Fisheries and Oceans Canada | Pêches et Océans Canada
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Pacific Region

Canadian Science Advisory Secretariat
Science Advisory Report 2023/039

COASTWIDE EVALUATION AND CLASSIFICATION OF PACIFIC REGION ESTUARIES BASED ON ANTHROPOGENIC ACTIVITIES AND SIGNIFICANT FISH HABITAT

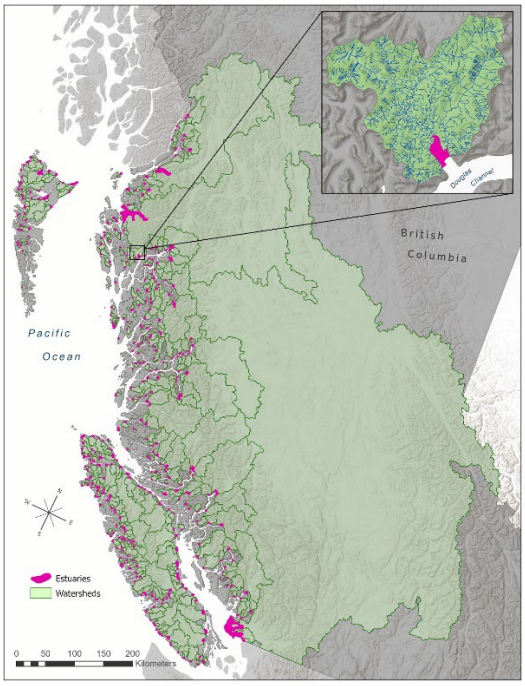

Figure 1. Estuaries and watersheds included in the analysis. The inset map shows an example of the high resolution stream network data used to delineate the watersheds.

Context:

Estuaries are highly productive ecosystems that support a high diversity of habitats, including eelgrass beds, saltmarshes, and mudflats. Estuaries are also the site of many anthropogenic activities and the fish species and habitats within are threatened by multiple factors, including habitat degradation and modification, pollution, invasive species, overexploitation of fish, and climate change.

The Fish and Fish Habitat Protection Program (FFHPP) has requested that Science Branch provide a coastwide evaluation of Pacific Region estuaries for activities that may impact fish and fish habitat and help to identify the importance of the estuaries to salmon, other significant fish species (e.g., herring), and the presence of sensitive fish habitat (e.g., eelgrass). The assessment will assist managers in developing management and conservation actions appropriate to estuaries along the Pacific coast.

This Science Advisory Report is from the April 12-13, 2023 regional peer review on the Coastwide Evaluation and Classification of Pacific Region Estuaries based on Anthropogenic Activities and Significant Fish Habitat. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

October 2023

Canada

SUMMARY

- Estuaries are highly productive and diverse ecosystems that are the site of many anthropogenic activities. While only comprising 3% of the British Columbia (BC) coastline, there are over 400 individual estuaries, making management difficult and highlighting the need for regional approaches.
- A literature review was used to compile anthropogenic activities, including climate change and other associated stressors (physical, chemical, or biological processes that have the potential to change an ecosystem) relevant to estuarine environments throughout the BC coast across terrestrial, marine, and atmospheric zones.
- Based on the literature review, 45 available coastwide spatial data layers were compiled and used to assess the spatial overlap, frequency, or intensity of activities and stressors relevant to 439 estuaries and their associated watersheds.
- All estuaries assessed had at least one marine or terrestrial activity present. The most marine activities were identified in estuaries in the Strait of Georgia and the Skeena River estuary, while the most terrestrial activities occurred in estuaries in the Strait of Georgia, the Skeena River estuary, the Kitimat estuary, and estuaries along the west coast of Vancouver Island closer to population centers.
- A cluster analysis was used to characterize the estuaries based on the type and intensity of activities that occur. Five clusters of estuaries and the associated characteristic activities were identified.
- The analysis identified one cluster of estuaries that had high numbers of anthropogenic activities and tended to be associated with activities in the watershed (e.g., agriculture, dams) or that were associated with populated areas (e.g., wastewater outflow, marinas). The other four clusters were associated primarily with marine activities. Two clusters had intermediate numbers of activities, one with more forestry and crab and shrimp fishing, and the other having more salmon fishing. The last two clusters had low numbers of activities - one cluster was associated with shipping and recreational boating, and the other had no association with any one activity.
- Climate change (air temperature change, stream temperature change, precipitation change, and/or sea level rise) is expected to impact all estuaries to varying extents. In particular, the highest degree of stream temperature increase is expected in estuaries at the end of long inlets (e.g., Bute Inlet, Observatory Inlet). The estuaries that are projected to experience the highest degree of sea level rise are around Haida Gwaii.
- Available coastwide spatial data for salmon, other ecologically significant fish species, sensitive fish habitat, and other habitat characteristics (e.g., presence of eelgrass, macroalgae, and saltmarsh) was compiled.
- The presence of fish and fish habitat varied among estuaries. There were observations of at least one species of Pacific salmon since 1990 for 76% of the estuaries, and 20% of the estuaries had all five species present. Estuaries with the highest salmon biomass and richness were associated with the most human activities. Dungeness Crab was likely present in 84% of the estuaries. Eelgrass was present in 43% of the estuaries, understory kelp in 82%, and saltmarsh in 81%. All three biogenic habitat types were present in 36% of the estuaries.
- The assessment of fish and fish habitats highlighted coastwide data gaps, which limited the assessment of all species/habitats of interest, particularly for non-commercial species.

- This analysis provides a significant data resource and initial assessment to help focus further estuarine conservation and management efforts. It can be used to identify estuaries that face similar types of concerns, potential management options, and relevant partners and resource users.
- This work is the first step towards a comprehensive assessment of how human activities may combine and cumulate to impact estuaries. Although this work is not a cumulative impacts assessment, future analysis could combine the outputs from this work with vulnerability scores of individual estuarine species to quantify an overall risk to each estuary.

BACKGROUND

In the Pacific Region of Canada, estuaries comprise only 3% of the British Columbia (BC) coastline (Figure 1), but their productivity and habitat diversity are of immense importance for a variety of species (Ryder et al. 2007). Estuaries across the coast have been identified as Ecologically and Biologically Significant Areas (EBSAs) because of the diversity of habitats they contain, including eelgrass beds, salt and tidal marshes, sand and mud flats, channels, and wetlands, and their importance for anadromous fishes, including Pacific salmon and Eulachon (DFO 2013).

