Comparison of the physical attributes of the central and eastern Gulf of Alaska Integrated Ecosystem Research Program inshore study sites

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Abstract

In this analysis, five eastern Gulf of Alaska (eGOA) inshore study sites from the North Pacific Research Board's (NPRB) Gulf of Alaska Integrated Ecosystem Research Program (GOAIERP: http://www.nprb.org/gulf-of-alaska-project) were characterized using multiple Geographic Information System (GIS) physical measurements including water volume, surface area, and shoreline length. These eGOA sites include three small bays (Islas Bay, Torch Bay and Graves Harbor), a large semi-protected body of water (Salisbury Sound), and a large bay (Whale Bay). These measurements provide quantitative metrics of study sites that may aid in the interpretation of biological differences among the sites. The analysis is similar to a previously published study of five central Gulf of Alaska (cGOA) sites that also included three small bays, an unprotected body of water, and a large bay. In addition, this analysis included new measures of the surface area of lakes within each sites' watershed, and the amount of nearby shallow (< 200 m) continental shelf area. Multivariate analyses were used to examine similarities among the cGOA and eGOA sites and suggested that location and size were both important grouping factors, with the cGOA and eGOA small bays forming unique groups. The cGOA non-bay and large-bay sites were the most distinct locations. It appears that there is some link between geographic location and physical similarity of study sites chosen for the GOAIERP.

Keywords: USA, Alaska, Gulf of Alaska, Fish, Habitat, Bathymetry, GIS metrics

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1. Introduction

Comparison of study sites is a potentially important part of assessing field results obtained from different locations, as were obtained during inshore surveys conducted by the middle trophic level (MTL) group of the North Pacific Research Board's (NPRB) Gulf of Alaska Integrated Ecosystem Research Program (GOAIERP; Ormseth et al., 2017). The goal of GOAIERP was to describe factors, including advection of larvae to appropriate settlement areas, that determine year-class strength of five focal species: arrowtooth flounder (*Atheresthes stomias*), Pacific ocean perch (*Sebastes alutus*), sablefish (*Anoplopoma fimbria*), Pacific cod (*Gadus macrocephalus*), and walleye pollock (*Gadus chalcogrammus*). This knowledge can help to improve commercial fisheries management and further an ecosystem approach to management. During 2011 and 2013 inshore study sites were sampled by GOAIERP MTL researchers to quantify the abundance and distribution of the focal species and other fishes. The sampling also included habitat descriptions and analyses of fish diets. These inshore study sites, most of which are bays, are hypothesized to be important settlement habitat for juvenile groundfish seeking a suitable place for settlement (Bailey and Picquelle, 2002). For the purposes of this project, the inshore study sites can be thought of as transition sites between the oceanic and terrestrial ecosystems, with bay size, depth, volume and other factors influencing the oceanic or terrestrial influence at each site.

Prior to GOAIERP, there have been multiple juvenile groundfish habitat surveys in the GOA that determined important factors in the preferred habitat of groundfish juveniles, and it might have been useful to those authors to have a full catalog of measurements of their study sites. For example, a researcher might want to know if a particular sample (e.g. a station) is typical for the entire study site (e.g. a bay), or if a study site is typical of other study sites (e.g.

other bays), such that results can be expanded across a larger area. Is a study site unusually deep or shallow, subject to large runoff or high tidal exchange, or relatively open to the ocean? Is the shoreline exposed or protected, is the seafloor steep or smooth, or composed of small or large grain sizes?

Location is often recognized as a key factor by researchers in describing groundfish or invertebrate habitat, but there is often a lack of information to describe location beyond geographic position (i.e. latitude and longitude). Latitude has also been used as a proxy for solar-related variables such as seasonality, day length, and incident solar radiation while longitude has been used as a substitute for west-east distance. Studies that relied solely on geographic position include analyses of Pacific halibut (*Hippoglossus stenolepis*) abundance conducted in the 1960s by the International Pacific Halibut Commission (IPHC; Best, 1969) and groundfish abundance estimation performed in the 1980s by the National Marine Fisheries Service (NMFS) and the Alaska Department of Fish and Game (ADFG; Smith et al., 1984; Walters et al., 1985).

More recently, analyses of groundfish distributions have included latitude and longitude as factors in addition to other habitat descriptors. Norcross et al. (1997) visited 169 stations within approximately 16 inshore sites and bays, addressing the location issue at Kodiak Island by completely circumnavigating the island. In a later study, study sites were categorized *post hoc* into open, intermediate or closed (width divided by length of bay) to test whether this affected species composition (Norcross et al., 1999). Woodby et al. (2009) divided study sites into zones north and south of the Aleutian Islands (AI) as a proxy for how coral growing conditions might vary between northern and southern study sites. Also working in the AI, Reuter and Spencer (2007) used longitude as an environmental parameter to describe rockfish (*Sebastes* spp.) communities in NMFS bottom trawl surveys. Using both latitude and longitude, Bizarro et al.

(2014) described skate distributions off California and in the GOA, and Duffy-Anderson et al. (2003) described juvenile pollock distributions in the GOA and eastern Bering Sea (EBS). Sigler et al. (2015) distinguished between EBS slope and submarine canyon areas by using a suite of physical measurements that included latitude and longitude to analyze fish and invertebrate communities. In addition, longitude was an important factor in modeling the distribution of juvenile and adult Pacific ocean perch in the Aleutian Islands (Laman et al., 2015).

