ShoreZone Verification in Preparation for Marine Oil Spills

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Abstract

Unconsolidated segments of shoreline, including sand, pebble and boulder beaches, increase marine biodiversity by providing habitat variation in intertidal and subtidal environments. Small pocket beaches are of particular ecological importance, especially in bedrock-dominated fjord environments, as they provide hydrodynamic refuge and high quality feeding grounds for juvenile fish, including salmon. These areas, however, are also particularly sensitive to marine oil spills, as the interstitial spaces between the sediment particles can trap oils and allow for resuspension on subsequent tides. Unconsolidated beaches also cause complications for marine response teams, as the sediments must often be completely removed if contaminated. Accurate knowledge of both the location and area of sensitive beach habitats is therefore critical, particularly in areas of heavy tanker traffic. We collected ground-truth GPS points at all segments of unconsolidated shoreline for six islands in the Douglas Channel, British Columbia, to quantify the accuracy of ShoreZone, an available and widely used shoreline database. We found that, due largely to its coarse spatial resolution, ShoreZone greatly overestimates the total amount of unconsolidated beach on these islands, while failing to identify important pocket beaches. Further, the ShoreZone database does not provide reasonable estimates of beach area. We explored other possible methods to develop accurate physical shoreline data for the British Columbia coastline, including the use of terrestrial laser scanning data and satellite and aerial imagery. Our results highlight the need for improvements in physical shoreline classification, as well as the importance of accuracy assessments of large datasets.

1 Introduction

Marine oil spills pose serious economic and environmental risks to coastal communities, making it critical for marine transport authorities to develop thorough oil spill preparedness and response plans. The Government of Canada has committed to providing a World Class Tanker Safety system to ensure sufficient measures are in place to prevent marine accidents, prepare for and respond to oil spills, and assign liability and provide compensation where necessary (Transport Canada 2015). In order to establish effective response plans and prioritize ecologically sensitive areas, however, response teams require accurate and reliable information on coastal habitat geography, including the shoreline type and area. While hydrographic and geomorphic shoreline maps are available for most of coastal British Columbia, it is important to validate and improve upon existing data, particularly when new oil and gas transport projects are implemented, existing maps become outdated, or data are used outside of their expressed purpose. The methods for developing shoreline classification maps must also be revisited in light of technological advances in remote sensing and geographic information systems. Ensuring that baseline data are accurate, precise and up-to-date is critical for providing a world-leading marine response system.

1.1 Oil Spills on Unconsolidated Shoreline

Petroleum products are detrimental to most marine flora and fauna, causing acute mortality due to chemical toxicity or smothering, chronic illness and long-term impacts on growth and reproductive health, and compromised survival due to habitat displacement and loss of prey base (Peterson *et al.* 2003). Small marine spills (10 – 100 m^3) occur approximately twice per year in Canada, and medium spills (100 – 1000 m^3) occur every 1.5 years (Transport Canada 2013). While larger spills have not yet occurred in Canada, increasing tanker traffic increases the probability of spill incidents, and therefore the associated environmental risk. Additionally, oil spills occurring in neighboring nations can impact Canadian shorelines, and have done so in the past (*e.g.* the 1988 *Nestucca* oil spill). The severity of damage incurred from a marine oil spill depends on several factors, including the size and extent of the spill, the type of oil, and the area exposed. When marine oil spills encounter consolidated rocky shorelines, the oil is frequently left to weather naturally and ecological recovery is relatively rapid (WCMRC 2014). In contrast, unconsolidated shorelines complicate clean-up efforts as oil becomes trapped in porous sediments or buried as wave activity redistributes sediments (Gundlach *et al.* 1978; Taylor and Reimer 2008). This can exacerbate environmental damage as buried oil can persist for years and continue polluting shorelines (Hayes and Michel 1999; Short 2004) and oiled sediments often must be entirely removed from the shoreline (WCMRC 2013). Additionally, unconsolidated beach habitats are often less steep than rocky intertidal surfaces, particularly in fjord environments, and therefore increase the exposed area to clean and biological loss to mitigate.

Unconsolidated shorelines function as important ecological habitat in marine systems. Sand, cobble and boulder beaches support a large variety of epi- and in-faunal invertebrate species, including clams, crabs and amphipods, which are a critical component of marine food webs. Unconsolidated beaches also act as important breeding grounds for many economically valuable fish species, including Pacific herring and surf smelt (Penttila 2007), supporting recreational, commercial and First Nations fisheries. Pocket beaches, small beaches less than 1 km in length, have unique sedimentary and morphological features, though less is known about their ecology (Nielsen *et al.* 2013). Pocket beaches are known to harbour high faunal diversity (Gauci *et al.* 2005), but support different communities than those of long beaches, including a greater abundance of terrestrial birds, algal wrack and wrack-associated invertebrates (Barreiro *et al.* 2011; Deidun and Schembri 2008; Nielsen *et al.* 2013). Pocket beaches are especially important in bedrock-dominated fjord environments, as they provide hydrodynamic refuge and feeding grounds for small migratory fish including salmon (Beamer and Fresh 2012), and increase habitat heterogeneity, which in turn increases biodiversity (Buhl-Mortensen *et al.* 2012; Kovalenko *et al.* 2012). Because of their small size however, pocket beaches are more likely to be overlooked during an oil spill, which could lead to resuspension of trapped oil residues and threaten local marine life (Taylor and Reimer 2008).