Estuaries are also the location of many anthropogenic activities. A global study of estuaries and coastal seas found anthropogenic activities have resulted in large decreases in seagrass and wetland habitats within estuaries and over 90% depletion of the historical abundance of species considered commercially, structurally, or functionally important (Lotze et al. 2006).

Within Fisheries and Oceans Canada (DFO), the Fish and Fish Habitat Protection Program (FFHPP) is tasked with estuary and coastal management planning for fish and fish habitat. FFHPP requested that Science Branch develop a coastwide evaluation of Pacific Region estuaries for management and conservation based on the activities that may threaten fish and fish habitat. Additionally, they wanted to better understand the importance of individual estuaries to salmon, other significant fish species (e.g., Pacific Herring), and the presence of sensitive fish habitat (e.g., eelgrass).

Specific objectives of this working paper are to provide a starting point to address this management need and:

1. Review and map current anthropogenic activities in Pacific Region estuaries;
2. Use available data to map significant fish species distributions and sensitive fish habitat within Pacific Region estuaries;
3. Classify estuaries based on anthropogenic activities; and
4. Highlight estuaries particularly important for significant fish species and sensitive fish habitat.

Significant fish species are defined as those found to meet the criteria for Ecologically Significant Species (ESS) (Gale et al. 2019). Sensitive fish habitats are defined broadly and similarly to Sensitive Benthic Areas (DFO 2019) as estuarine habitat types sensitive to, and with the potential to overlap, a variety of detrimental activities identified through a literature review, though not limited to fishing.

ASSESSMENT

Study Area

This analysis examines anthropogenic activities and fish and fish habitat occurring in estuaries and their upstream watersheds along the coast of BC. The analysis focused on 439 estuaries mapped by the Pacific Birds Habitat Joint Venture (PBHJV Technical Team 2020). Generally, estuary locations were identified as the areas at the intersection of the coastline with moderately sized streams (4th order or greater) and extended from the intertidal zone lowest normal tide up to a maximum of 500 m upstream (Ryder et al. 2007). The boundaries of the watersheds that flow into each estuary were identified by linking all stream segments upstream of each estuary from the Freshwater Atlas of BC (GeoBC 2010).

Activities and Stressors

Activities are defined as actions that may produce one or more stressors on the ecosystem under assessment (O et al. 2015). Hereafter referred to as activities, this includes anthropogenic activities such as commercial and recreational fisheries, as well as human-induced climate change. Stressors are physical, chemical, or biological processes that, depending on the level of intensity, have the potential to change an ecosystem, habitat, or a component within (O et al. 2015). In essence, an activity can generate a stressor which can result in an impact to a species or habitat (Murray et al. 2020). Although wetland degradation and habitat loss can also occur through natural processes, this review and assessment focuses on human-induced estuary stressors.

Activities with the potential to impact estuaries, and their associated stressors, were compiled through a review of literature in Web of Science and the Government of Canada Publications database published between 2010 and 2022. Each of the articles was reviewed for their geographic and topic relevance and to identify activities referenced in the paper and those which were the focus of estuary-based field studies along the west coast of North America. These activities were used to supplement and adapt lists of estuarine activities and stressors compiled for previous analyses in the Pacific Region (Robb 2014; Hodgson et al. 2020). Spatial data were then compiled to represent each activity. Activity counts were generated for each estuary and a cluster analysis was performed to identify groups of estuaries that have similar types and intensities of activities.

Spatial data compilation

Terrestrial activities

Guided by the literature review, spatial data were compiled to represent 12 terrestrial activities overlapping estuary and watershed systems (Table A.1). To quantify terrestrial threats to estuaries, the overlap of activities occurring within a watershed or along the shoreline adjacent to an estuary was calculated. Stressors generated by activities in the watershed were assumed to be transported by river or stream flow to the estuary (e.g., increased sedimentation from logged areas) (Thrush et al. 2004), directly overlapping the estuary causing habitat modification, or to be transported by surface runoff (e.g., a road built directly on the shoreline). For most activities, the footprint area of overlap or intensity value (e.g., tonnes mined) within the watershed or shoreline zone was used. Summed threat values were normalized by the log of the watershed or shoreline zone area to allow for comparison among watersheds and act as a dilution effect, as the intensity of stressors generated in very large watersheds are likely reduced as they are transported to the estuary (Boyd et al. 2022).

Marine activities

Spatial data were compiled for 29 marine activities (Table A.1). Activity values were quantified by the direct overlap with estuaries as well as modeling the potential range of influence of a stressor generated by certain activities (e.g., pollution spreading from a point source), following approaches used in marine cumulative effects assessments (Clarke Murray et al. 2015). For activities with information on level of use, such as commercial fishing and shellfish aquaculture, the potential impact was based on intensity values (e.g., total kilograms harvested, market sales). The one exception was the threat from aquatic invasive species which was summarized as species richness. To generate activity values comparable among estuaries, the overlap values were normalized by dividing by estuary area.

Human-induced climate change

Stressors associated with climate change included in this report were projected end-of-century changes in sea level, precipitation, air temperature, and stream temperature, which were averaged for each estuary. Precipitation and air temperature data were modeled on a 1 km grid, stream temperature data were calculated at the point of outflow on the coast, and sea level rise was calculated for coastline segments (Table A.1).

Activity counts

The number of activities present in each estuary or watershed was calculated as the total number of activities that had non-zero values. Activity counts were calculated for terrestrial activities, marine activities, or all activities.

Cluster analysis

To better understand which estuaries may be impacted by similar anthropogenic activities and associated stressors, a cluster analysis was performed to group estuaries based on the frequency and intensity of marine and terrestrial activities, using the spatial data described above. The stressors associated with climate change were not included in the analysis but were compared to the resulting clusters.

Hierarchical clustering was used to define groups of estuaries where anthropogenic activity tends to be similar. The number of clusters was selected using 22 indices of cluster number optimization, with the chosen number of clusters being that which was selected by the most indices.

To differentiate how the clusters are broadly defined by the anthropogenic activities, a multilevel pattern analysis was applied. This analysis identifies the highest association between each activity and the clusters and then tests the association for statistical significance ($p < 0.05$). Thus, while this indicator analysis captures the highest associations it does not provide information about whether the activities are also associated with other clusters.