As the latter studies suggest, analyses of fish ecology can benefit from supplementing latitude and longitude with quantitative measures describing physical attributes of study sites that might have an influence on the species of interest. This manuscript continues earlier work which used metrics derived in a Geographic Information System (GIS) to quantify the physical characteristics of five GOAIERP inshore study sites in the central Gulf of Alaska (cGOA; Kiliuda Bay, Izhut Bay, the Barren Islands, Port Dick and Aialik Bay; Zimmermann et al., 2015). The metrics of each study site (including water volume, average depth, openness to the ocean, exposure of shoreline, watershed size, estimated annual freshwater runoff, and mean and median grain size; Zimmermann et al., 2015) were based on smooth sheets, the highly detailed and hand-drawn nautical charts that were the precursors to the navigational charts published by the National Ocean Service (NOS; Zimmermann and Benson, 2013). The results of the cGOA analysis have been used to improve the planning of GOAIERP field studies as well as to help with the interpretation of results. For example, smooth-sheet bathymetry was used to properly position a current meter deployed in Cross Sound in the eastern GOA (Phyllis Stabeno, NOAA, pers. comm.) and the identification of a shallow sill dividing Kiliuda Bay in the cGOA aided in the understanding of hydrographic variation within the bay (Olav Ormseth, NMFS, pers. comm.).

In this paper a similar analysis was applied to an additional five GOAIERP sites in the eastern GOA (Islas Bay, Torch Bay, Graves Harbor, Salisbury Sound and Whale Bay; Fig. 1). The approach originally used to describe the cGOA sites is expanded here to include two additional metrics. An additional measure of lakes within each watershed was incorporated for both cGOA and eGOA sites due to an unusually large lake noticed in the Islas Bay watershed, Lake Elfendahl, which is about half the size of the bay. Continental shelf width was hypothesized early in the GOAIERP planning to have a significant impact on possible differences between cGOA and eGOA study sites (Mueter and Norcross, 2002), as the shelf is much wider in the cGOA than the eGOA (Fig. 1). Therefore a measure of the area of seafloor shallower than 200 m within 100 km of the mouth of each site was added to the current analysis. All metrics for all 10 study sites were analyzed with clustering and ordination methods to group similar study sites together in order to determine if bays are more similar to each other by size (small, large, or non-bay site) or by location (cGOA versus eGOA).

2. Materials and methods

Most of the methods in the analysis of eGOA study sites closely followed the previously published analysis of cGOA sites (Zimmermann et al., 2015) to facilitate regional comparison and for consistency in results for use by other scientists. One exception is the use of an updated version of ArcMap GIS software (from v.10.0 to 10.2.2, ESRI, Redlands, CA). The National Geophysical Data Center (NGDC; http://www.ngdc.noaa.gov) was again utilized as the source of smooth sheets and unproofed digital bathymetry. The bathymetry data obtained from NGDC were edited and relevant smooth-sheet elements such as features, shorelines, and sediment grain size were digitized. All work was done in the horizontal North American Datum of 1983 (NAD83) and in the vertical datum of mean high water (MHW).

2.1. Smooth sheets

In general, the smooth sheets for the eGOA sites were a few years older and of the same scale as for the cGOA, but were less detailed than for the cGOA sites (Table 1 provides smooth sheet numbers, years and scales; Figs. 2A-2E show partly obscured smooth sheets). Three study sites were completely covered by single smooth sheets: Islas Bay was covered by NOS smooth sheet H04527 (Fig. 2A), while Torch Bay (Fig. 2B) and Graves Harbor (Fig. 2C), which are separated by a very short distance, were both covered by NOS smooth sheet H04640. At Islas Bay, the digitized bathymetry needed to be shifted about 220 m NNE to align with smooth sheet H04527. For Torch Bay and Graves Harbor the digital bathymetry from NGDC was fairly complete and needed slight horizontal distorting (see Fig. 20, Zimmermann and Benson, 2013) to align with smooth sheet H04640 (Table 1).

Salisbury Sound was well-covered with smooth sheets from five relatively recent NOS multibeam surveys (Fig. 2D). These smooth sheets provided a small subset of soundings from the millions of multibeam bathymetry observations, similar to the spatial resolution of soundings from smooth sheets at other study sites. To be more consistent with other study sites, we used this heavily subsampled version of bathymetry rather than available multibeam bathymetry rasters. These smooth sheets also supplied inshore features (e.g. kelp beds and rocky reefs), but the shoreline was coarser and there were fewer sediment descriptions (n = 54) relative to other sites. The coarse shoreline, with a mean segment length of 23.3 m, was retained rather than trying to digitize a more detailed shoreline from older data even though shorelines at the other sites were finer (3.0 – 17.0 m). The SS multibeam surveys contained few sediment observations within the bounds of SS, so these were supplemented with sediments from older smooth sheets (n = 452; Table 6).

Only the upper reaches of Whale Bay (Fig. 2E) were covered by NOS smooth sheet H04431. The NOS smooth sheet H04430, covering the rest of Whale Bay, could not be located and NOS Chart 17328 (Scale 1:40,000), which was derived from H04430, was used as a substitute. The digitized NGDC bathymetry needed to be shifted horizontally about 180 m NNE, and soundings, shoreline, features and sediments were digitized from NOS Chart 17328 in order to cover the lower half of the study area.

2.2. Bathymetry interpolation

The individual soundings were combined with shoreline points (defined as the vertical elevation of MHW) and gridded with a 20 m cell size at all sites using a slightly different method than in the original analysis for the cGOA (Zimmermann et al., 2015). Instead of interpolating a raster surface using a spline function in ArcMap, which produced some small, deep holes in the cGOA bathymetry surfaces (Zimmermann et al., 2015), these artifacts were avoided by first converting the bathymetry soundings (points) into a triangulated irregular network (TIN) which utilizes angled triangles drawn between the bathymetry data points. The TIN was then converted into a 20 m raster surface using local area weighting ("natural neighbors" function in ArcMap). The initial TIN result is a stiff, angular, literal surface, while the resulting raster is a smoother surface that stays within the bounds of the input TIN.

