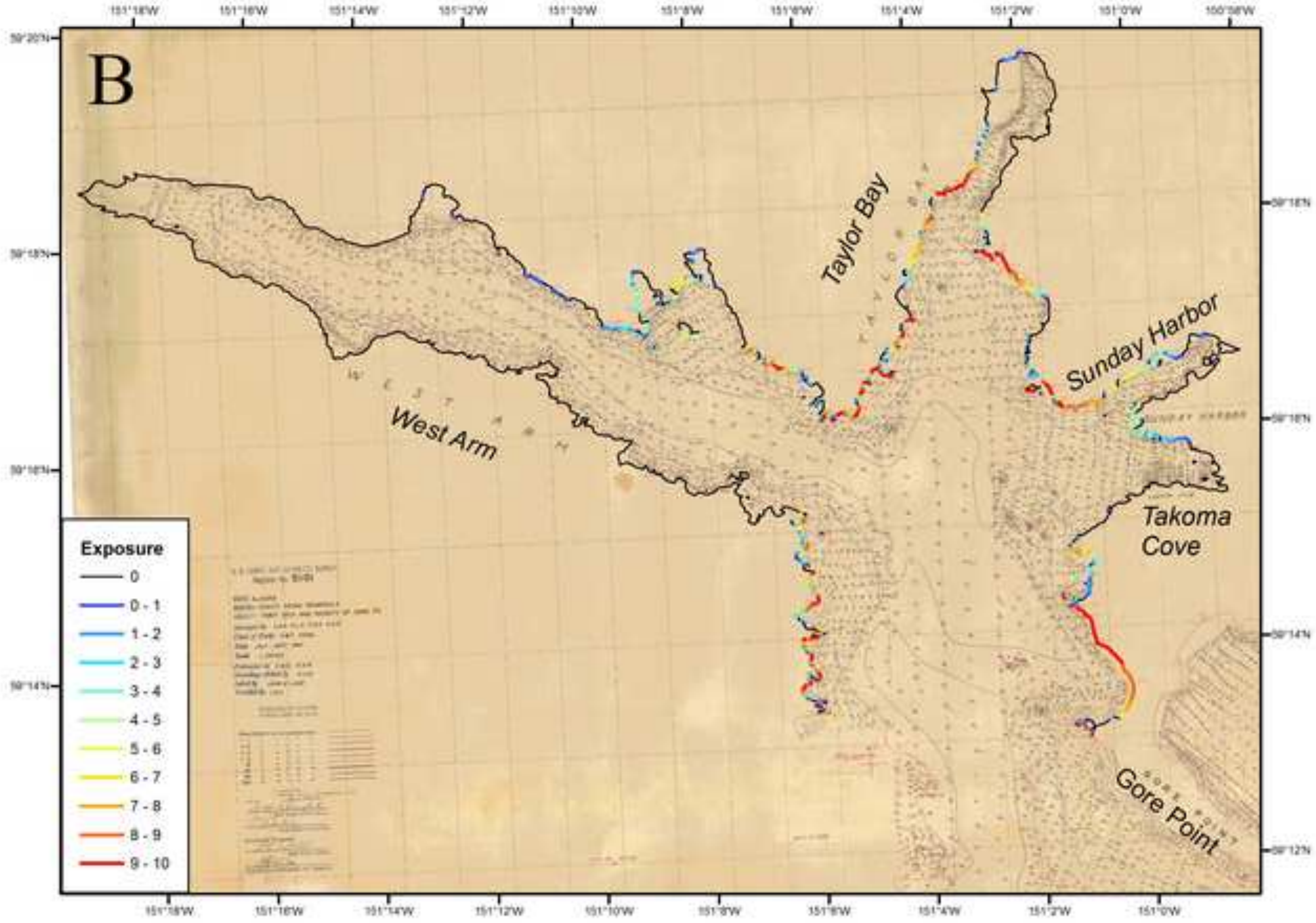

B
151°18'W
151°16'W
151°14'W
151°12'W
151°10'W
151°8'W
151°6'W
151°4'W
151°2'W
151°0'W
150°58'W
59°20'N
59°18'N
59°16'N
59°14'N
59°18'N
59°16'N
59°14'N
59°12'N
Taylor Bay
Sunday Harbor
West Arm
Takoma Cove
Gore Point
Exposure
0
0 - 1
1 - 2
2 - 3
3 - 4
4 - 5
5 - 6
6 - 7
7 - 8
8 - 9
9 - 10

Figure5C

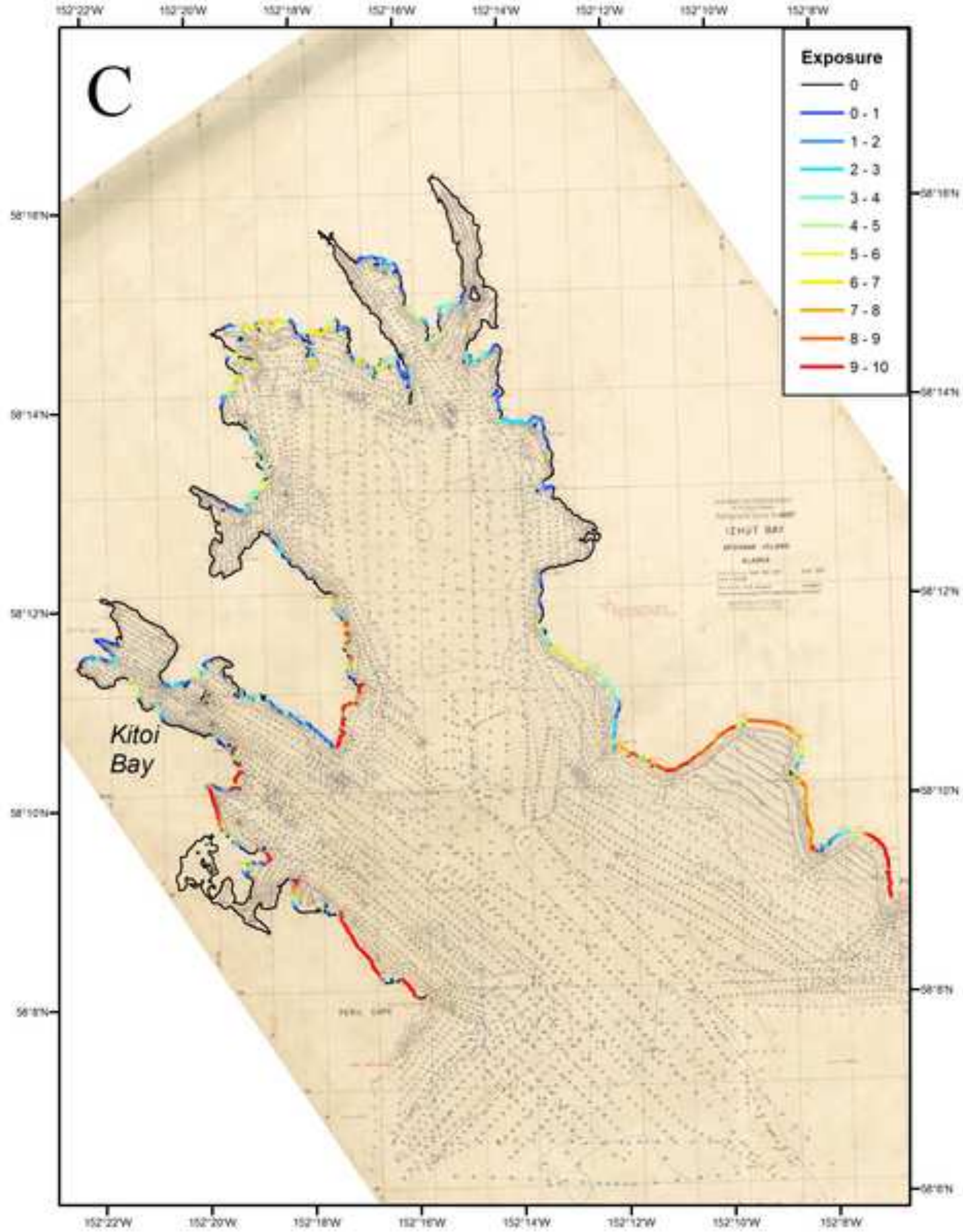

C
Exposure
0
0 - 1
1 - 2
2 - 3
3 - 4
4 - 5
5 - 6
6 - 7
7 - 8
8 - 9
9 - 10
Kitoi Bay
IZHUT BAY
152°22'W
152°20'W
152°18'W
152°16'W
152°14'W
152°12'W
152°10'W
152°8'W
58°16'N
58°14'N
58°12'N
58°10'N
58°8'N
58°6'N