Fish and Fish Habitat Evaluation

The presence of significant fish species and sensitive fish habitat within estuaries (Table A.2) was quantified and compared to the cluster analysis results and activity counts. Ecologically significant fish and invertebrate species were identified based on their ecological role as upper-level predators, forage species, nutrient transporters, and habitat-forming species (DFO 2006; Gale et al. 2019). Spatial data, where available, were compiled to represent each species and overlaid with the estuaries, and scatterplots were used to compare the fish and fish habitat data with activity counts.

Significant fish species

Pacific salmon are a key component of marine and coastal ecosystems in BC, important for nutrient transfer and as a prey and predator species (Gale et al. 2019), and are of high ecological, cultural, and economic importance. Biomass and richness within the estuaries were calculated for five species of salmon (Chinook, Chum, Coho, Pink, and Sockeye) using information on adult salmon returning to spawn (termed "escapements") from the New Salmon Escapement Database System (NuSEDS; DFO 2023)[1]. Biomass was calculated based on the average maximum escapement for each salmon population, summed across species and populations upstream of a given estuary. In this case, species richness is the number of Pacific salmon species that have been recorded in rivers and streams in the estuary, but differentiating between even and odd years of Pink Salmon as two separate species for a maximum possible richness of six. Sufficient spatial data were not available for Dolly Varden, Cutthroat Trout, and Steelhead to allow further assessment. The number of Conservation Units (CUs) of Pacific salmon present in each estuary and watershed system was also calculated. A CU is defined as a "group of wild salmon sufficiently isolated from other groups that, if extirpated, is very unlikely to recolonize naturally within an acceptable timeframe" (DFO 2005).

Forage fish are an important food source for other species and experience high mortality due to predation (DFO 2009). Estuarine fishes that have been identified as Ecologically Significant due to their role as forage species include Eulachon, Pacific Herring, Pacific Sand Lance, Surf Smelt, and Shiner Perch (Gale et al. 2019). Based on available spatial datasets, the presence of Eulachon important areas for spawning and rearing, Pacific Sand Lance suitable habitat, and Pacific Herring spawn biomass were determined for each estuary. Sufficient spatial data were not available to develop layers for Surf Smelt and Shiner Perch.

For invertebrate species identified as Ecologically Significant, data from research surveys and commercial fisheries were used to inform their presence in estuaries. While not identified as an ESS, Dungeness Crab were identified in the review meeting as an important component of estuarine ecosystems. Presence in estuaries was estimated from a species distribution model (Nephin et al. 2023).

Estuarine habitats

Spatial data were compiled for the following important estuary habitats and features: biogenic habitats (eelgrass, brown canopy kelp, brown understory kelp, green kelp, and salt marsh), substrate type (sand, mud, mixed, hard), and rugosity (a measure of surface roughness). Additionally, biogenic habitat richness was calculated as the count of biogenic habitat types in each estuary.

Comparison with Other Assessments

In addition to the fish and fish habitat assessment, the results of the cluster analysis and estuary-specific activity counts were compared with metrics calculated in other studies, including cumulative impact map scores[2] and estuary rankings for waterbirds (PBHJV 2020). Cumulative effects assessments are a tool used around the globe to estimate the potential habitat impacts associated with multiple, often overlapping human activities (Halpern et al.

[1] Robb, C.K., Proudfoot, B., Thompson, P.L., and Rubidge E.M. Salmon biomass and richness – implications for the relative importance of estuaries in British Columbia, Canada. In prep.

[2] Selina Agbayani, Cathryn Murray, Craig Schweitzer. Cumulative impact mapping for marine habitats: 2023 update. Unpublished data.

2008). Cumulative impact scores and waterbird rankings for BC were overlapped with each estuary to assess the distribution of scores per cluster and by activity count.

Results

Activities and stressors

Anthropogenic activities can be broadly divided into three source areas or zones: terrestrial, marine, and atmospheric. Anthropogenic activities within these zones can generate stressors for estuary ecosystems, including stressors associated with human-induced climate change (atmospheric zone). The literature review identified 23 activities (some broader categories than others) and 16 associated stressors detrimental to estuaries, which guided the development of 45 spatial datasets for relevant activities. There were 29 possible marine activities, 12 possible terrestrial activities, and 4 climate stressors. Habitat modification and pollution were the predominant stressors, linked to the most anthropogenic activities, and habitat modification stemmed from all three zones. Within the terrestrial zone, sedimentation and pollution were the predominant estuarine stressors. Within the marine zone, pollution, and habitat modification predominated.

All 439 estuaries had at least one marine or terrestrial activity present (Figure 2). There were five estuaries with only one marine activity present – these were generally located at the end of fjords on the north coast (e.g., Hastings Arm – Observatory Inlet, Kitlope Anchorage – Gardner Canal, Green Lagoon). There were 84 estuaries without any terrestrial activities present – dispersed across the north and central coasts and the west coast of Vancouver Island, and typically associated with small watershed areas further from population centers. In general, the central coast had very few terrestrial activities present except for estuaries at the end of long inlets with large watersheds that extend beyond the Coast Mountains, where activities such as logging and burned areas were more prevalent (e.g., Bella Coola watershed).

No estuaries had either all of the marine or all of the terrestrial activities present (Figure 2). The areas with the most marine activities present were estuaries in the Strait of Georgia and the Skeena River estuary near Prince Rupert. The estuary with the most marine activities (19 of 29 marine activities) was the Cowichan River estuary, followed by the Fraser and Skeena river estuaries (17 of 29 marine activities). The areas with the most terrestrial activities (11 of 12 activities) were estuaries in the Strait of Georgia, the Skeena River estuary, and estuaries along the west coast of Vancouver Island closer to population centers (Port Alberni, Sooke). The areas with the most total activities (both marine and terrestrial) were in the Strait of Georgia and the Skeena River estuary, with the Cowichan River having the highest total activity counts (30 activities).