2.3. Shoreline creation

Shoreline was digitized by hand for four of the eGOA sites, rather than following the semi-automated vectorization process (see Zimmermann and Benson, 2013) used for the cGOA sites. The exception was Salisbury Sound, where the shoreline was downloaded as the continually updated shoreline product (CUSP; produced from aerial photos in conjunction with the multibeam surveys) from the National Geodetic Survey (NGS) via the NOAA Shoreline Explorer web site (http://www.ngs.noaa.gov/NSDE/). In general CUSP shorelines do not follow smooth sheet shorelines because the CUSP is derived from the T-sheet (topographic sheets created by the NGS for depicting shoreline prior to a hydrographic survey: http://nosimagery.noaa.gov/images/shoreline_surveys/survey_scans/NOAA_Shoreline_Survey_Scans.html), and the smooth sheet shoreline is derived during the bathymetry surveys. In Salisbury Sound, however, the multibeam smooth sheets appear to have utilized the T-sheet shoreline rather than deriving their own. Still, the Salisbury Sound multibeam smooth sheets showed where the vessel interpretation of the shoreline differed from the aerial interpretation of the T-sheets and these empirical differences (n = 33) were incorporated into the shoreline generated for this analysis. The eGOA sites were partially enclosed areas (bays) with a single, western opening to the GOA, except for Salisbury Sound, which had four openings. The Sound has its largest opening (> 6 km) on the west side facing the GOA but has smaller openings (all < 1 km) in the northeast leading to Kakul Narrows, in the southeast leading to Neva Strait, and in the south there appears to be a partial, narrow, shallow opening to Krestof Sound (Fig. 2D). All sites were enclosed with artificial borders, called mouths, where the shoreline trended outward to the GOA except the three smaller, internal openings in Salisbury Sound which were placed with respect to GOAIERP sampling sites.

2.4. Biological importance of physical variables

Shoreline digitization allowed calculation of several shore-based GIS metrics, including area of bay within 100 or 1000 m of shore (a measure of shore-importance, or “shoriness”), and direct linear shoreline exposure to 10 evenly spaced nodes across the mouth of each site (Table 2). Shoriness was hypothesized to measure a site's connection to the land while shoreline exposure was hypothesized to measure a site's vulnerability to ocean waves and swells - both assessing the potential terrestrial versus oceanic influence on sites. Combining the digitized shoreline with the offshore soundings allowed interpolation of a complete depth raster as well as bathymetric derivatives such as slope and rugosity (Table 3) that are common descriptors of fish habitat. Water surface areas were calculated by intersecting the interpolated depth surface with horizontal planes at different depths, allowing calculation of tidal or seabed exposure at low tide, a metric for describing the temporal variability of the inshore area (Table 4). Water volumes below different depths were also calculated from the interpolated depth raster and freshwater runoff was calculated by intersecting the digitized watershed area with a precipitation polygon surface (Jones and Fahl, 1994; Table 5). These volume calculations, which included the tidal prism (MHW-MLLW volume), allowed comparison of watershed runoff volume to bay volume, and the amount of time it would take to refill an empty bay with watershed runoff alone (runoff refill years; Table 5). These metrics can be used as an indicator of freshwater influence. Rocky reefs and kelp beds were digitized as polygons, and verbal surficial substrates (e.g. gravel, sand, mud) were digitized as points and converted into phi values (where phi = $-\log_2$ grain size diameter in mm; Krumbein, 1934) using a modified version of Jenkins' method (1997; Table 6). Site openness was calculated with three methods: as a linear metric (distance across mouth of bay divided by the total interior shore length; Table 2), an area metric (area of a vertical plane at the mouth of the bay divided by the MHW surface area; Table 4), and a volume metric (tidal prism divided by MHW volume; Table 5), as it was not known which was the best method for describing how a site might be open or closed to a larval fish needing to settle at an appropriate location. The new eGOA calculations of the area of lakes within each watershed (Table 5), and the amount of shallow (< 200 m) shelf near the mouth of each bay (Table 4), were also created for the cGOA sites (Table 7).

2.5. Lakes

Lake areas within the watershed of each of the cGOA and eGOA study sites were hand-digitized from the U. S. Geological Survey (USGS) topographic sheet supplied as a continuous layer from ArcMap online services (http://www.esri.com/software/arcgis/arcgisonline/features/maps). This same data source was used for watershed analysis in both the cGOA and eGOA. In general, these maps are produced at a scale of 1:63,360 but map scale at a particular location is not indicated within the continuous surface. Total area of lakes within each watershed, and percent of each watershed covered by lakes, were added as metrics to determine the amount of lacustrine ecosystem influence for each study site. No effort was made to remove the area of islands that might occur within the lakes because it was a small fraction of the total lake area.

2.6. Shelf

Each of the cGOA and eGOA study sites were characterized by the proportion of shelf area, defined as areas with seafloor < 200 m in depth, within 100 km of the mouth of the study site (Fig. 1). The dataset used for this metric was the GOA offshore bathymetry compilation, which was created specifically to cover the offshore extent of the GOAIERP study area (Zimmermann and Prescott, 2015). This bathymetry compilation excluded the inside waters of SE Alaska such as Chatham Strait and Glacier Bay which were partially within 100 km of the eGOA site mouths, and also excluded interior waters such as Shelikof Strait and Cook Inlet (Zimmermann and Prescott, 2014), which were partially within 100 km of the site mouths (Fig. 1) because the focus of GOAIERP was on the eggs and larvae crossing the shelf, from deep, offshore GOA waters where some of the groundfish spawning is hypothesized to take place (Bailey and Picquelle, 2002).