Figure5D

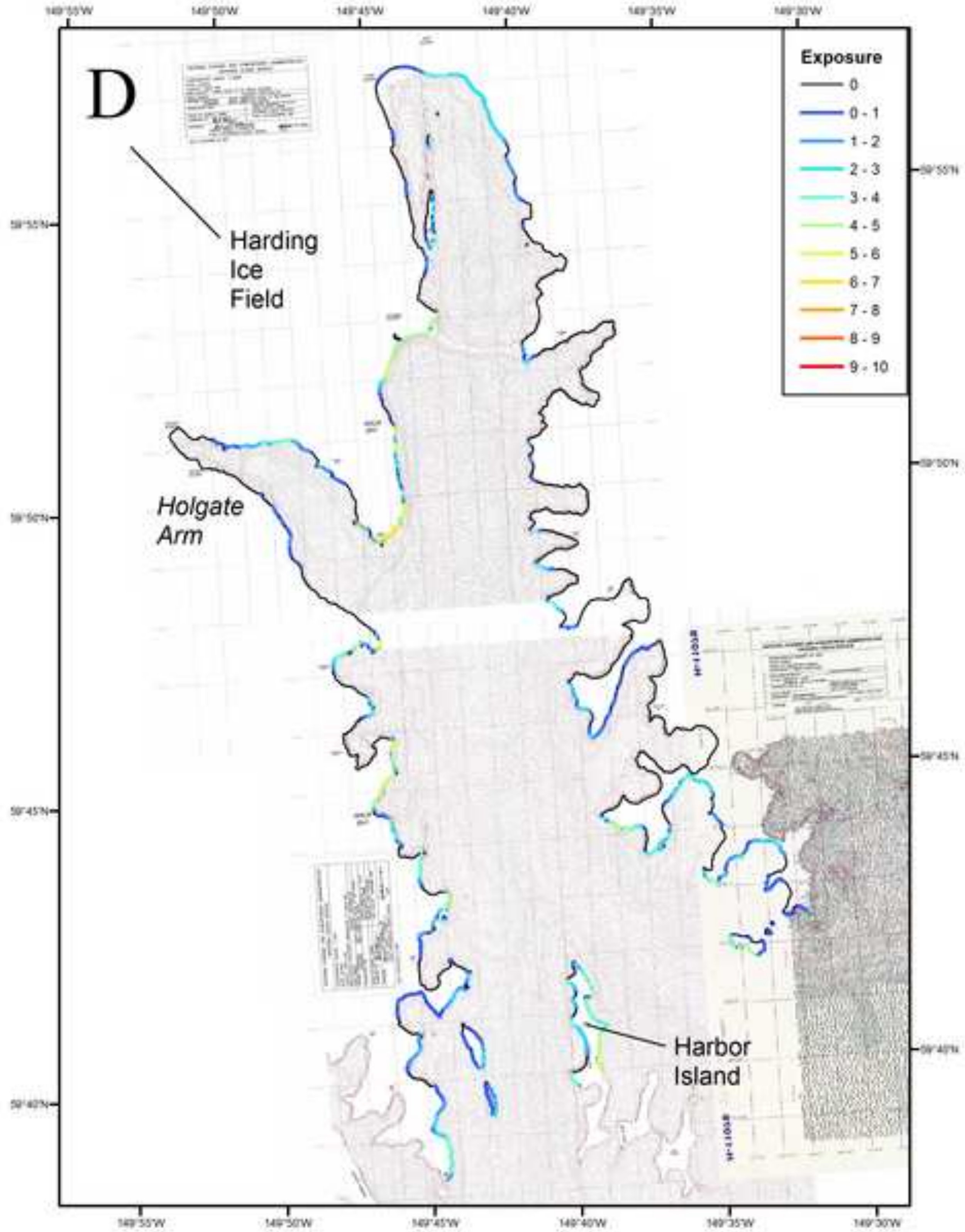

D
Harding Ice Field
Holgate Arm
Harbor Island
Exposure
0
0 - 1
1 - 2
2 - 3
3 - 4
4 - 5
5 - 6
6 - 7
7 - 8
8 - 9
9 - 10
149°55'W
149°50'W
149°45'W
149°40'W
149°35'W
149°30'W
59°55'N
59°50'N
59°45'N
59°40'N

Figure5E

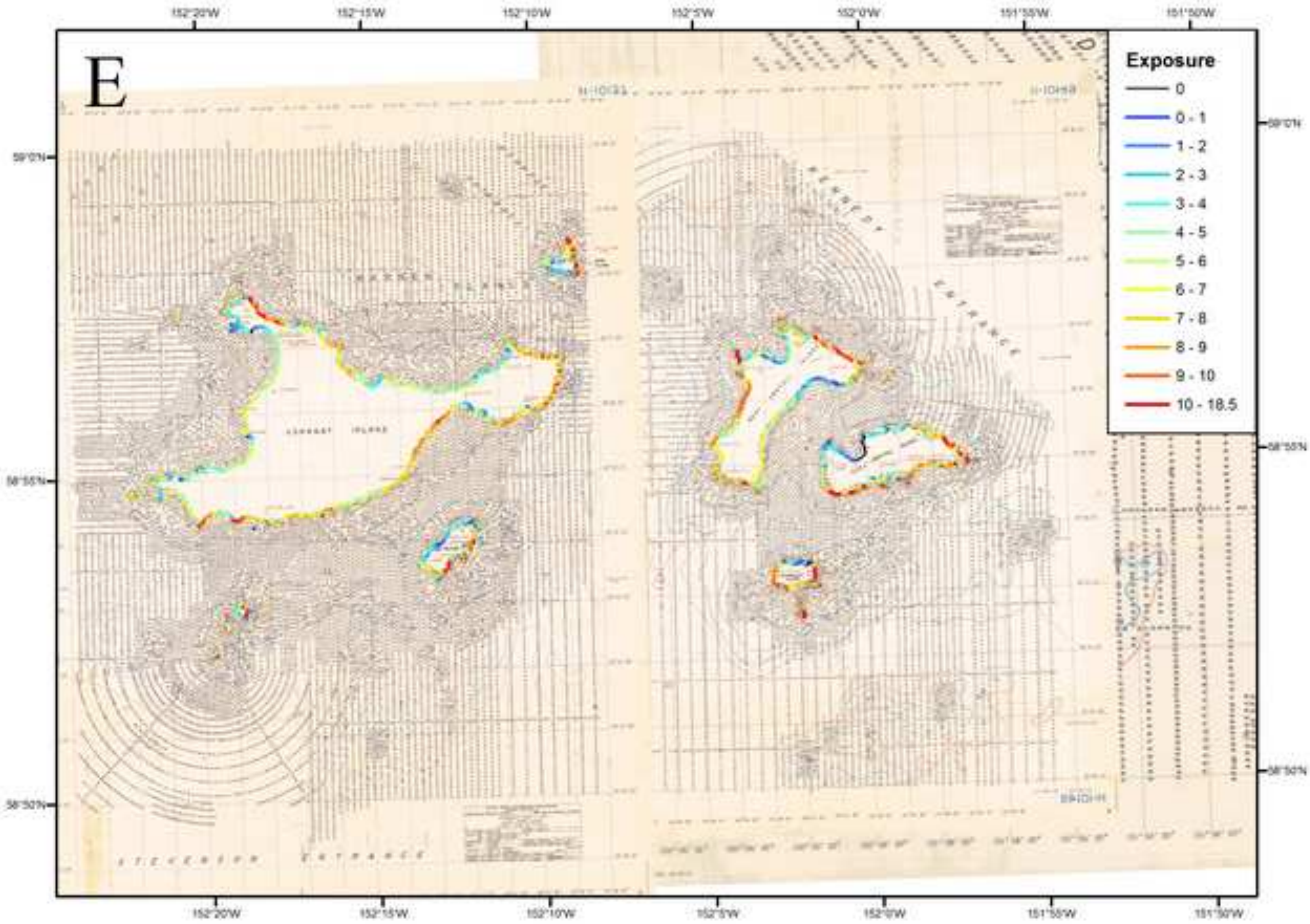

E
Exposure
0
0 - 1
1 - 2
2 - 3
3 - 4
4 - 5
5 - 6
6 - 7
7 - 8
8 - 9
9 - 10
10 - 18.5
152°20'W
152°15'W
152°10'W
152°5'W
152°0'W
151°55'W
151°50'W
59°0'N
58°55'N
58°50'N
BARREN ISLANDS
KENNEDY ENTRANCE
STEVENSON ENTRANCE

Figure6A

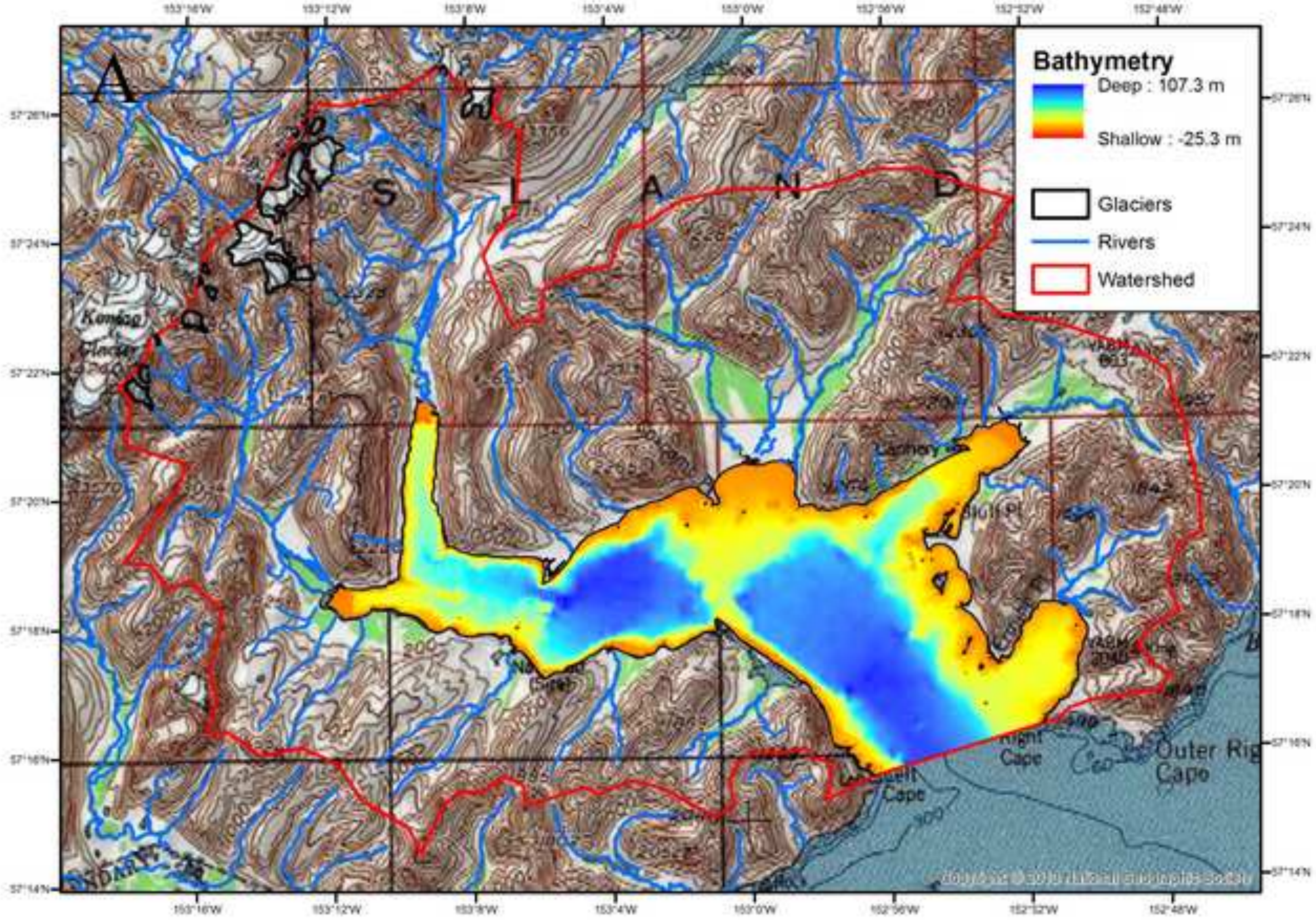

A
Bathymetry
Deep : 107.3 m
Shallow : -25.3 m
Glaciers
Rivers
Watershed
S
L
A
N
D
Outer Rig
Cape
153°16'W
153°12'W
153°8'W
153°4'W
153°0'W
152°56'W
152°52'W
152°48'W
57°26'N
57°24'N
57°22'N
57°20'N
57°18'N
57°16'N
57°14'N