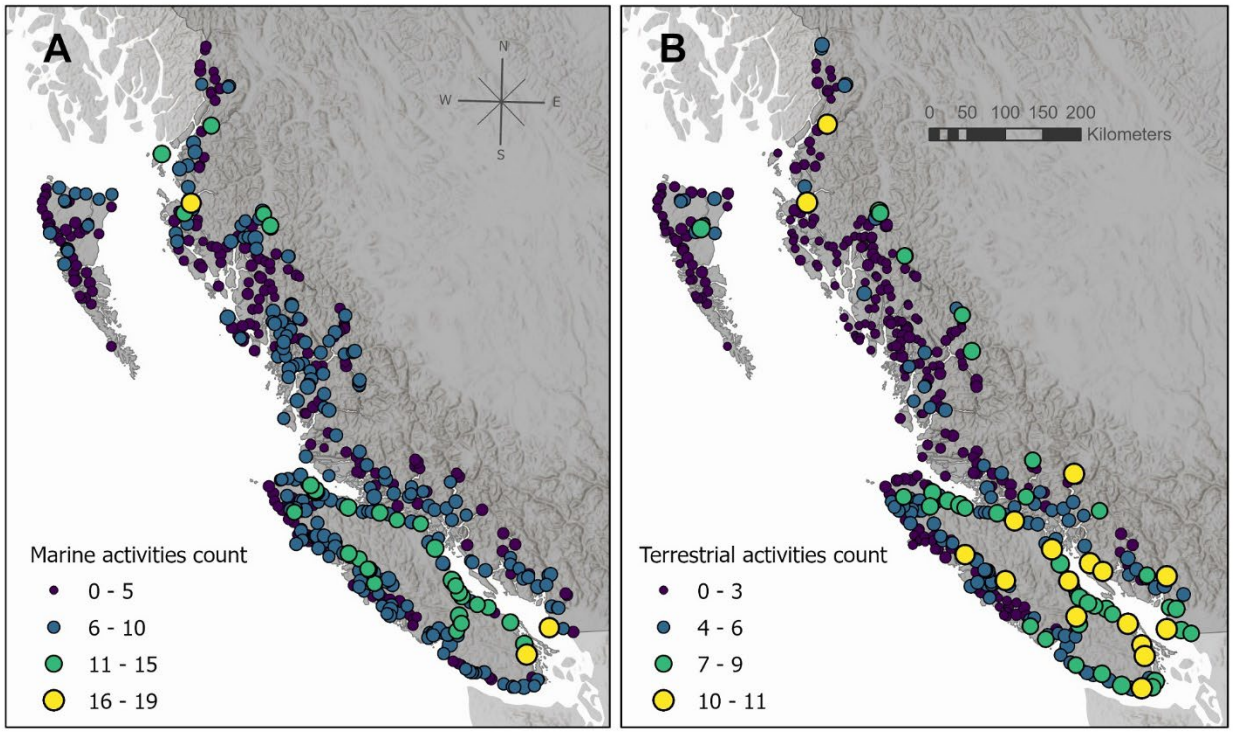

Figure 2. Count of (a) marine and (b) terrestrial human activities relevant to BC estuaries. There were 29 possible marine activities and 12 possible terrestrial activities analyzed.

Human-induced climate change

Every estuary is expected to experience some degree of human-induced climate change based on the compiled spatial data for air temperature change, stream temperature change, precipitation change, and sea level rise. Projected air and stream temperature change were highest for estuaries located up long inlets on the mainland of BC (e.g., Bute Inlet), and lowest for more northerly and exposed estuaries (e.g., Haida Gwaii). Projected precipitation change was greatest for estuaries along the outer coast of Haida Gwaii and the north coast. The northwest coast of Vancouver Island is projected to experience increases in precipitation relative to the rest of the island. The south coast of mainland BC is projected to experience little change in precipitation. Lastly, all estuaries are projected to experience at least 0.35 m of sea level rise, with sea level rise in some areas as high as 0.85 m by 2099. The most prominent areas were along the coast of Haida Gwaii and around the low-lying areas of the south coast near the Fraser River. Estuaries in Johnstone Strait are projected to experience the least amount of sea level rise.

Cluster analysis

The analysis classified estuaries into five clusters based on 41 spatial datasets representing marine and terrestrial activities that occur within the estuaries and their watersheds (Figure 3, Figure 4). This analysis does not provide a quantitative ranking of anthropogenic activity intensity for each estuary, but instead identified groupings of estuaries that experience common types and intensities of anthropogenic impacts. The estuary categories are described in Table 1.

The analysis identified five clusters that span a gradient from low to high numbers of anthropogenic activities (Figure 3, Table 1). The cluster with the highest numbers of activities was comprised of estuaries with the most terrestrial development (e.g., shoreline development, agriculture, mining, industry in the watershed, general watershed development) or marine

activities that occur near populated areas (e.g., marinas, dredging, derelict vessels, wastewater outflow). Estuaries in this cluster tended to be the largest and are associated with the largest rivers and watersheds (e.g., Fraser, Nass, Skeena; Table 1). The remaining four clusters were mainly associated with marine activities and forestry, reflecting that they tend to occur in less populated areas of the coast (Figure 3). Two of these clusters had intermediate numbers of activities (Table 1), one (Cluster 2) associated with forestry and prawn, shrimp, and crab fishing, the other (Cluster 5) associated with salmon and recreational groundfish fishing. Two other clusters had low numbers of activities (Table 1), one (Cluster 4) associated with shipping, recreational boating, and select types of commercial fishing (dive, hook and line, pressure hose), while the other (Cluster 3) had no significantly associated activities.

Fish and fish habitat evaluation

The presence of fish and fish habitat varied among estuaries. There were escapement observations for at least one species of Pacific salmon in 76% of the estuaries, 20% of the estuaries had all five Pacific salmon species present, and 21% of the watersheds associated with estuaries had CUs for salmon populations. In addition, 21% of the estuaries were adjacent to areas of herring spawn biomass. Generally, estuaries in Cluster 1 had the highest salmon biomass and conservation unit count, but also high activity counts, with the largest estuaries (Fraser, Nass, Skeena) having some of the highest values and counts (Figure 4). Dungeness Crab was likely present in 84% of the estuaries (based on probability of occurrence 50% or greater). Eelgrass was present in 43% of the estuaries, understory kelp in 82% (i.e., brown and green kelp), and saltmarsh in 81%. All three habitat types were present in 36% of the estuaries. Notable species and habitat associations in the clusters are listed in Table 1.

Comparison with past processes

Cumulative impact mapping values and estuary rankings for waterbirds varied among the clusters (Table 1). Cumulative impact scores scaled with the number of activities present per estuary, with Cluster 1 having the highest scores and activities count, and Clusters 3 and 4 having the lowest scores and activities counts. Generally, estuaries in Cluster 1 were most important for waterbirds, but also had the highest activity counts.