2.7. Multivariate site groupings

All study sites, including the five cGOA sites described in Zimmermann et al. (2015), and the five eGOA study sites described in this analysis, were compared to each other in multivariate analyses using the 56 metrics described above. Grouping of sampling sites was done with clustering and principal components analysis (PCA) using PC-ORD (v. 5.33, MjM Software, Gleneden Beach, Oregon, USA) utilizing data scaled by the maximum value across all study sites so that the GIS metrics all ranged up to one. The clustering method utilized Euclidean distance and Ward's linkage. The PCA utilized a variance/covariance (centered) cross-products matrix. The MHW data values (Table 3) were converted from negative to positive by multiplying by -1, and the mean and median phi values (Table 6) were also converted to positive numbers by adding 9 for PC-ORD processing. The first clustering and PCA utilized all 56 of the absolute and relative measures. A second clustering and PCA were run using only the relative measures in an attempt at removing study-site size from the analysis.

3. Results

Three of the eGOA bays were relatively small (Table 4): Islas Bay (IB; 7.3 km^2), Torch Bay (TB; 7.5 km^2) and Graves Harbor (GH; 12.6 km^2). In addition, there was a large, non-bay site (Salisbury Sound; SS; 70.2 km^2; Table 4), and one large bay (Whale Bay; WB; 71.5 km^2; Table 4) (Fig. 2A-E). The diversity of the eGOA sites is similar to the diversity of the cGOA sites (three small bays, one large bay, and an island archipelago) (Fig. 1) (Zimmermann et al., 2015). Islas Bay, south of Cross Sound, is shaped like an equilateral triangle with a deep central channel. Islas Bay is constricted near the mouth of the bay by a shallow, offshore bank that rises slightly above MHW at one point (Fig. 2A). The northern shoreline of IB has several long, slender inlets and a rocky coastline which hampered the bathymetric survey work (Descriptive Report for H04527: http://surveys.ngdc.noaa.gov/mgg/NOS/coast/H04001-H06000/H04527/DR/H04527.pdf). Torch Bay is the northernmost of the eGOA sites, has a single, deep, central channel, with the greatest depths near the center of the bay, a short arm to the east, and a long, flat-bottomed arm arcing to the north (Fig. 2B). Graves Harbor has a deep, wide, and long channel on the southern side, terminating in a natural harbor, and a shallower, narrower, and shorter side channel on the northern side that terminates in Murk Bay (Fig. 2C). Salisbury Sound has deep southern and northern channels, which merge into a central channel about 4 km inside the sound (Fig. 2D). There are four long, relatively narrow and shallow inlets to the south and east and there are numerous islands and banks throughout the sound, which complicate the bathymetry. Whale Bay has a narrow, deep (~300 m) central channel that is blocked by a shallow sill (~90 m) about 6 km into the bay (Fig. 2E). Inside the sill is a basin with maximum depths of ~ 200 m that is connected on the east to the Great Arm (~ 17 km long, ~1 km wide). The Small Arm (~10 km long, < 1 km wide) is connected to the north side of the central basin and a shallow sill (~65 m) exists at the mouth of the Small Arm.

3.1. Small sites (Islas Bay, Torch Bay, and Graves Harbor)

The three small bays have similar shoreline metrics (Table 2), including shorter mainland shorelines, smaller mouths, greater linear openness, larger percentage of surface area near 100 m of shore, and more shoreline exposure than the larger sites. These three small bays were such small indentations in the coastline that about one quarter or more of their surface areas were within 100 m of shore, while nearly all of their entire surface areas were within 1000 m of shore (Table 2). The small bays were also shallower, flatter and smoother than the larger sites, with IB the shallowest, flattest and smoothest among all sites (Table 3). Despite the smaller surface areas and smaller amount of seafloor exposed at mean lower low water (MLLW), this translated into a higher percentage of seafloor area exposed at MLLW for IB, TB, and GH (Table 4). There was also generally a larger percentage of island surface area, and smaller mouth cross-sections for the three smaller bays (areal openness, Table 4). They had greater amounts of nearby shallow shelf areas than the larger sites. They also had smaller volumes, fewer tidal refill days, smaller watersheds, and less freshwater runoff, although the runoff refill years varied (Table 5). The three smaller bays lacked glaciers. Islas Bay had nearly 12% of its watershed composed of lakes, TB had none, and GH had only 1.5% of its watershed composed of lakes. Similarly, all of the cGOA sites had low percentages (0.2 - 1.5%) of their watersheds composed of lakes except for Izhut Bay, whose 285 bodies of water covered 4.9% of the watershed (Table 7). The three smaller bays lacked reefs and had at least 0.7% of their surface areas covered in kelp beds (Table 6). The mean and median phi were larger in the smaller bays and had more area covered in mud (≥ 4.0 phi) (Table 6).