Figure6B

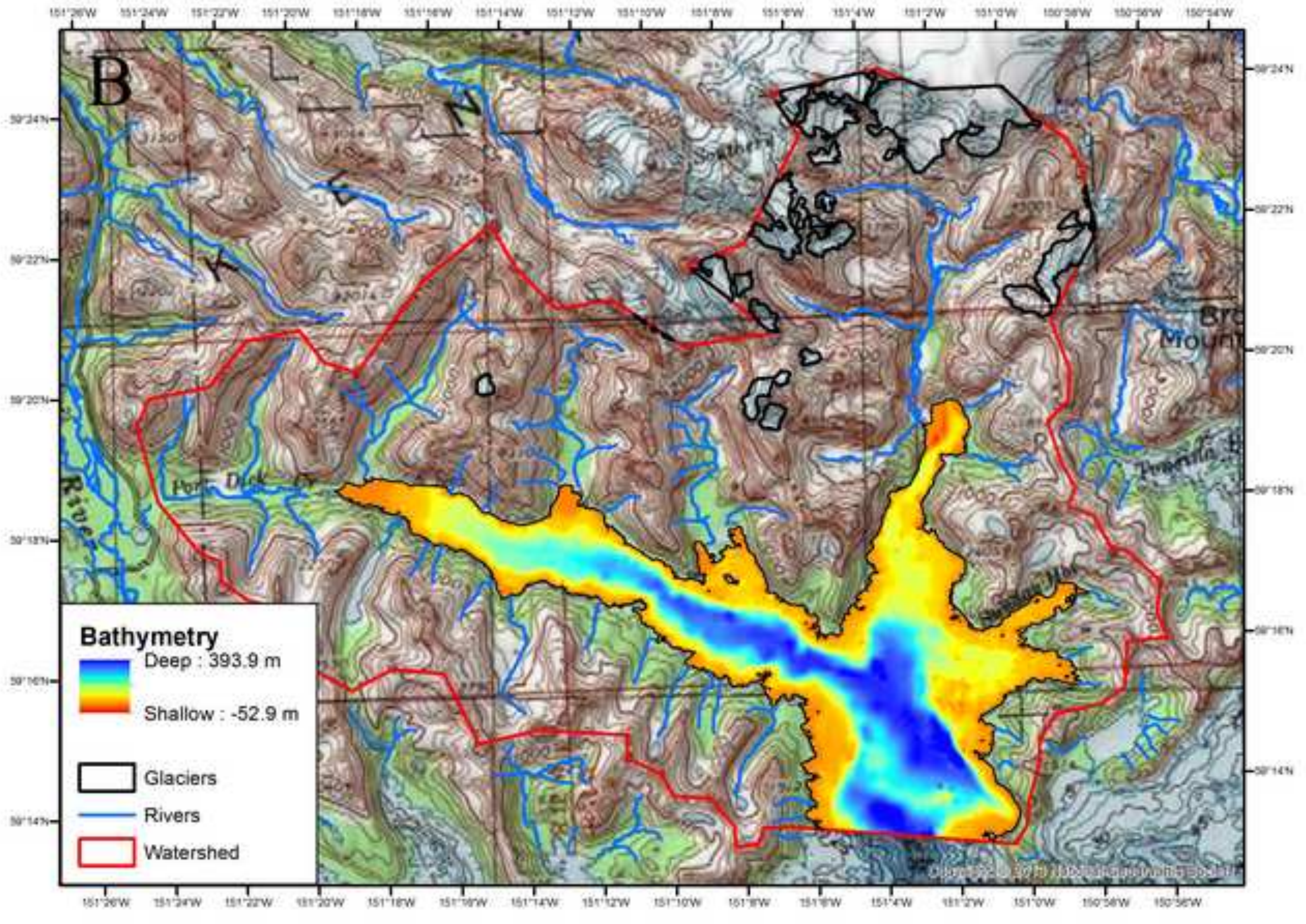

B
Bathymetry
Deep : 393.9 m
Shallow : -52.9 m
Glaciers
Rivers
Watershed
151°26'W
151°24'W
151°22'W
151°20'W
151°18'W
151°16'W
151°14'W
151°12'W
151°10'W
151°8'W
151°6'W
151°4'W
151°2'W
151°0'W
150°58'W
150°56'W
150°54'W
59°24'N
59°22'N
59°20'N
59°18'N
59°16'N
59°14'N
Port Dick Cr
River

Figure6C

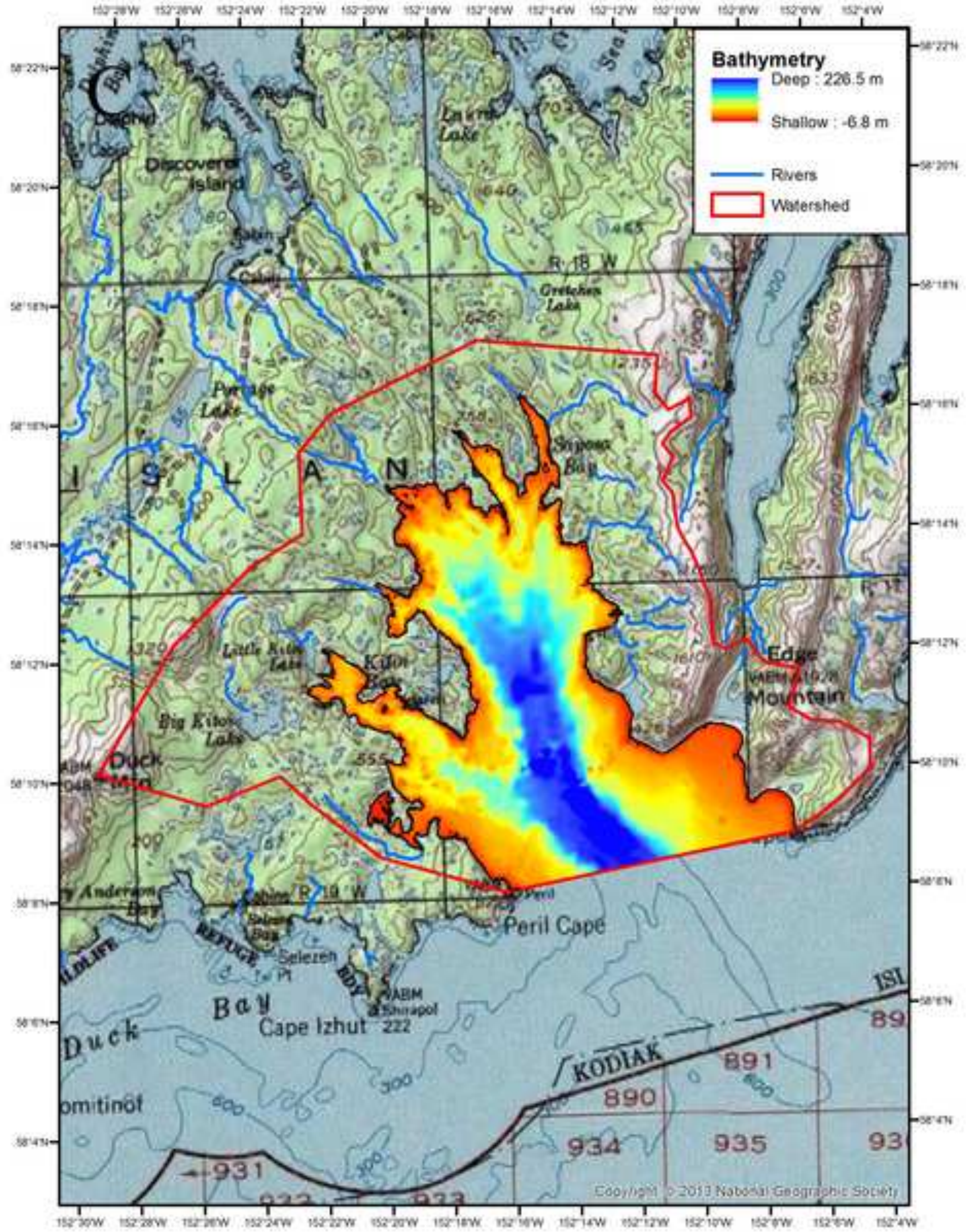

C
Bathymetry
Deep : 226.5 m
Shallow : -6.8 m
Rivers
Watershed
Discoverer Island
Portage Lake
Gretchen Lake
I S L A N D
Little Kitoi Lake
Big Kitoi Lake
Kitoi
Duck Mtn
Sitkinak Bay
Edge Mountain
Peril Cape
Selezen Pt
Cape Izhut
Duck Bay
KODIAK
R 18 W
R 19 W
152°30'W
152°28'W
152°26'W
152°24'W
152°22'W
152°20'W
152°18'W
152°16'W
152°14'W
152°12'W
152°10'W
152°8'W
152°6'W
152°4'W
58°22'N
58°20'N
58°18'N
58°16'N
58°14'N
58°12'N
58°10'N
58°8'N
58°6'N
58°4'N
Copyright © 2013 National Geographic Society