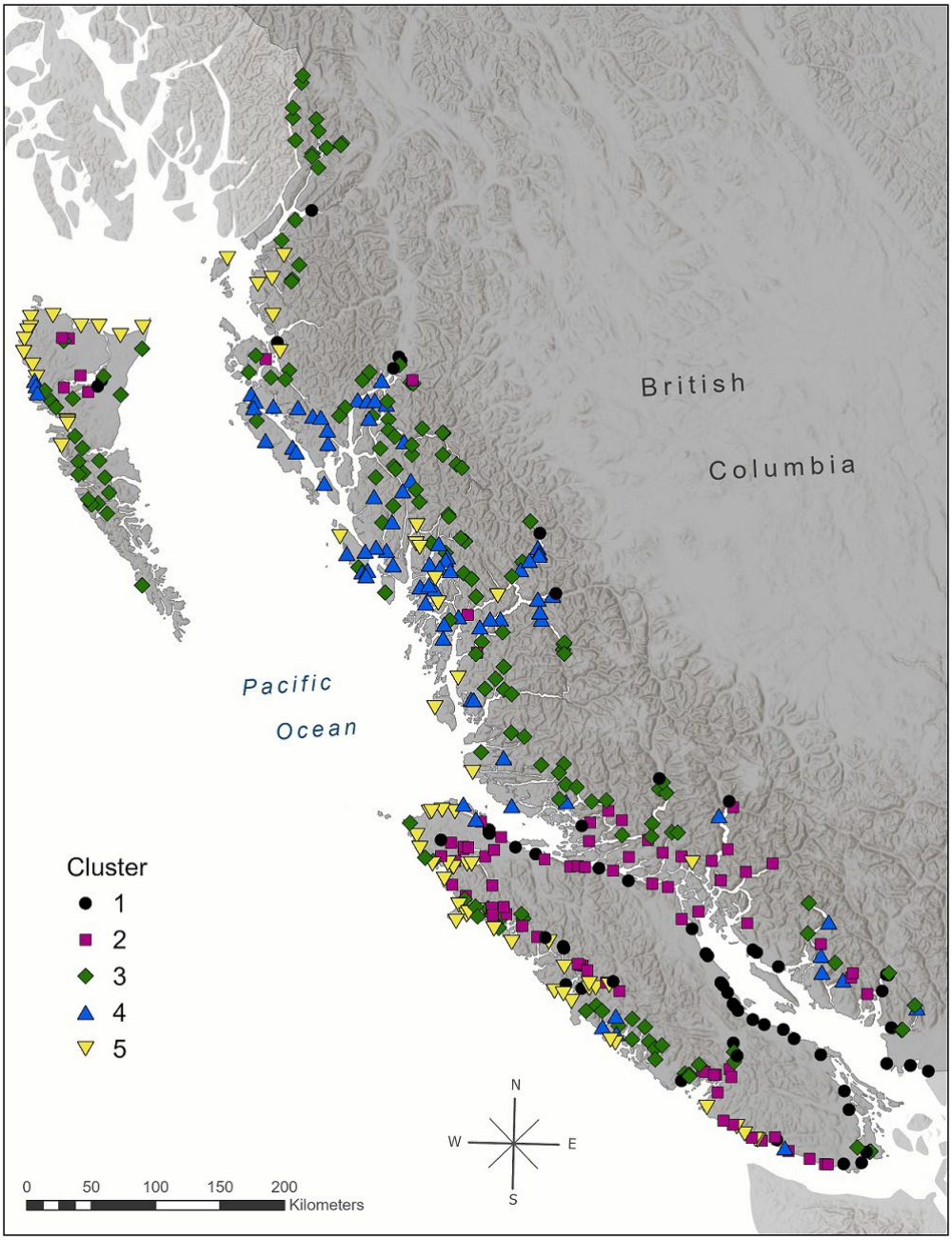

Figure 3. Map of the estuaries across the BC coast, with the colour and shape of each point specifying its cluster based on associated anthropogenic activities.

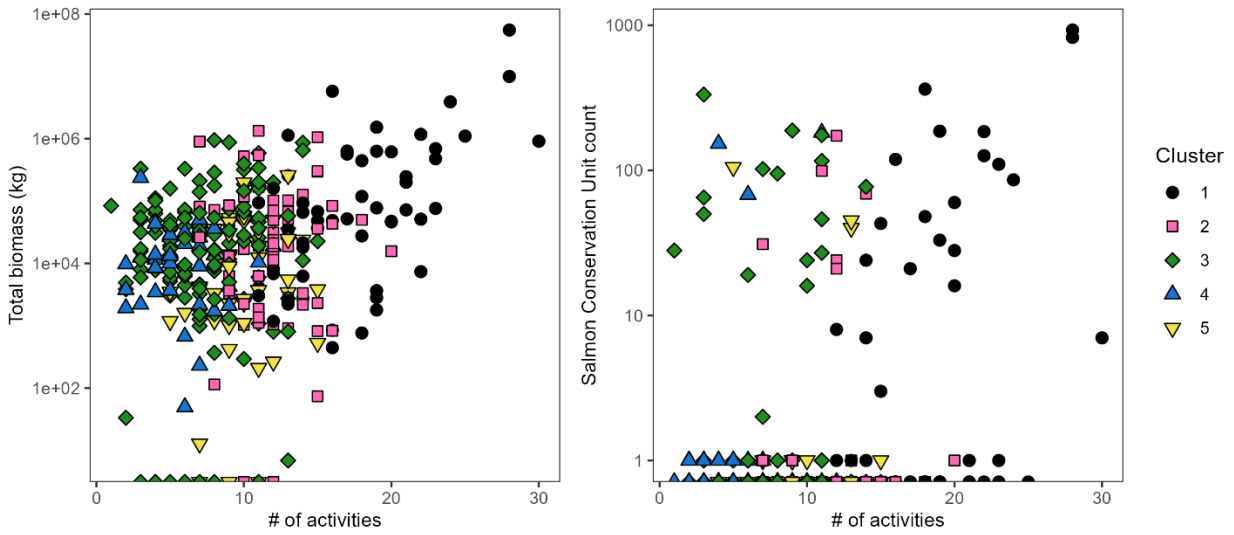

Figure 4. Scatterplot comparing the number of activities that occur within each estuary with total escapement biomass and Conservation Unit counts of Pacific salmon (all species). The colour and shape of each point indicates the estuary cluster based on associated anthropogenic activities. The y-axis is log transformed to reduce the emphasis on the few estuaries with extremely high escapement biomass. Estuaries with 0 recorded escapement biomass are shown at the lower margin of the y-axis.

Table 1. Description of estuary categories resulting from cluster analysis of associated anthropogenic activities and stressors. Associated activities are those that have significantly ($p<0.05$) higher magnitude in a cluster compared to the other clusters.