3.2. Large sites (Salisbury Sound and Whale Bay)

The two large sites (SS and WB) were similar by numerous measures. Both sites had mouths about 7 km across, both had low measures of linear openness, but the WB shoreline was longer than that of SS (Table 2). Salisbury Sound had the lowest percentage of surface area within 100 or 1000 m of shoreline while WB had the lowest mean shoreline exposure. The mean depth of both large sites was about 80 m, much greater than the mean depth of the smaller sites, and both large sites had high average slope and rugosity measurements (Table 3). Both sites had a MHW surface area of about 70 km^2, nearly ten times the surface area of IS and TB, with large amounts of seafloor area exposed at MLLW, but this difference in area between MHW and MLLW translated into low percentage of total MHW surface area (Table 4). Both large sites had similar surface areas at 50 m and 100 m in depth and both sites generally had more island area, but this generally accounted for lower percentages of the total study sites than for the smaller sites. Both large sites had large cross-sectional openings, but this was small in comparison to the surface area of the sites as a whole. Both large sites had lower percentages of nearby (100 km) shallow shelf area (< 200 m) than the small sites. The water volume of both large sites was nearly 6 km^3, with similar volumes below 50 m and 100 m in depth, but the tidal prism (volume at MLLW subtracted from MHW) was larger in SS than WB (Table 5). Whale Bay required more tidal refill days than SS. The watershed of WB was more than double that of SS, and the estimated annual freshwater runoff was more than five times that of SS. Salisbury Sound required the most years to refill from freshwater alone. Whale Bay was the only eGOA site with glaciers (< 1%) in the watershed, and it also had the largest surface area of lakes in the watershed but this translated into a smaller percentage of watershed area covered by lakes than for IB. Both WB and SS had kelp beds and rocky reefs, with SS having seven times the percentage of area covered by reefs in WB (Table 6). Whale Bay had the lowest mean and median phi (larger grain sizes) among all sites.

3.3. Grouping of study sites with absolute and relative metrics

The clustering analysis on all absolute and relative metrics had a low degree (15%) of chaining (defined as the sequential addition of entities to a group, with low chaining indicating that entities readily divide into groups) and identified several distinct groups (Fig. 3A): cGOA small bays, eGOA small bays, eGOA large sites (SS and WB). Aialik Bay and the Barren Islands formed distinct entities (Fig. 3A). The SS/WB group was more closely linked to the cGOA small bay group but, in general, the clustering grouped sites on the basis of geographical proximity: there was greater similarity within sites (eGOA and cGOA) sites than between sites.

The first three axes from the PCA (Fig. 3B) explained 76.4% of the variance and showed the same separation seen in the clustering, including the outlier status of AB and BI. Volume and surface area metrics were the strongest negative (< -0.4) loadings on PC1 (43.3% of variance) while the strongest positive (> 0.4) loadings were relative littoral and watershed measures, such as percentage of bay within 100 and 1000 m of shoreline, ratio of watershed area to bay area, and ratio of runoff volume to bay volume. The most negative loadings on PC2 (22.8% of variance) were mainly absolute littoral and watershed measures, such as watershed area, mainland shore length, and percent and area of glaciers in the watershed, while the most positive loadings were the percentage of site area occupied by islands, three measures of site openness, and shoreline exposure. For PC3 (10.3% of variance) the most negative loadings were for sediment grain size and shelf metrics and the most positive loadings included percent and area of reefs.

3.4. Grouping of study sites with only relative metrics

Because the numerous volume and area metrics with high negative loadings on PC1 in the previous analysis indicated that site size was highly important, there was concern that these measurements exaggerated the differences between cGOA and eGOA sites. For example, the three small cGOA bays have an average of 9.0 times the MHW surface area of the three small eGOA bays (Table 4; also see Table 3 Zimmermann et al., 2015) and the cGOA small bays were similar in size to the eGOA non-bay (Salisbury Sound) and large-bay (Whale Bay). Therefore the cluster and PC analyses were repeated using only the relative measures (n = 26) with somewhat different results. The clustering analysis (Fig. 4A) had a high degree of chaining (75%, indicating that the sites did not separate into groups well), but retained much of the structure as the original analysis, except that Islas Bay, and to a lesser extent Kiliuda Bay, were more distinct entities. The groups that were retained (small cGOA, Izhut and Port Dick; small eGOA, Torch and Graves; large eGOA, Salisbury and Whale) were based both on size and location.

The first three axes of the PCA explained 72.9% percent of the variance (Fig. 4B), which was a slight decline from the first PCA analysis, but this new PCA showed less distance between the cluster groups, making them less distinctive entities than in the earlier analyses using all measures. Similar to the cluster analysis, the PCA indicated a cGOA small bay group (minus Kiliuda Bay), an eGOA small bay group (minus Islas Bay), and the SS/WB group together. The PCA also reinforced the different characters of Islas Bay and Kiluda Bay in addition to retaining the uniqueness of Aialik Bay and the Barren Islands from the first analysis.

4. Discussion

This analysis confirmed some cGOA and eGOA dissimilarities in study sites despite not including any measures of location, such as latitude and longitude, alongshore distance, or categorical variables such as "central" and "east" in the analysis, although it seems that study site size is driving some of the results and differences. These results indicate that there are regional dissimilarities between the landscape of the cGOA and eGOA study sites chosen for the GOAIERP, especially in absolute measures, and to a lesser extent in relative measures. Similar GIS-based analyses in other regions have been done across large areas and for more sites, including New Zealand (Hume et al., 2007; n=443), the island of Ireland (Cooper, 2006; n=~400), and the United Kingdom (Townsend, 2005; n=79). All of these studies sought to develop different methods for classifying bays. All of these larger efforts also demonstrated that bay groupings were influenced by geography, i.e. similar sites were likely to be geographic neighbors. Thus regional landscapes driving local bay morphology may be a global phenomenon.

The GOAIERP studies were initiated with the expectation that there would be differences in the physical and biological properties of the cGOA and eGOA shelf, but not necessarily the bays. Although the exact borders in their study were somewhat different, Mueter and Norcross (2002) cited several biological and physical differences between western and eastern GOA regions. Physical differences included greater upwelling, stronger tidal currents, stronger alongshore currents, and a broader shelf area (the only variable included in this GOAIERP analysis). Perhaps as a result of the physical environment, the western region had higher primary productivity and higher fish and invertebrate benthic biomass. Contrasting the higher fish biomass in the west were greater species diversity and richness in the east. It is important to recognize that Mueter and Norcross (2002) were discussing the offshore shelf area, rather than the inshore study sites that were the subject of this GIS analysis (except possibly the cGOA Barren Islands). However the analysis presented here suggests that these offshore differences may translate into onshore differences in the landscape of the study sites, with the size and shape of the bays possibly determined by the height and steepness of the coastal mountains and the depth and breadth of the coastal shelf.