Figure6D

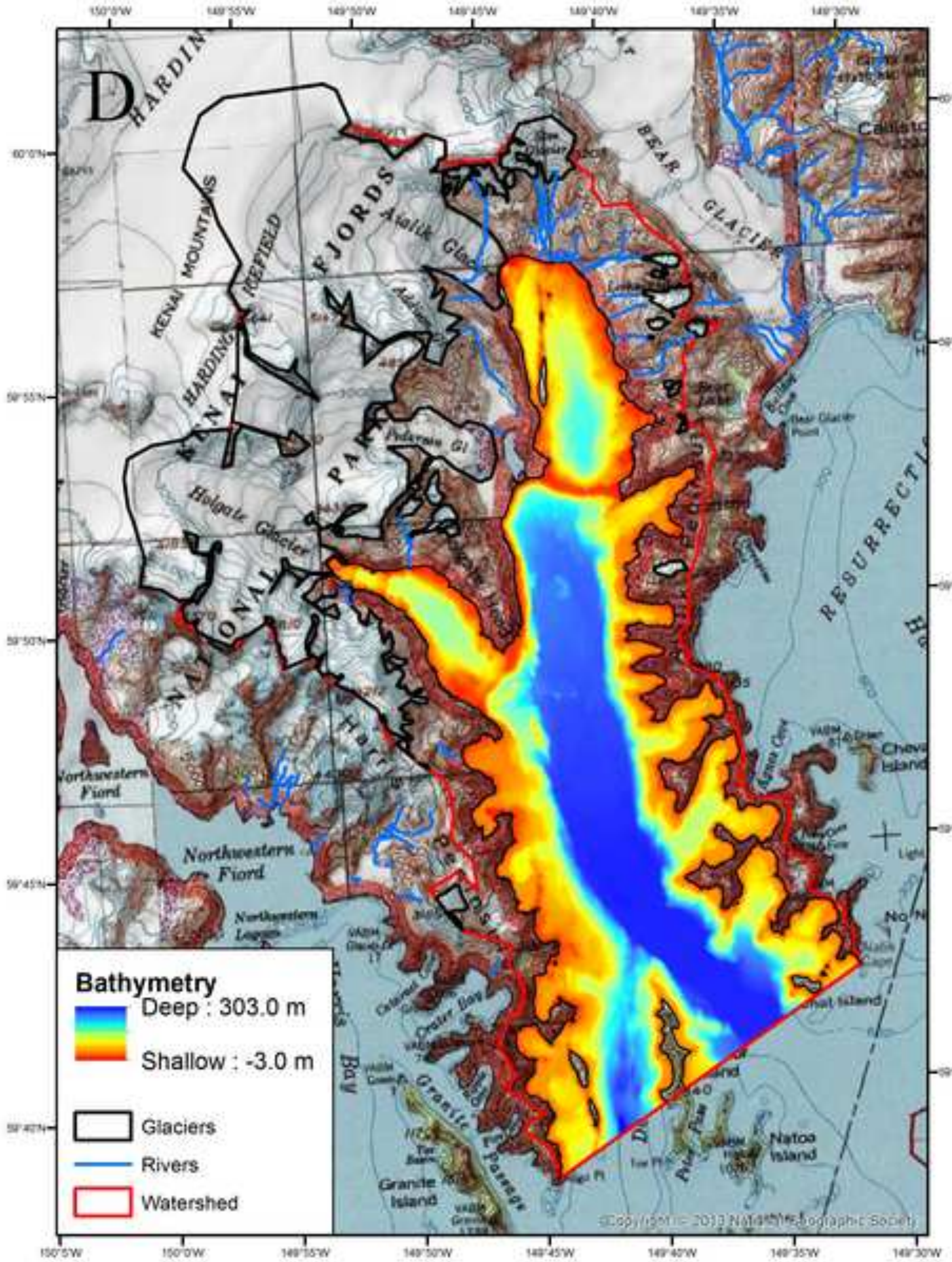

D
Bathymetry
Deep : 303.0 m
Shallow : -3.0 m
Glaciers
Rivers
Watershed
150°0'0"W
149°55'0"W
149°50'0"W
149°45'0"W
149°40'0"W
149°35'0"W
149°30'0"W
150°5'0"W
60°0'0"N
59°55'0"N
59°50'0"N
59°45'0"N
59°40'0"N
HARDING
KENAI MOUNTAINS
HARDING
ICEFIELD
KENAI
FJORDS
NATIONAL
PARK
Aialik Glacier
Pedersen Gl
Holgate Glacier
BEAR GLACIER
RESURRECTION
Northwestern Fiord
Northwestern Lagoon
Granite Passage
Granite Island
Natoa Island
Chiswell Island
Harris Bay
Copyright: © 2013 National Geographic Society

Figure6E

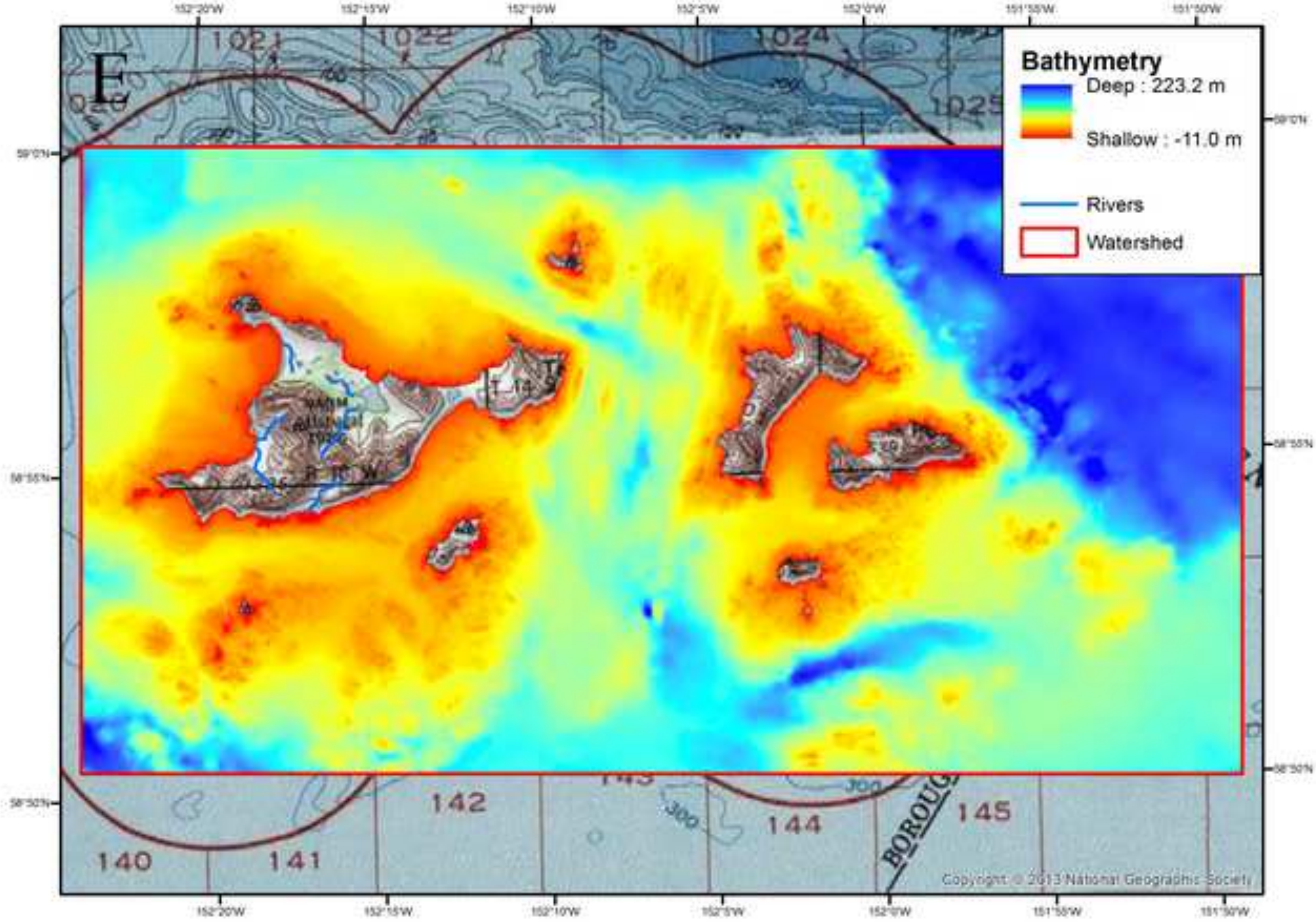

E
Bathymetry
Deep : 223.2 m
Shallow : -11.0 m
Rivers
Watershed
152°20'W
152°15'W
152°10'W
152°5'W
152°0'W
151°55'W
151°50'W
59°0'N
58°55'N
58°50'N
1021
1022
1024
1025
140
141
142
143
144
145
BOROUG
Copyright © 2013 National Geographic Society

Figure7A

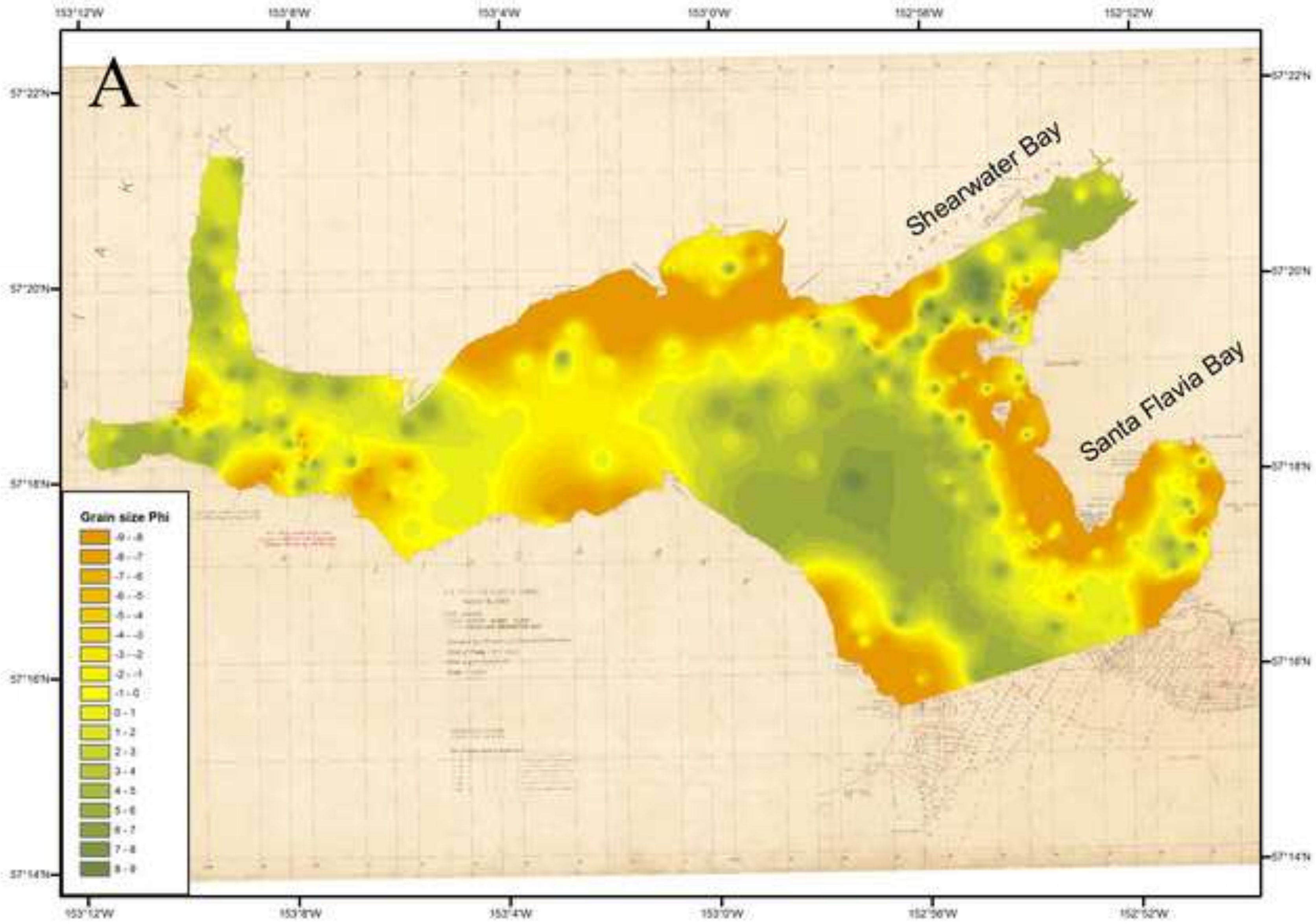

A
Shearwater Bay
Santa Flavia Bay
Grain size Phi
-9 - -8
-8 - -7
-7 - -6
-6 - -5
-5 - -4
-4 - -3
-3 - -2
-2 - -1
-1 - 0
0 - 1
1 - 2
2 - 3
3 - 4
4 - 5
5 - 6
6 - 7
7 - 8
8 - 9
153°12'W
153°8'W
153°4'W
153°0'W
152°56'W
152°52'W
57°22'N
57°20'N
57°18'N
57°16'N
57°14'N