Cluster # and symbol	General description	# estuaries	# significantly associated activities	# of non-zero activities (mean and range)	Associated activities	Location	Fish and fish habitat examples	Climate highlights (mean values)
1 ●	Large estuaries and watersheds with highest numbers of human activities (e.g., Fraser, Skeena, Nass)	59	16	17.5 [11 - 30]	shellfish aquaculture freshwater obstructions dams general development industry in watershed shoreline development mining dredging wastewater outflow (organic) wastewater outflow (inorganic) burned areas agriculture aquatic invasives anchor scours derelict vessels marinas	Mainly Strait of Georgia; also scattered across all parts of the region.	Geometric mean salmon escapement biomass – 29883 kg % of estuaries with two or more intertidal biogenic habitat types present: 97%	Highest temperature (3.41 ºC) and stream temperature (2.53 ºC) change Lowest precipitation change (20.2 mm/yr.) Second lowest sea level rise (0.551 m)

Cluster # and symbol	General description	# estuaries	# significantly associated activities	# of non-zero activities (mean and range)	Associated activities	Location	Fish and fish habitat examples	Climate highlights (mean values)
2 	Medium sized estuaries and watersheds with moderate levels of human activity (e.g., Sarita River, Jordan River, Mohun Creek)	78	6	11.7 [7 - 20]	forestry cut blocks recreational prawn and shrimp fishing recreational crab fishing commercial trap fishing log handling floating homes and lodges	Mainly Vancouver island, and mainland to the east of Vancouver Island, with a few estuaries scattered across other regions.	Geometric mean salmon escapement biomass – 5052 kg % of estuaries with two or more intertidal biogenic habitat types present: 77%	Second highest temperature (3.37 ºC) and stream temperature (2.41 ºC) change Second lowest precipitation change (27.2 mm/yr.) Lowest sea level rise (0.537 m)
3 	Medium sized estuaries and watersheds with lower levels of human activity (e.g., Kitlope River, Deena Creek, Bear River)	157	0	7.4 [1 - 15]	-	Throughout region but more common on Haida Gwaii and on the central and northern coast.	Geometric mean salmon escapement biomass – 4396 kg % of estuaries with two or more intertidal biogenic habitat types present: 75%	Moderate temperature (3.20 ºC) and stream temperature (2.37 ºC) change Second highest precipitation change (40.8 mm/yr.) Second highest sea level rise (0.612 m)

Cluster # and symbol	General description	# estuaries	# significantly associated activities	# of non-zero activities (mean and range)	Associated activities	Location	Fish and fish habitat examples	Climate highlights (mean values)
4 	Small estuaries and watersheds with lower levels of human activity (e.g., Betterridge Inlet, Havenor Lagoon, Oyster Bay)	77	5	6.0 [1 – 12]	shipping recreational boating commercial dive fishing commercial hook and line fishing commercial pressure hose fishing	Mainly Central and Northern Coast.	Geometric mean salmon escapement biomass – 86 kg % of estuaries with two or more intertidal biogenic habitat types present: 57%	Second lowest temperature (3.02 ºC) and stream temperature (2.24 ºC) change Second highest precipitation change (40.9 mm/yr.) Moderate sea level rise (0.585 m)
5 	Small estuaries and watersheds with moderate levels of human activities (e.g., San Josef River, Pachena River, Skonun River)	68	4	9.16 [4 – 15]	debris and litter recreational groundfish fishing recreational salmon fishing commercial salmon trolling	Mainly exposed estuaries on the west and north sides of Vancouver Island and Haida Gwaii but also some scattered across the central and northern coast.	Geometric mean salmon escapement biomass – 148 kg % of estuaries with two or more intertidal biogenic habitat types present: 75%	Lowest temperature (2.91 ºC) and stream temperature (1.93 ºC) change Highest precipitation change (41.1 mm/yr.) Highest sea level rise (0.614 m)

Sources of Uncertainty

- The parameters of the literature review constrained the anthropogenic activities and associated stressors that were identified as impacting estuaries. There are other activities and stressors known from research outside the temporal scope of the search and from marine ecosystems that impact estuaries, such as goose grubbing, algal blooms, and noise pollution from vessel activity. Furthermore, Indigenous uses of estuaries were not included in this compilation of activities or resulting analysis.
- The spatial dataset used to define the estuaries may underestimate estuary presence and does not include all small estuaries (Ryder et al. 2007; PBHJV Technical Team 2020).
- The list of species considered Ecologically Significant for this work was taken from a regional assessment focused on the Northern Shelf Bioregion (Gale et al. 2019) that considered a broad suite of coastal and offshore ecosystems but did not assess all species known to reside in estuaries.
- Assessments of fish and fish habitats highlighted coastwide data gaps, which limited the assessment of all species/habitats of interest, particularly for non-commercial species. For example, spatial data for Pacific Sand Lance were only available for the Strait of Georgia and limited data were available for tidal marsh.
- Some data inputs were limited by one or more of the following issues: uncertainty of activity and biological data overlap with estuary boundaries, variable temporal and spatial coverage, and coarse resolution of activity data in relation to estuary size (e.g., gridded commercial fishing and vessel traffic data).
- Intensity values were not available for all anthropogenic activities, so instead % area overlap of the activity occurrence with the estuaries was used. In some cases, this might change the interpretation of the activity impact. For example, the impact of anchorages may best be represented by frequency of use as opposed to the footprint area.
- Not all activities are equivalent in their impact to estuaries. This study is not a cumulative impact assessment and estuaries are not ranked by their overall risk.

CONCLUSIONS AND ADVICE

- Acknowledging the overlapping and interconnected nature of anthropogenic activities and their generated stressors has implications for restoration and understanding estuarine responses to anthropogenic disturbances.
- This analysis provides a significant data resource and initial assessment to help focus further estuarine conservation and management efforts. It can be used to identify estuaries that face similar concerns, potential management options, and relevant partners and resource users.
- All estuaries assessed had at least one marine or terrestrial activity present. The most marine activities were identified in estuaries in the Strait of Georgia and the Skeena River estuary, while the most terrestrial activities occurred in estuaries the Strait of Georgia, the Skeena River estuary, the Kitimat estuary, and estuaries along the west coast of Vancouver Island closer to population centers.
- A cluster analysis was used to characterize the estuaries based on the type and intensity of activities that occur. Five clusters of estuaries and the associated characteristic anthropogenic activities (terrestrial, marine, and atmospheric) were identified.