It is often difficult for researchers to map study sites and describe the physical attributes prior to conducting field work, even if those attributes are known to be different prior to conducting comparative biological studies. Visiting study sites twice during a single project incurs additional costs in vessel time and fuel, arranging logistics, and data analysis. Nevertheless there are examples in the literature of successful Alaska projects that described sites prior to sampling. Woodby et al. (2009) identified coral taxa and their habitat from minisubmersible dive transects on mapped areas in the Aleutian Islands. Rooper et al. (2007) conducted multibeam and sidescan sonar mapping of study sites in the Aleutian Islands prior to biological sampling for juvenile Pacific ocean perch, but this still required underwater video ground-truthing for interpretation of the mapping work (Rooper and Zimmermann, 2007). O'Connell et al. (2003) collected mini-sub visual density estimates of yelloweye rockfish (*Sebastes rubberimus*) and developed biomass estimates by utilizing underwater mapping and habitat classification. Working in the nearshore area of the Alaska Peninsula, Hogrefe et al. (2014) was able to map eelgrass beds using a combination of satellite imagery and ground-truthing. While it would have been very useful for GOAIERP researchers to have detailed seafloor maps of all study sites prior to conducting the field work, such an effort was not part of this research program. Some inshore areas in Alaska have been mapped with multibeam by the NOS, but the GOAIERP MTL study sites could not rely on previous mapping efforts (only Aialik Bay and Salisbury Sound were mapped with multibeam). Using NOS smooth sheets to make maps was a cheaper and more practical alternative to multibeam mapping that put GOAIERP on more equal footing with other projects where the seafloor mapping was fully funded.

Physical classification of bays has been done in conjunction with biological studies in some areas. Some of these projects have sought to classify bays into single categories such as open (Norcross et al., 1999) or wind exposed (Phil and van der Veer, 1992), to increase the understanding of how the bays might function for rearing juvenile fish. Projects that involved fieldwork (i.e. physically visiting, mapping and quantifying attributes of bays across large areas), are rare but do exist. For example, such work has been performed for the fjords of British Columbia, Canada (fjord length, width and depth; Pickard, 1961), and the inshore, shallow (<10

m) fish habitat along 400 km of the Swedish coast (depth, sediment, and some benthic flora and fauna; Stal and Pihl, 2007). The metrics described here, derived from the NOS smooth sheets, were provided as a substitute for visiting and thoroughly mapping the study sites and provided a valuable addition to the biological studies.

The GOAIERP project was structured to examine the longitudinal differences within the GOA, with the sampling design set up to contrast sites in the cGOA with those in the eGOA, and no sampling in between (Fig. 1). Results may have changed if mid-longitude sites between the cGOA and eGOA regions were included. These additional sites could have shown a continuous cline among study sites across the range of longitudes, better defined the exact border between the cGOA and eGOA, or revealed a third, mid-longitude region. Thus the interpretation of the findings in this GIS analysis may change if additional study sites are added to the analysis in the future.

Another important consideration is the actual study sites chosen for the MTL work. The results in this analysis mostly reflected dissimilarities between absolute measures in the larger cGOA small bays versus the smaller eGOA small bays, and these dissimilarities may have been less pronounced between bays of comparable sizes, as the analysis of relative measures indicated. All analyses indicated that the heart of the eGOA small bay group, Torch Bay and Graves Harbor, are nearly identical. Geographically they almost touch, and are almost mirror images of each other (Figs. 2A and B). The cGOA small bay sites are similar in absolute measures such as shoreline length, surface area and volume, putting them on par with the eGOA large sites (SS/WB), so it might not be surprising that the cGOA small bay group was fairly constant in analyses, that the SS/WB group was fairly constant, and that these two groups were sometimes more similar to each other, confounding the cGOA versus eGOA geographic membership. The Barren Islands and Aialik Bay from the cGOA were distinctive outliers. Groupings may have changed if these two outliers from the cGOA had been more comparable to the other cGOA sites (Kiliuda, Izhut, and Port Dick), perhaps enforcing more of a cGOA versus eGOA grouping.

This analysis did not seek to quantify differences between study site groups or to develop a classification system of study sites, but instead sought to determine which sites formed groups based on an analysis of a distance or similarity measure. This approach was taken because there is not enough information available to produce bay classifications of known relevance to the five focal species we are studying in GOAIERP. For example, while it has been known for two decades that Saint John the Baptist Bay (within Salisbury Sound) is the site of persistent high juvenile sablefish abundance (Rutecki and Varosi, 1997), the reason for its habitat suitability is still not known (Coutre et al., 2017). As more knowledge is gained about which site attributes benefit different species, the process of quantifying study sites can be advanced to a more predictive stage.

The inshore work during the GOAIERP attempted to address how differences among bays influences the growth and survival of young fish. Bays may provide small fish with shallower waters, protection from oceanic conditions, and links to the terrestrial environment. Little is known about whether the GOAIERP focal species actively seek out certain bays, or if they are passively advected to them and certain characteristics of the bays enhance survival. The metrics developed for this study were used by other GOAIERP researchers to identify physical attributes that influence the ecosystem. For example, currents in cGOA canyons closely follow smooth sheet bathymetry, making nutrient pathways much more comprehensible than when using navigational chart bathymetry (Mordy et al., in review). Several studies analyzed chemical tracers in fishes (e.g. fatty acid and stable isotope signatures of nearshore fishes, and elemental signatures of age-0 Pacific cod) and interpreted the results relative to the physical metrics described here Study-site groupings were also used by the GOAIERP MTL for structuring their analysis of patterns in the acoustic measurements of fish schools and in analyzing growth differences among walleye pollock and Pacific cod (Olav Ormseth, Alaska Fisheries Science Center, pers. comm.). The results of these studies will determine whether the GIS-based effort captured the appropriate fish habitat variables.