Figure7B

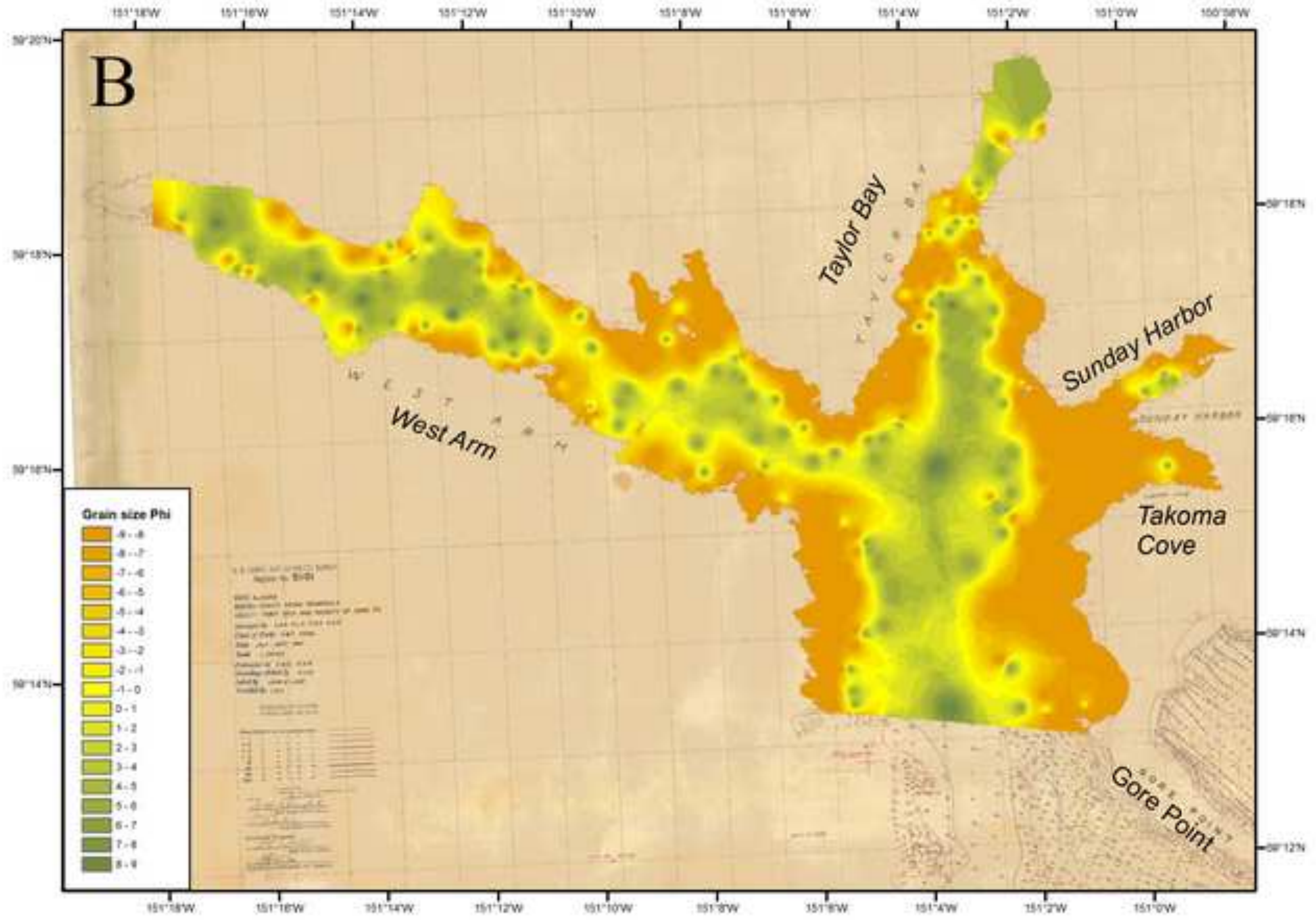

B
Taylor Bay
Sunday Harbor
West Arm
Takoma Cove
Gore Point
Grain size Phi
-9 - -8
-8 - -7
-7 - -6
-6 - -5
-5 - -4
-4 - -3
-3 - -2
-2 - -1
-1 - 0
0 - 1
1 - 2
2 - 3
3 - 4
4 - 5
5 - 6
6 - 7
7 - 8
8 - 9
151°18'W
151°16'W
151°14'W
151°12'W
151°10'W
151°8'W
151°6'W
151°4'W
151°2'W
151°0'W
150°58'W
59°20'N
59°18'N
59°16'N
59°14'N
59°12'N

Figure7C

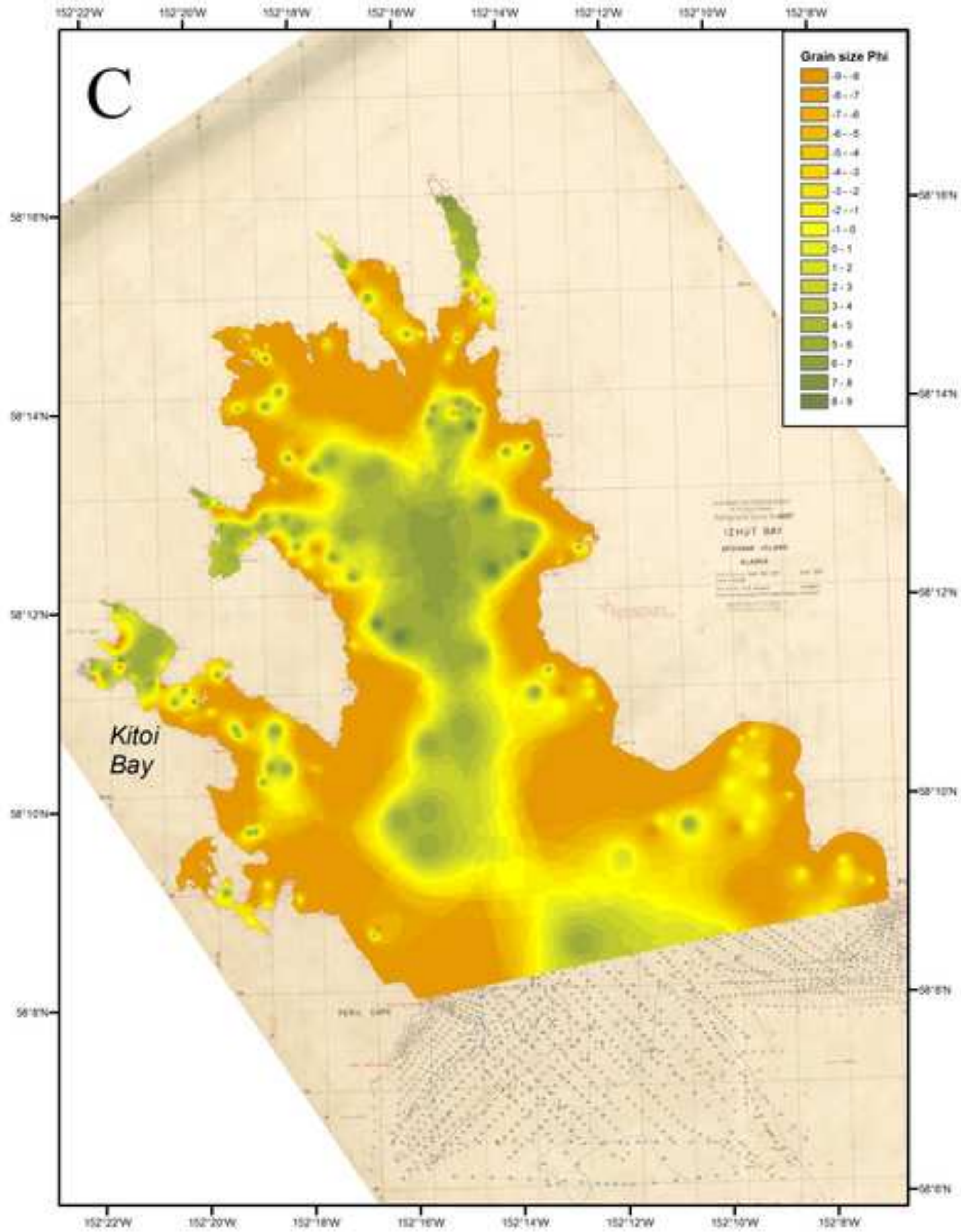

C
Grain size Phi
-9 - -8
-8 - -7
-7 - -6
-6 - -5
-5 - -4
-4 - -3
-3 - -2
-2 - -1
-1 - 0
0 - 1
1 - 2
2 - 3
3 - 4
4 - 5
5 - 6
6 - 7
7 - 8
8 - 9
Kitoi Bay
IZHUT BAY
152°22'W
152°20'W
152°18'W
152°16'W
152°14'W
152°12'W
152°10'W
152°8'W
58°16'N
58°14'N
58°12'N
58°10'N
58°8'N
58°6'N