- The analysis identified one cluster of estuaries that had high numbers of anthropogenic activities and tended to be associated with activities in the watershed (e.g., agriculture, dams) or that were associated with populated areas (e.g., wastewater outflow, marinas). The other four clusters were associated primarily with marine activities. Two clusters had intermediate numbers of activities, one with more forestry and crab and shrimp fishing, and the other having more salmon fishing. The last two clusters had low numbers of activities - one cluster was associated with shipping and recreational boating, and the other had no association with any one activity.
- Climate change (air temperature change, stream temperature change, precipitation change, and/or sea level rise) is expected to impact all estuaries to varying extents. In particular, the highest degree of stream temperature increase is expected in estuaries at the end of long inlets (e.g., Bute Inlet, Observatory Inlet). The estuaries that are projected to experience the highest degree of sea level rise are around Haida Gwaii.
- Available coastwide spatial data for salmon, other ecologically significant fish species, sensitive fish habitat, and other habitat characteristics (e.g., presence of eelgrass, macroalgae, and saltmarsh) was compiled.
- The presence of fish and fish habitat varied among estuaries. There were observations of at least one species of Pacific salmon since 1990 for 76% of the estuaries, and 20% of the estuaries had all five species present. Estuaries with the highest salmon biomass and richness were associated with the most human activities. Dungeness Crab was likely present in 84% of the estuaries. Eelgrass was present in 43% of the estuaries, understory kelp in 82%, and saltmarsh in 81%. All three biogenic habitat types were present in 36% of the estuaries.
- This work is the first step towards a comprehensive assessment of how human activities may combine and cumulate to impact estuaries. Although this work is not a cumulative impacts assessment, future analysis could combine the outputs from this work with vulnerability scores of individual estuarine species to quantify an overall risk to each estuary.
- It is recommended that management strategies consider estuaries of all sizes and may need to vary between estuaries associated with large watersheds and a distinct mix of terrestrial and marine activities versus those that are primarily associated with small watersheds and only marine activities. The range of activities that can impact estuaries creates the unique challenge of managing across jurisdictions in marine, coastal, and terrestrial environments.
- Effective management requires consideration of ongoing climate change. This assessment highlighted a subset of estuaries projected to experience more change, which may be candidates for enhanced management or mitigation to reduce multiple stressors.
- This is not a ranking or prioritization of estuaries based on overall risk, but it can be used to inform future work on cumulative impacts based on specific management needs.
- Fine-scale ecological data is needed to improve coastwide datasets and for local estuary management work. Facilitating the coordinated collection of finer scale spatial data for fish and fish habitats within estuaries could address data gaps and ground-truth existing data. Complete and validated datasets could facilitate a coastwide prioritization of estuaries based on the presence of important species and their vulnerability to anthropogenic activities.
- Estuary prioritization can continue to be advanced through partnerships, such as a coastwide working group that includes managers and local and Indigenous experts and knowledge holders.

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SOURCES OF INFORMATION

This Science Advisory Report is from the April 12-13, 2023 regional peer review on the Coastwide Evaluation and Classification of Pacific Region Estuaries based on Anthropogenic Activities and Significant Fish Habitat. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

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APPENDIX

Table A.1. Data custodians and sources for activities and associated stressors within the marine, terrestrial and climate zones. Data sources noted as 'restricted' require a data request to the custodian for access.

Activity/Stressor		Data Custodian	Data Source
Marine	Disposal at sea	Environment and Climate Change Canada	Open Data Canada - Active and Inactive Disposal at Sea
	Underwater infrastructure	Province of BC - Lands Branch	BC Data Catalogue - Crown Tenures
	Commercial anchorages	Natural Resources Canada	Pending release
	Recreational anchorages	Fisheries and Oceans Canada	Open Data Canada - ACHARE
	Anchor scours	Natural Resources Canada	Open Data Canada
	Ports and terminals	Province of BC - GeoBC	BC Data Catalogue - BC Ports and Terminals
	Docks	Fisheries and Oceans Canada	Open Data Canada - Floating structures
	Marinas	Fisheries and Oceans Canada	Open Data Canada - Floating structures
	Lodges and floating homes	Fisheries and Oceans Canada	Open Data Canada - Floating structures
	Derelict vessels	Transport Canada	Restricted
	Dredging	Environment and Climate Change Canada	Restricted
		Fisheries and Oceans Canada	Restricted - Program Activity Tracking for Habitat (PATH)
	Log handling	Province of BC - Lands Branch	BC Data Catalogue - Crown Tenures
		Province of BC - GeoBC	BC Data Catalogue - Coastal BC Marine Industrial Sites
	Aquaculture - finfish	Fisheries and Oceans Canada	Restricted
		Province of BC - Lands Branch	BC Data Catalogue - Crown Tenures
	Aquaculture - shellfish	Fisheries and Oceans Canada	Restricted
		Province of BC - Lands Branch	BC Data Catalogue - Crown Tenures
	Commercial fishing - trawl	Fisheries and Oceans Canada	Restricted
	Commercial fishing - pressure hose	Fisheries and Oceans Canada	Restricted
	Commercial fishing - hook and line	Fisheries and Oceans Canada	Restricted
	Commercial fishing - dive	Fisheries and Oceans Canada	Restricted
	Commercial fishing - trap	Fisheries and Oceans Canada	Restricted
	Salmon fishing - gill net	Fisheries and Oceans Canada	Restricted