5. Conclusions

This project sought to demonstrate that multiple GIS metrics could be extracted from NOS smooth sheets so that researchers could describe study sites on the basis of physical attributes rather than simpler, but less useful descriptors such as latitude and longitude. Fifty-two of these metrics were previously published to demonstrate how they could be used to estimate preferred fish habitat for two flatfish species at cGOA study sites (Zimmermann et al., 2015). Few of these metrics were previously available for the study sites and some of them are unknown to the literature, as they were created from the smooth sheet data specifically for GOAIERP. In addition, four variables were added to this study to quantify lakes within each watershed and to quantify nearby shallow shelf areas. The relevance of these 56 variables to the abundance, distribution, and condition of the forage fish and the juveniles of the five focal species will be determined in other GOAIERP analyses, including modeling efforts to describe preferred habitat for juveniles of the five focal species.

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Figures

Fig. 1. Regional map showing the locations of the central Gulf of Alaska study sites: Kiliuda Bay, Izhut Bay, the Barren Islands, and Aialik Bay; and the eastern Gulf of Alaska study sites: Islas Bay, Torch Bay, Graves Harbor, Salisbury Sound, and Whale Bay. These locations were chosen for intensive inshore field work by the mid-trophic level (MTL) group of NPRB's GOAIERP.

Fig. 2. Interpolated bathymetric surfaces based on the smooth sheet data. Red is shallow and blue is deep. (A) Islas Bay, (B) Torch Bay, (C) Graves Harbor, (D) Salisbury Sound, and (E) Whale Bay.

Fig. 3. Clustering and ordination results based on 56 absolute and relative GIS-based measurements, mostly derived from NOS smooth sheet data. (A) Clustering, (B) Principal Components Analysis. The small eGOA sites (Islas Bay, Torch Bay, and Graves Harbor) are circled in red, the large eGOA sites (Salisbury Sound and Whale Bay) are circled in green, and the small cGOA sites (Kiliuda Bay, Izhut Bay, and Port Dick) are circled in blue.

Fig. 4. Clustering and ordination results based on 26 relative GIS-based measurements, mostly derived from NOS smooth sheet data. (A) Clustering, (B) Principal Components Analysis. A reduced group of small eGOA sites (Torch Bay and Graves Harbor) is circled in red, the large eGOA sites group (Salisbury Sound and Whale Bay) is circled in green, and a reduced group of small cGOA sites (Izhut Bay and Port Dick) is circled in blue.

Table 1. National Ocean Service (NOS) smooth sheets used for analysis for the five study sites. Vertical datum is MHW (Mean High Water) for all smooth sheets. Horizontal datum was either unknown, the North American Datum of 1927 (NAD27), or the North American Datum of 1983 (NAD83).

Location	Smooth sheet	Year	Scale	Horizontal Datum
Torch Bay	H04640	1926	1:20,000	Unknown
Graves Harbor	H04640	1926	1:20,000	Unknown
Islas Bay	H04527	1925	1:10,000	Unknown
Salisbury Sound	H11109	2002	1:10,000	NAD83
	H11111	2002-03	1:10,000	NAD83
	H11112	2003	1:10,000	NAD83
	H11113	2003	1:10,000	NAD83
	H11131	2003	1:10,000	NAD83
(Salisbury Sound supplemental sediments)				
	H04847	1928	1:20,000	Unknown
	H07675	1948	1:5,000	NAD27
	H07676	1948	1:10,000	NAD27
	H07860 (Kakul Narrows)	1950	1:5,000	NAD27
	H07860 (Sukoi Inlet)	1950-51	1:10,000	NAD27
	H07861	1950-51	1:10,000	NAD27
Whale Bay	H04431	1924	1:20,000	Unknown
	NOS Chart 17328	2003 ed.	1:40,000	NAD83

Table 2. The length of shoreline was calculated from digitizing the shoreline on the smooth sheets, except for Salisbury Sound, where the shoreline was downloaded as the continually updated shoreline product (CUSP) and edited against the smooth sheet shoreline. Mouth openness compares the length across the mouth of the bay to the length of the mainland and island shoreline. Shore buffers are the amount of water area (km^2) and percent of whole bay within 100 and 1000 m of shoreline. Shoreline exposure was calculated by radiating thousands of lines into the bay from 10 nodes equally spaced across the mouth of the bay, with each shoreline segment having a potential of being intersected by as many as 10 radiating lines, one from each node. Mean shoreline exposure is the length-weighted average of exposure of all shoreline segments: 10 of 10 possible intersections is Full, 1 to 9 intersections is Partial, and 0 intersections is Zero.

	Islas Bay	Torch Bay	Graves Harbor	Salisbury Sound	Whale Bay
Shore length (m)					
Mainland	28,520	24,949	26,616	109,469	143,066
Islands	15,934	1,541	12,715	26,840	20,627
Mouth	3,948	2,520	3,912	6,763	6,962
Mouth openness	8.9%	9.5%	9.9%	5.0%	4.3%
Shore buffers					
100 m (km^2)	3.1	2.2	3.1	12.2	15.2
1000 m (km^2)	7.3	7.5	12.3	54.3	61.9
100 m	42.4%	28.5%	24.4%	17.4%	21.6%
1000 m	100.0%	100.0%	97.0%	77.4%	88.2%
Shoreline exposure (range 0 to 10)					
Mean	1.5	2.4	2.5	1.5	1.1
Full	0%	5%	2%	2%	2%
Partial	49%	44%	54%	36%	22%
Zero	51%	51%	44%	62%	76%

Table 3. Bathymetric measures for the five study sites. Mean High Water (MHW) was determined empirically during each hydrographic survey. Average depth is calculated from the interpolated surface but the maximum sounding is from the raw input data. Slope is the maximum difference between each interpolated depth and up to eight immediate neighbors while rugosity is the ratio of true surface area to planar surface area.