Figure7D

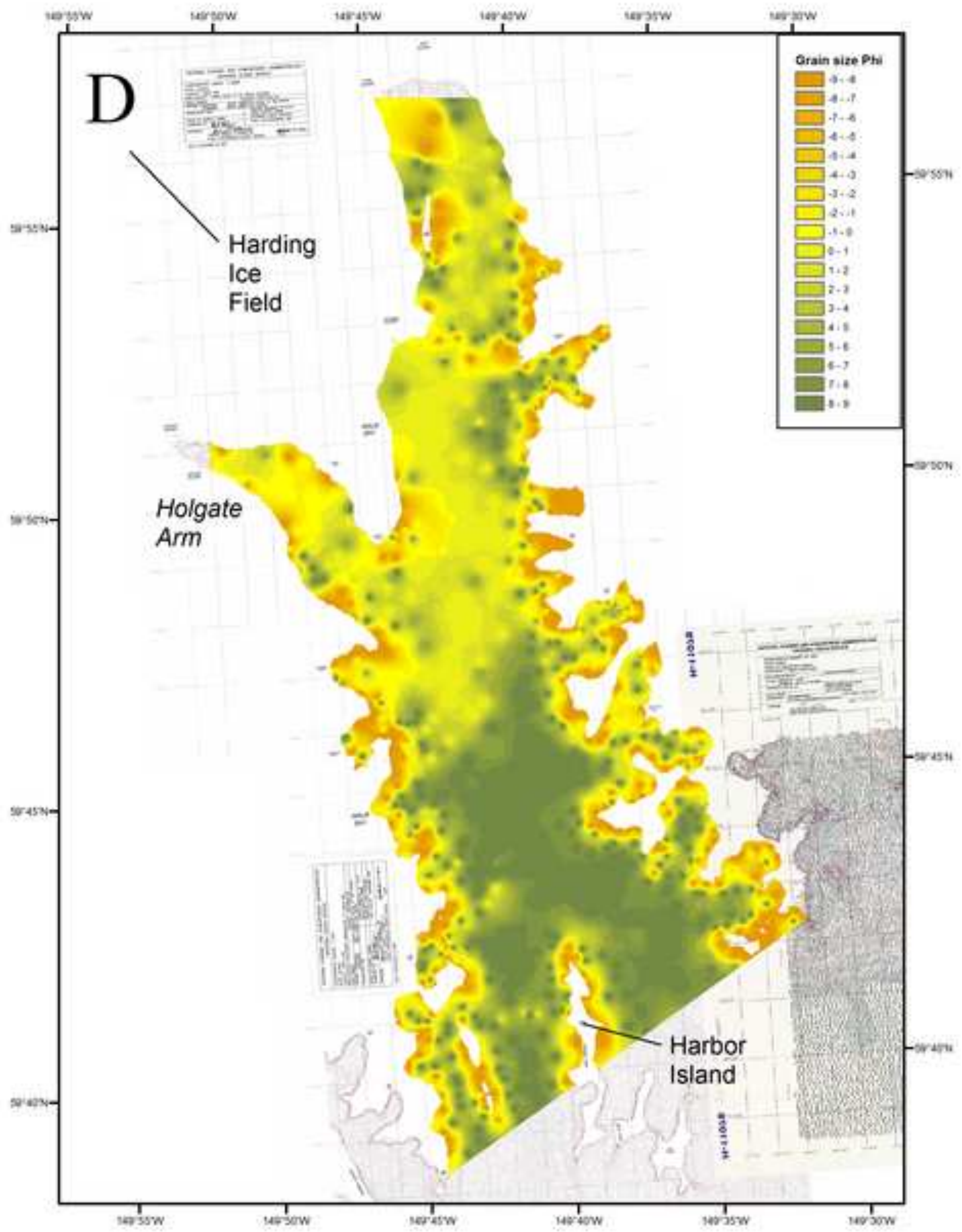

D
Harding Ice Field
Holgate Arm
Harbor Island
Grain size Phi
-9 - -8
-8 - -7
-7 - -6
-6 - -5
-5 - -4
-4 - -3
-3 - -2
-2 - -1
-1 - 0
0 - 1
1 - 2
2 - 3
3 - 4
4 - 5
5 - 6
6 - 7
7 - 8
8 - 9
149°55'W
149°50'W
149°45'W
149°40'W
149°35'W
149°30'W
59°55'N
59°50'N
59°45'N
59°40'N
H-11038

Figure7E

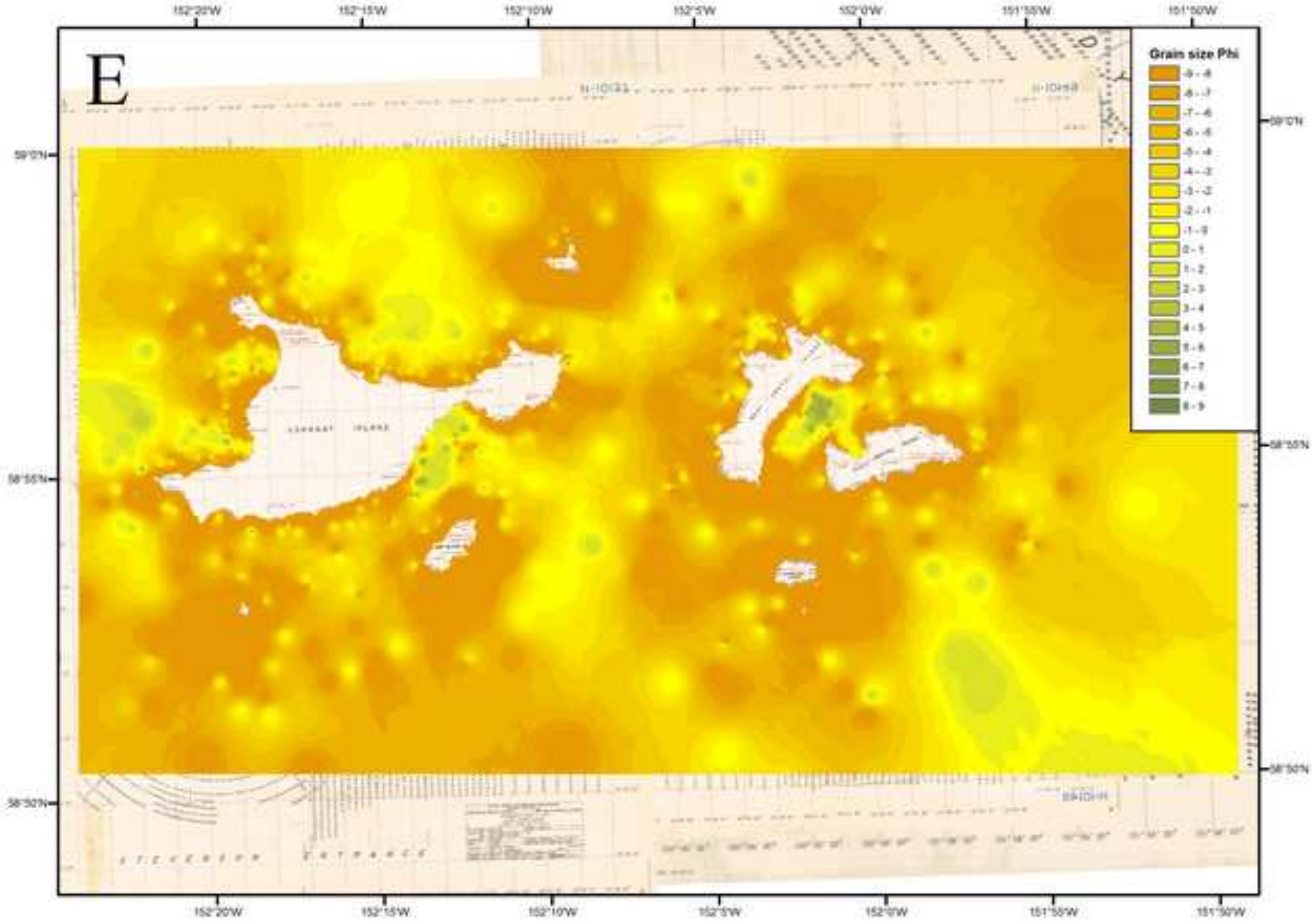
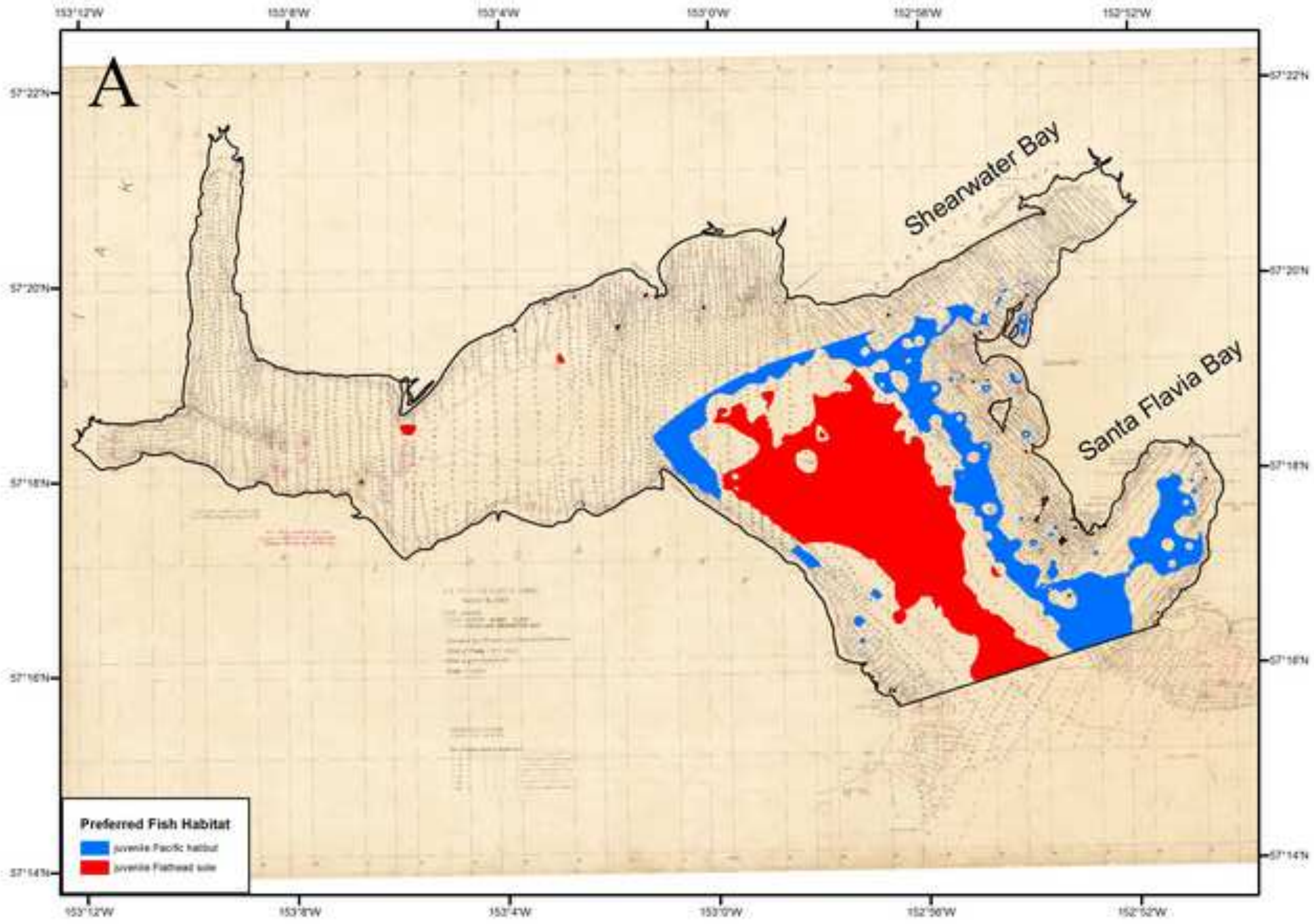

E
Grain size Phi
-9 - -8
-8 - -7
-7 - -6
-6 - -5
-5 - -4
-4 - -3
-3 - -2
-2 - -1
-1 - 0
0 - 1
1 - 2
2 - 3
3 - 4
4 - 5
5 - 6
6 - 7
7 - 8
8 - 9
152°20'W
152°15'W
152°10'W
152°5'W
152°0'W
151°55'W
151°50'W
59°0'N
58°55'N
58°50'N

Figure8A



A
Shearwater Bay
Santa Flavia Bay
Preferred Fish Habitat
🟦 juvenile Pacific halibut
🟥 juvenile Flathead sole
153°12'W
153°8'W
153°4'W
153°0'W
152°56'W
152°52'W
57°22'N
57°20'N
57°18'N
57°16'N
57°14'N