Activity/Stressor		Data Custodian	Data Source
	Salmon fishing - seine	Fisheries and Oceans Canada	Restricted
	Salmon fishing - troll	Fisheries and Oceans Canada	Restricted
	Recreational fishing - anadromous	BC Marine Conservation Atlas	BC Marine Conservation Atlas - Sport Fishing
	Recreational fishing - crab	BC Marine Conservation Atlas	BC Marine Conservation Atlas - Sport Fishing
	Recreational fishing - groundfish	BC Marine Conservation Atlas	BC Marine Conservation Atlas - Sport Fishing
	Recreational fishing - prawn	BC Marine Conservation Atlas	BC Marine Conservation Atlas - Sport Fishing
	Recreational boating	Transport Canada	Restricted
	Shipping vessel traffic	Transport Canada	Restricted
	Aquatic invasive species	Province of BC - Ecosystems	BC Data Catalogue - Aquatic Invasive Species of BC
		Fisheries and Oceans Canada	Gale et al. (2023). European Green Crab Surveys
Terrestrial	Agriculture	Esri, Impact Observatory, Microsoft	Esri - Sentinel-2 Land Use
	Forestry cutblocks	Province of BC - Forest Analysis and Inventory	BC Data Catalogue - Harvested Areas of BC
	Burned areas	Province of BC - BC Wildfire Service	BC Data Catalogue - Fire Perimeters
	Dams	Province of BC - Freshwater Atlas	BC Data Catalogue- Freshwater Atlas Obstructions
	Freshwater obstructions	Fisheries and Oceans Canada	Restricted - Program Activity Tracking for Habitat (PATH)
		Province of BC - Knowledge Management	BC Data Catalogue - PSCIS Fish Habitat Confirmations
	Sewage and wastewater outflow - organic	Environment and Climate Change Canada	Pollutants Affecting Whales and their Prey Inventory Tool
	Sewage and wastewater outflow - inorganic	Environment and Climate Change Canada	Pollutants Affecting Whales and their Prey Inventory Tool
	Shoreline debris	Province of BC - Environmental Protection Division	BC Data Catalogue - PICES 5km Debris Ratings
	Mining	Province of BC – Geological Survey	BC Data Catalogue - MINFILE Production Database
	Shoreline development (500 m inland)	Esri, Impact Observatory, Microsoft	Esri - Sentinel-2 Land Use
		Province of BC - GeoBC	BC Data Catalogue - Digital Road Atlas
		Province of BC - Forest Tenures Branch	BC Data Catalogue - Forest Tenure Road Segment Lines
		Natural Resources Canada	Open Data Canada - National Railway Network
		Province of BC - Water Management	BC Data Catalogue - Flood Protection Structural Works
		Province of BC - Lands Branch	BC Data Catalogue - Crown Tenures
		Province of BC - GeoBC	BC Data Catalogue - Coastal BC Marine Industrial Sites
		Coastal and Ocean Resources	ShoreZone

Activity/Stressor		Data Custodian	Data Source
		Province of BC - Economics and Trade Branch	BC Data Catalogue - BC Major Timber Processing Facilities
		BC Energy Regulator	Pipeline segments and rights-of-way
	Industry in watershed	Province of BC - Economics and Trade Branch	BC Data Catalogue - BC Major Timber Processing Facilities
		Province of BC - Lands Branch	BC Data Catalogue - Crown Tenures
		Province of BC - Lands Branch	BC Data Catalogue - Crown Tenures
		Province of BC - GeoBC	BC Data Catalogue - Coastal BC Marine Industrial Sites
		BC Energy Regulator	Pipeline segments and rights-of-way
	General development in watershed (not including shoreline area)	Esri, Impact Observatory, Microsoft	Esri - Sentinel-2 Land Use
		Province of BC - GeoBC	BC Data Catalogue - Digital Road Atlas
		Province of BC - Forest Tenures Branch	BC Data Catalogue - Forest Tenure Road Segment Lines
		Natural Resources Canada	Open Data Canada - National Railway Network
Atmospheric	Sea level rise	Natural Resources Canada	Open Data Canada - CanCoast
	Air temperature change	Wang et al. (2016); Mahoney et al. (2022)	ClimateBC
	Precipitation change	Wang et al. (2016); Mahoney et al. (2022)	ClimateBC
	Stream temperature change	Fisheries and Oceans Canada	Weller et al. (In prep.)[3]

[3] Weller, J.D., Moore, R.D., and Iacarella, J.C. In prep. Development of Stream Thermalscape Scenarios for British Columbia, Canada.

*Table A.2. Estuarine fish and invertebrate species identified as ecologically significant based on criteria developed by Gale et al. (2019) and estuary habitats identified in estuary management plans for British Columbia. *Dungeness crab were not identified as ecologically significant by Gale et al. (2019) but were recommended by review participants as an important component of estuary ecosystems.*

Common Name	Scientific Name
Fish Species	
Big Skate	*Raja binoculata*
Cutthroat Trout	*Oncorhynchus clarkii*
Dolly Varden	*Salvelinus malma lordi*
Eulachon	*Thaleichthys pacificus*
Green Sturgeon	*Acipenser medirostris*
Lingcod	*Ophiodon elongatus*
Longnose Skate	*Raja rhina*
Pacific Hake	*Merluccius productus*
Pacific Herring	*Clupea pallasii*
Pacific Sand Lance	*Ammodytes hexapterus*
Pacific Salmon - Chinook	*Oncorhynchus tshawytscha*
Pacific Salmon - Chum	*Oncorhynchus keta*
Pacific Salmon - Coho	*Oncorhynchus kisutch*
Pacific Salmon - Pink	*Oncorhynchus gorbuscha*
Pacific Salmon - Sockeye	*Oncorhynchus nerka*
Shiner Perch	*Cymatogaster aggregata*
Spiny Dogfish	*Squalus suckleyi*
Steelhead	*Oncorhynchus mykiss*
Surf Smelt	*Hypomesus pretiosus*
Walleye Pollock	*Theragra chalcogramma*

Common Name	Scientific Name
Invertebrate Species	
Dungeness Crab*	*Metacarcinus magister*
Littleneck Clam	*Leukoma staminea*
Nuttall's Cockle	*Clinocardium nuttallii*
Horse Clam/Fat Gaper	*Tresus capax*
Horse Clam/Pacific Gaper	*Tresus nuttallii*
Ochre Sea Star	*Pisaster ochraceus*
Sunflower Sea Star	*Pycnopodia helianthoides*
Littorina snails	*Littorina sp.*
Coonstripe/Dock Shrimp	*Pandalus danae*
Bay Ghost Shrimp	*Neotrypaea californiensis*
Spot Prawn	*Pandalus platyceros*
Habitats	
Eelgrass	*Zostera marina*
Macroalgae	Multiple species
Salt or tidal marshes	Multiple species
Channels	-
Gravel bar/reef	-
Mudflats	-
Sand flats	-

Appendix References

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THIS REPORT IS AVAILABLE FROM THE:

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ISSN 1919-5087
ISBN 978-0-660-67933-4 N° cat. Fs70-6/2023-039E-PDF

Correct Citation for this Publication:

DFO. 2023. Coastwide Evaluation and Classification of Pacific Region Estuaries based on Anthropogenic Activities and Significant Fish Habitat. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2023/039.

Aussi disponible en français :

MPO. 2023. Évaluation et classification des estuaires à l'échelle de la côte de la région du Pacifique selon les activités anthropiques et les habitats importants du poisson. Secr. can. des avis. sci. du MPO. Avis sci. 2023/039.