	Islas Bay	Torch Bay	Graves Harbor	Salisbury Sound	Whale Bay
Depth (m)					
MHW	-3.75	-2.32	-2.32	-2.79	-1.71
Average	22	36	47	80	81
Maximum	95	102	144	273	364
Slope (steepness in degrees)					
Average	5.2	7.5	6.6	9.8	11.5
Maximum	29.8	33.7	44.1	68.3	71.1
Area <1.000°	22.5%	6.7%	12.9%	5.7%	5.7%
Rugosity (true surface area/planimetric area)					
Average	1.009	1.014	1.014	1.032	1.040
Maximum	1.156	1.210	1.401	2.733	3.090
Area <1.001	26.9%	13.8%	27.0%	12.6%	13.7%

Table 4. Water surface area is calculated at four depths: MHW (Mean High Water), MLLW (Mean Lower Low Water), 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. The areal openness of a bay is calculated by dividing the cross-sectional area of the mouth of the bay by the surface area of the bay at MHW.

	Islas Bay	Torch Bay	Graves Harbor	Salisbury Sound	Whale Bay
Water surface area (km^2)					
MHW	7.3	7.5	12.6	70.2	71.5
MLLW	5.2	6.9	11.3	66.5	68.4
Tidal exposure	2.1	0.7	1.4	3.7	3.1
Tidal exp./MHW	28.5%	9.0%	10.8%	5.3%	4.3%
50 m	1.2	2.5	4.2	40.7	38.0
100 m	0.0	0.0	2.3	22.9	24.1
Islands					
Area (km^2)	0.3	0.0	0.5	0.4	1.2
Percent of site	4.1	0.2	4.0	0.6	1.6
Mouth cross-section area					
Opening (km^2)	0.1	0.1	0.2	0.7	0.5
Divided by MHW	1.4%	1.4%	1.8%	1.1%	0.7%
Shelf <200 m within 100 km					
Area (km^2)	7,004	8,779	8,571	5,728	5,994
Ratio shallow/deep	0.41	0.61	0.59	0.34	0.35

Table 5. Water volume is calculated below four depths: MHW (Mean High Water), MLLW (Mean Lower Low Water), 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. Volumetric bay openness is a comparison of the tidal prism (MHW-MLLW) to the MHW volume of the bay. Tidal refill days are the number of days it would take to refill the bay with tidal volumes alone, assuming two high tides per day. Watershed runoff refill years are the number of years it would take to refill the bay through runoff alone.

	Islas Bay	Torch Bay	Graves Harbor	Salisbury Sound	Whale Bay
Water volume (km^3)					
MHW	0.2	0.3	0.6	5.8	5.9
MLLW	0.2	0.3	0.6	5.6	5.8
Tidal prism	0.02	0.02	0.03	0.19	0.12
T. p./MHW	11.1%	5.6%	4.3%	3.3%	2.0%
Below 50 m	0.0	0.0	0.2	3.0	3.1
Below 100 m	0.0	0.0	0.1	1.4	1.6
Tidal refill days	4.5	9.0	11.5	15.3	24.9
Watersheds					
Area (km^2)	44	19	35	153	394
Ratio to bay area	5.8	2.5	2.6	2.2	5.4
Runoff (km^3)	0.12	0.05	0.10	0.40	2.19
Ratio to bay volume	0.661	0.182	0.157	0.069	0.372
Runoff refill years	1.5	5.5	6.4	14.5	2.7
Glacier					
Area (km^2)	0	0	0	0	3.4
%Watershed	-	-	-	-	0.9
Lakes					
Area (km^2)	5.2	0	0.5	2.7	14.4
%Watershed	11.8	-	1.5	1.7	3.7

Table 6. Cartographic features (rocky reefs and kelp beds) and substrate observations were hand-digitized from the smooth sheets. The substrates are the verbal surficial substrate observations within each study site. Phi is the -log$_2$ of the estimated grain size particle diameters in mm, with the largest grain size of -9 (Rock or rocky) and the smallest grain size 9 (Clay).

	Islas Bay	Torch Bay	Graves Harbor	Salisbury Sound	Whale Bay
Features (km^2)					
Reefs	0.000	0.000	0.000	1.757	0.252
Kelp	0.049	0.184	0.177	0.112	0.424
%Reefs	-	-	-	2.50	0.36
%Kelp	0.67	2.43	1.40	0.16	0.60
Count of substrates					
From soundings	107	70	159	508	294
From features	129	122	174	2,299	439
Total	236	192	333	2,807	733
Count/km^2	32.28	25.44	26.33	39.98	10.25
Substrate measures (grain size)					
Mean (phi)	-3.2	-2.7	-2.6	-3.7	-6.8
Median (phi)	-3.4	-3.3	-2.6	-3.3	-8.1
Area mud	9.2%	14.3%	12.0%	0.8%	1.3%

Table 7. Lake and shelf area measurements for the five cGOA sites.

	Kiliuda Bay	Izhut Bay	Barren Islands	Port Dick	Aialik Bay
Lakes					
Area (km^2)	5.2	0	0.5	2.7	14.4
%Watershed	11.8	-	1.5	1.7	3.7
Shelf <200 m within 100 km					
Area (km^2)	17,350	19,836	14,988	16,340	14,235
Ratio shallow/deep	0.93	0.99	0.97	0.89	0.77