Figure8B

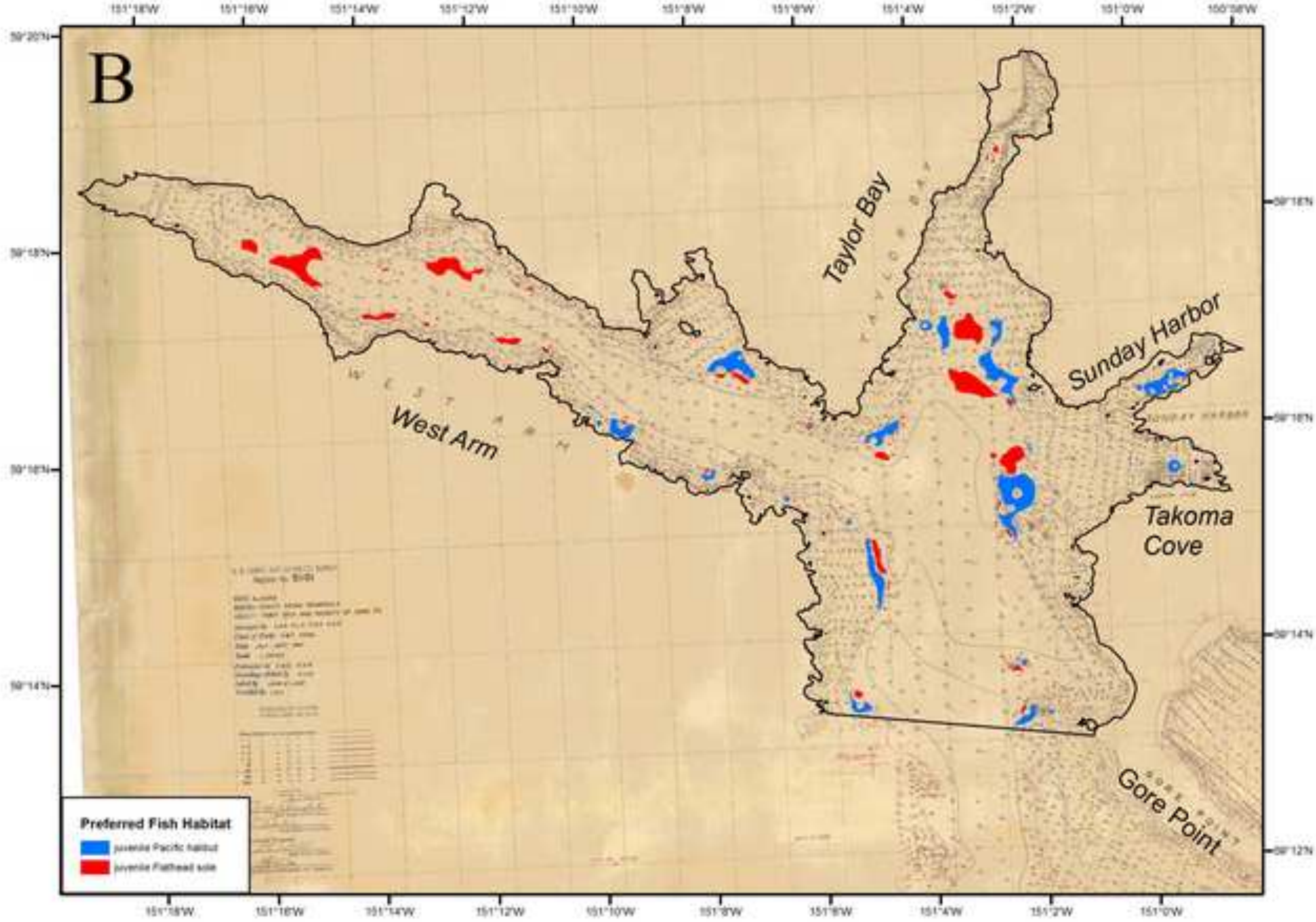

B
Taylor Bay
Sunday Harbor
West Arm
Takoma Cove
Gore Point
Preferred Fish Habitat
🟦 juvenile Pacific halibut
🟥 juvenile Flathead sole
151°18'W
151°16'W
151°14'W
151°12'W
151°10'W
151°8'W
151°6'W
151°4'W
151°2'W
151°0'W
150°58'W
59°20'N
59°18'N
59°16'N
59°14'N
59°12'N

Figure8C

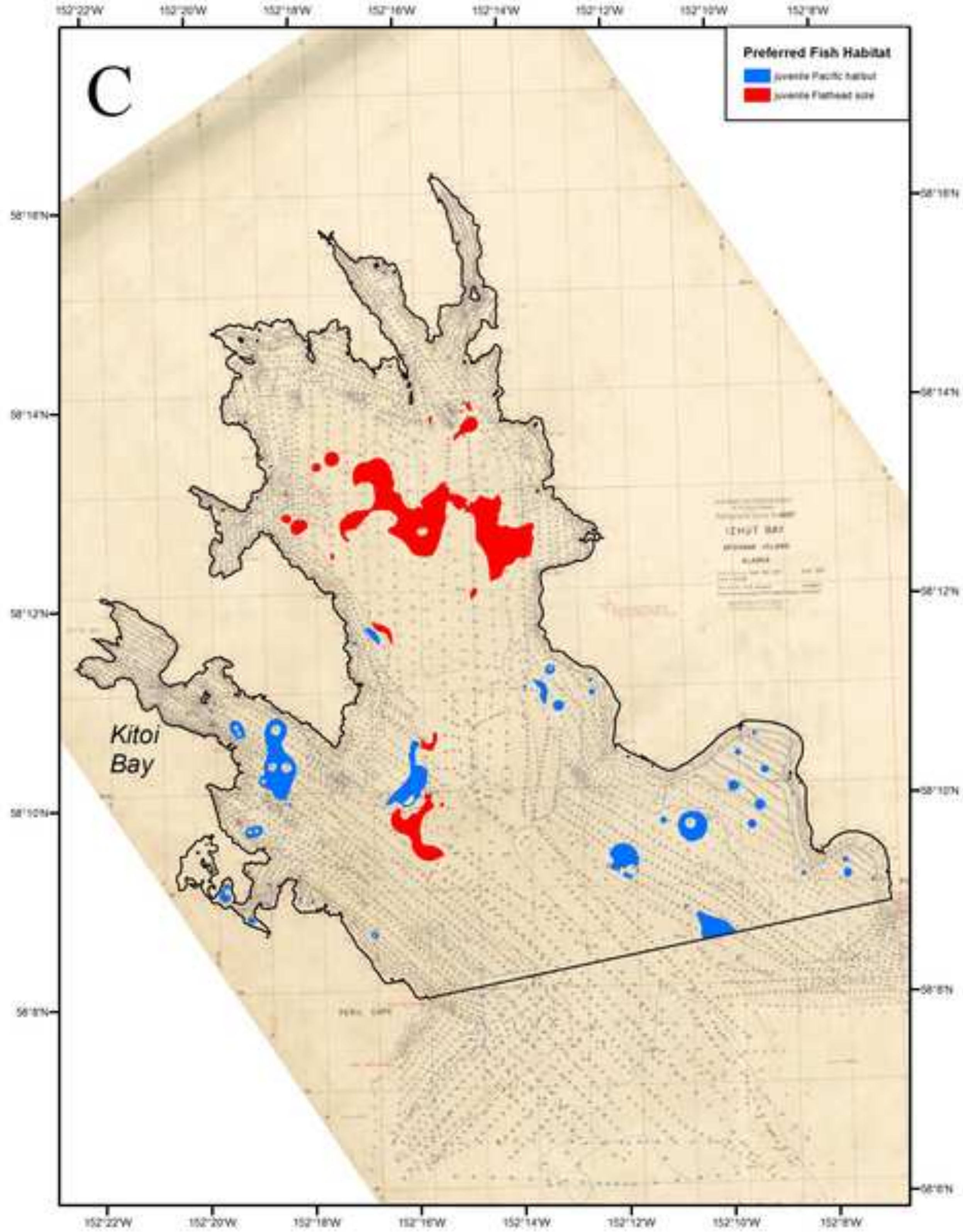
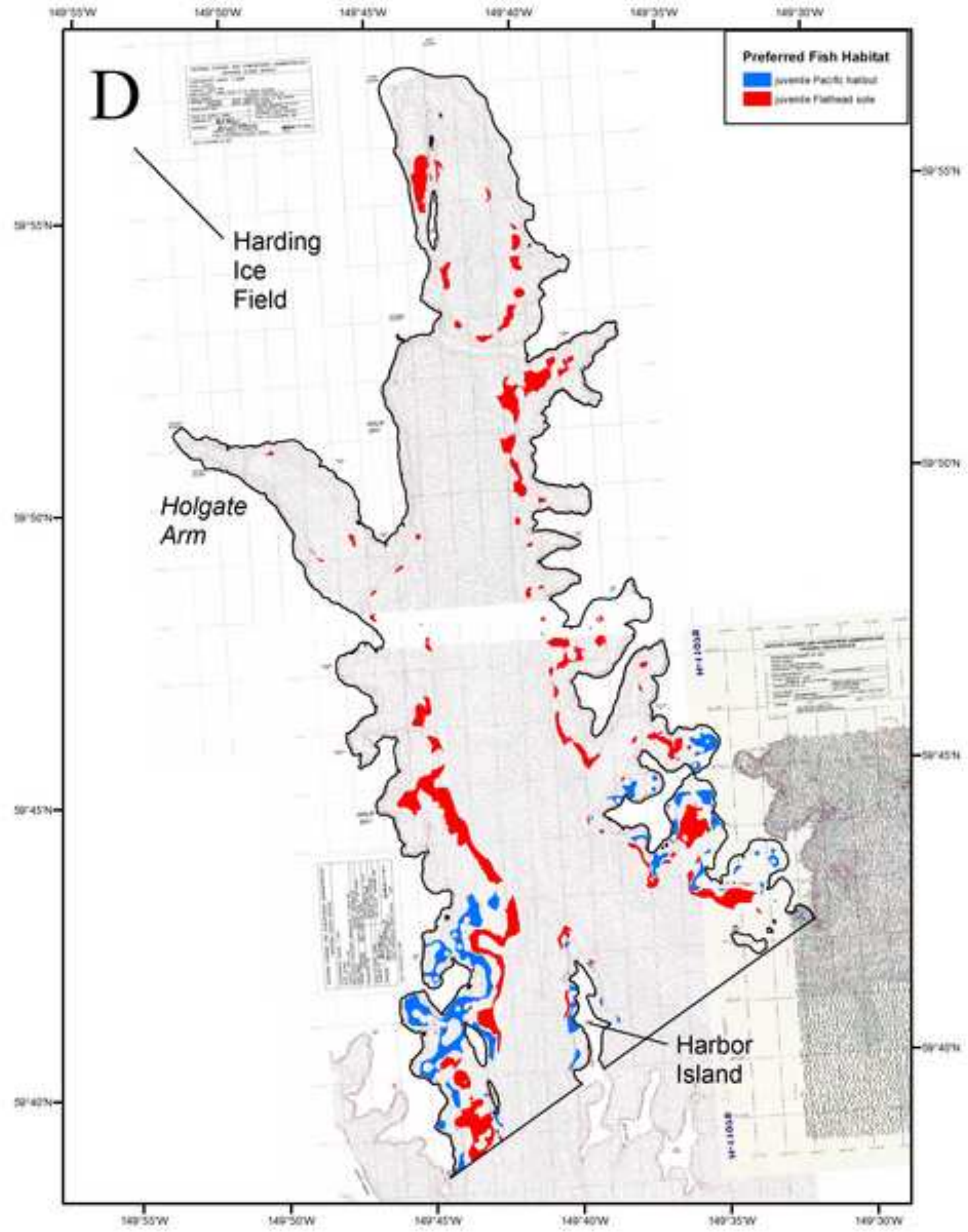

C
Preferred Fish Habitat
juvenile Pacific halibut
juvenile Flathead sole
Kitoi Bay
IZHUT BAY
152°22'W
152°20'W
152°18'W
152°16'W
152°14'W
152°12'W
152°10'W
152°8'W
58°16'N
58°14'N
58°12'N
58°10'N
58°8'N
58°6'N

Figure8D



D
Preferred Fish Habitat
🟦 juvenile Pacific halibut
🟥 juvenile Flathead sole
Harding
Ice
Field
Holgate
Arm
Harbor
Island
149°55'W
149°50'W
149°45'W
149°40'W
149°35'W
149°30'W
59°55'N
59°50'N
59°45'N
59°40'N

Figure8E

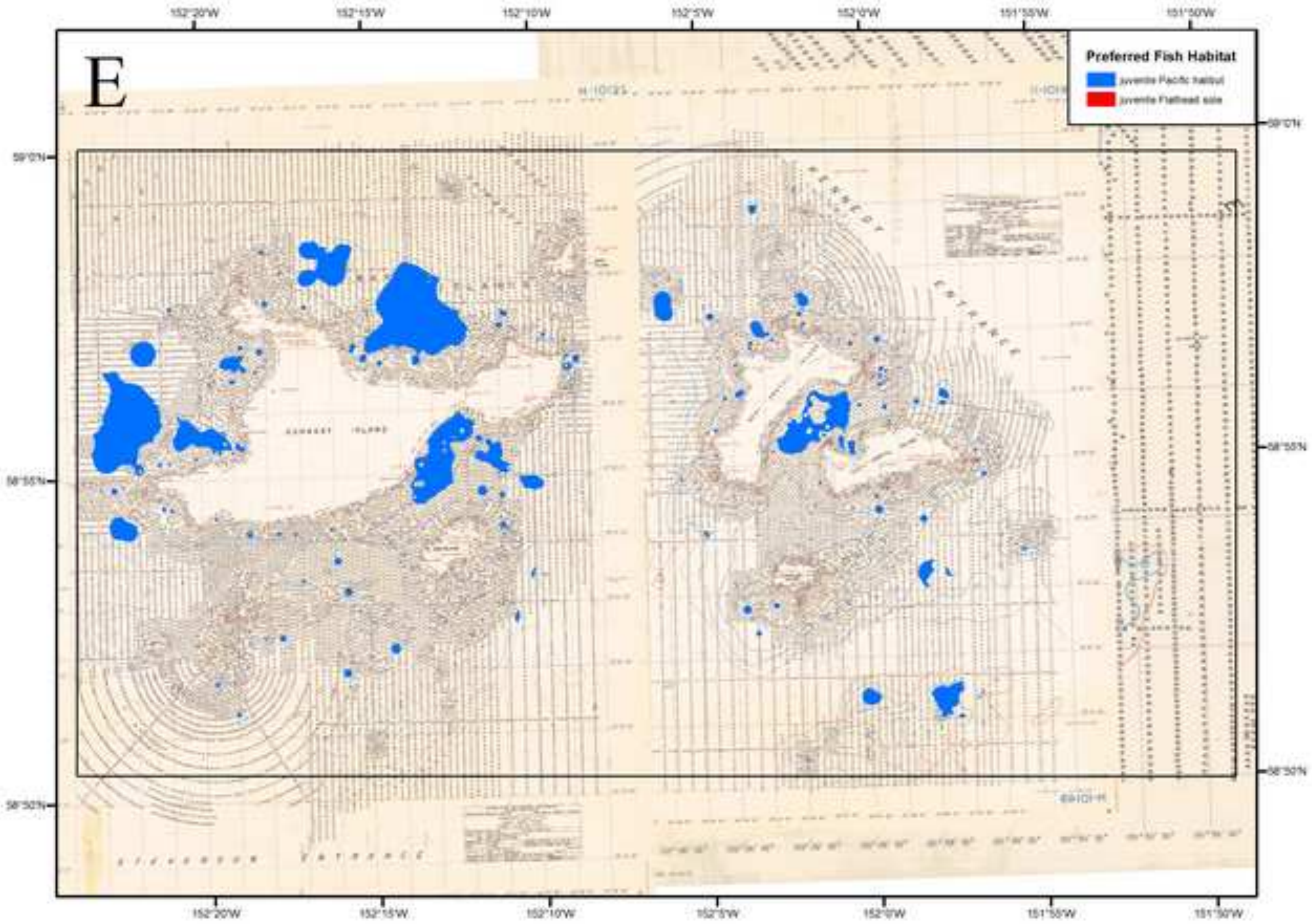

E
Preferred Fish Habitat
🟦 juvenile Pacific halibut
🟥 juvenile Flathead sole
152°20'W
152°15'W
152°10'W
152°5'W
152°0'W
151°55'W
151°50'W
59°0'N
58°55'N
58°50'N
H-10123
H-10148
KENNEDY ENTRANCE
STEVENSON ENTRANCE

Table. 1. Shoreline measures for the five study sites, with length of shoreline calculated from digitizing the shoreline on the smooth sheets.

	Kiliuda Bay	Izhut Bay	Barren Islands	Port Dick	Aialik Bay
Shore length (m)					
Mainland	88,911	99,539	73,198	89,945	195,199
Islands	6,699	13,327	31,283	14,529	31,285
Mouth	5,170	8,880	102,591	4,521	13,480
Mouth openness	5.4%	7.9%	98.2%	4.3%	6.0%
Shore buffers					
100 m (km^2)	9.1	10.2	10.5	9.6	20.7
1000 m (km^2)	66.5	51.7	110.3	51.9	150.0
100 m	9.6%	11.3%	1.9%	14.7%	8.7%
1000 m	70.7%	57.5%	19.8%	79.5%	62.7%
Shoreline exposure (range 0 to 10)*					
Mean	2.4	2.2	6.0	1.8	1.2
Full	8%	7%	12%	6%	0%
Partial	29%	37%	85%	26%	43%
Zero	63%	58%	3%	68%	57%

* Shoreline exposure: 10 of 10 possible intersections is Full, 1 to 9 of 10 is Partial, and 0 of 10 is Zero. Mean is the length-weighted average of exposure of all shoreline segments.

Table. 2. Bathymetric measures for the five study sites.

	Kiliuda Bay	Izhut Bay	Barren Islands	Port Dick	Aialik Bay
Depth (m)					
MHW	-2.41	-2.71	-3.93	-3.45	-2.96
Interpolated Avg.	47	69	86	100	141
Max. Sounding	106	220	221	291	303
Slope (steepness in degrees)					
Average	3.4	5.7	2.4	10.9	8.1
Maximum	39.6	53.8	59.6	67.0	80.1
Area <1.000	32.7%	11.4%	33.4%	7.0%	19.9%
Rugosity (true surface area/planimetric area)					
Average	1.005	1.009	1.001	1.036	1.018
Maximum	1.301	1.697	2.015	2.565	6.492
Area <1.001	58.8%	30.8%	64.0%	12.6%	32.2%

Table. 3. Surface area measures for the five study sites.

	Kiliuda Bay	Izhut Bay	Barren Islands	Port Dick	Aialik Bay
Water surface (km^2)*					
MHW	93.5	89.5	557.5	64.4	239.1
MLLW	88.3	84.5	552.4	58.7	236.0
Tidal exposure	5.2	5.0	5.1	5.7	3.1
Tidal exp./MHW	5.5%	5.6%	0.9%	8.9%	1.3%
50 m	42.9	47.3	426.6	37.6	186.4
100 m	0.6	24.2	194.0	26.7	132.8
Islands					
Area (km^2)	0.2	0.1	41.4	0.2	3.3
Percent of site	0.2	0.2	6.9	0.3	1.4
Mouth cross-section					
Opening (km^2)	0.3	0.7	12.4	0.6	2.1
Divided by MHW	0.3%	0.8%	2.2%	0.9%	0.9%

*Water surface area is calculated at four depths: MHW, MLLW, 50 m and 100 m. This process can be envisioned by starting with a study site with the water level at MHW, then draining the water level down to MLLW, then to 50 m, then to 100 m in depth.

Table. 4. Water volume measures for the five study sites.

	Kiliuda Bay	Izhut Bay	Barren Islands	Port Dick	Aialik Bay
Water volume (km^3)*					
MHW	4.6	6.5	50.7	6.8	34.4
MLLW	4.4	6.3	48.5	6.6	33.7
Tidal prism	0.2	0.2	2.2	0.2	0.7
Tidal prism/MHW	4.7%	3.6%	4.3%	3.0%	2.0%
Below 50 m	1.3	2.9	23.1	4.2	23.1
Below 100 m	0.0	1.2	7.2	2.6	15.2
Tidal refill days	9.7	14.0	11.6	16.4	24.6
Watersheds					
Area (km^2)	460	244	41	329	594
Ratio to bay area	3.9	1.7	0.1	4.0	1.4
Runoff (km^3)	0.97	0.27	0.08	0.69	1.13
Ratio to bay volume	0.209	0.042	0.002	0.102	0.033
Runoff refill years	4.8	23.6	602.7	9.8	30.6
Glacier					
Area (km^2)	5.4	0	0	16.0	192.6
%Watershed	1.2	-	-	4.9	32.4

*Water volume is calculated below four depths: MHW, MLLW, 50 m and 100 m. This process can be envisioned by starting with a study site with the water level at MHW, then draining the water level down to MLLW, then to 50 m, then to 100 m in depth.

Table. 5. Features and substrate measures for the five study sites.

	Kiliuda Bay	Izhut Bay	Barren Islands	Port Dick	Aialik Bay
Features (km^2)					
Reefs	0.157	0.004	0.549	0.005	0.000
Kelp	0.346	3.862	5.704	1.020	0.322
%Reefs	0.18	0.00	0.10	0.01	0.00
%Kelp	0.39	4.57	1.03	1.74	0.14
Count of substrates					
From soundings	313	276	719	296	849
From features	384	780	1,099	457	100
Total	697	1,056	1,818	753	949
Count/km^2	7.41	11.75	3.26	11.53	3.97
Substrate measures					
Mean phi	-0.5	-3.3	-4.8	-2.2	2.0
Median phi	0.4	-4.3	-5.1	-1.8	1.8
Area mud	19.8%	13.4%	0.1%	14.9%	37.5%

Table. 6. Predicted preferred habitat for Pacific halibut (*Hippoglossus stenolepis*) and Flathead sole (*Hippoglossoides elassodon*) from Norcross et al. (1997) for the five study sites.

	Kiliuda Bay	Izhut Bay	Barren Islands	Port Dick	Aialik Bay
Area (km^2)					
P. halibut	8.7	2.1	19.8	1.5	5.9
Flathead sole	12.5	3.5	0.0	1.3	12.8
Percent					
P. halibut	9.4	2.3	3.6	2.3	2.5
Flathead sole	13.4	3.9	0.0	2.0	5.3