1.2 Shoreline Classification

Accurate shoreline classification maps are critical in oil spill response planning, as they form the basis for setting priorities and determining response strategies and mitigation methods (WCMRC 2014). In addition to the location of different substrates along the coastline, it is necessary for response teams to know the width and slope of each shoreline segment, so they can estimate the total area of the potential impact to better allocate resources and estimate biological sensitivity. Developing such maps, however, is an enormous task, particularly in British Columbia where the coastline is extremely long (over 25,000 km) and complex. Such a project was first undertaken in BC in the early 1980s by the Coastal Task Force, using oblique aerial photography and videography to classify shoreline segments (Howes *et al.* 1994). This project, ShoreZone, was later extended to include coastlines of Washington, Oregon and Alaska (Coastal and Ocean Resources 2013), and the methodology has been replicated in similar coastal classification projects in the Canadian Arctic (Environment Canada eSPACE project; Wynja *et al.* 2015) and in Australia (Banks and Skilleter 2002; Short 2006). Few other large scale shoreline classification projects have been conducted, though recently smaller-scale studies have tested other remote sensing technologies for various coastal mapping projects. These include the use of satellite imagery (Casal *et al.* 2011; Reshitnyk *et al.* 2014), single-beam echosounding (Reshitnyk *et al.* 2014) and airborne hyperspectral scanning (Casal *et al.* 2012) to map coastal distributions of algae, acoustic multi-beam sonar (Goff *et al.* 2000) and laser airborne depth sounding (Finkl and Makowski 2015) to map benthic substrates, and satellite (Harris *et al.* 2011) and aerial (Benedet *et al.* 2006) imagery to classify beaches based on morphodynamics. Each of these methods possesses unique advantages and limitations related to accuracy, resolution, cost and feasibility.

1.3 The Shorezone Database

ShoreZone is a coastal habitat mapping system which provides an inventory of the geomorphic and biological attributes of the intertidal and nearshore environment in the Pacific Northwest (Coastal and Ocean Resources 2013). It is intended to serve a variety of purposes including oil spill response planning, habitat research, conservation management and development evaluations. Beginning in the 1980s, the coastal regions of British Columbia were surveyed using small aircraft equipped with digital video recording and high resolution photography systems during the lowest daylight tides of the year. Over 95% of the total coastline of BC has been surveyed, and the database also extends north into Alaska and south into Washington and Oregon (Coastal and Ocean Resources 2013). ShoreZone forms the basis of many provincial Geographic Information Systems (GIS) used for marine spatial planning and management, including DataBC and the British Columbia Marine Conservation Analysis Atlas (BCMCA).

The ShoreZone database includes qualitative descriptions of shoreline substrate features, as interpreted by experienced observers (Schoch 2009). However, there are four principal sources of error in the ShoreZone protocol which affect the accuracy and precision of the classification data: 1) human subjectivity in selecting qualitative feature descriptors and determining the boundaries between shoreline units, 2) a lack of adequate basemaps on which to map the interpretations, and 3) the lack of a standardized minimum mapping unit (Schoch 2009). Together, these sources of error lead to a non-negligible amount of ambiguity in the classification data. Several internal and external verification studies have therefore been conducted to assess the accuracy and repeatability of the ShoreZone database. Harper and Morris (2008) compared aerial mapping interpretations to ground survey observations in Victoria, BC, and found that the coastal class assignment by aerial and ground observers matched in 80% of cases. Harney *et al.* (2009) similarly compared classifications by aerial and ground interpreters in Sitka, Alaska, but found that coastal class assignment matched in only 58% of observations. Finally, Schroeder *et al.* (2011) compared ShoreZone to classifications made by boat in Southeast Alaska, and found a total match of only 24%. These studies suggest that the accuracy of the ShoreZone database may deeply depend on the area of study and the method of evaluation. Complex shorelines in particular may lead to a high degree of error, as the subjective nature of the qualitative classification categories and lack of a minimum width for inclusion of a given substrate will cause variation in interpretations by different observers. Further, the oblique aerial imagery tends to cause ShoreZone interpreters to underestimate the area of shoreline features (Harney *et al.* 2009). These findings suggest that the ShoreZone database may be particularly prone to omitting small pocket beaches, and that the accuracy of ShoreZone should be verified for the purpose, and in the region, of interest prior to initiating widespread use.

1.4 Study Objectives

The objective of this study is to determine the reliability of the ShoreZone database in distinguishing between consolidated and unconsolidated shoreline substrates, and to compare this database to other datasets and potential methods of shoreline classification. The study is focused on the Douglas Channel region of northern British Columbia, the location proposed for the Northern Gateway Project, as the associated port expansion would increase the likelihood of marine oil spills in the area. Specifically, this study aims to:

1) Use ground truth data to assess the utility and accuracy of ShoreZone in quantifying the length and area of unconsolidated shoreline, particularly small pocket beaches, in the Douglas Channel region;
2) Compare the shoreline classification of ShoreZone to that of Environment Canada's National Wildlife Research Center Geomatics map in relation to the ground truth data; and
3) Test methods of performing shoreline classifications using high resolution satellite imagery and terrestrial laser scanner data from the Canadian Hydrographic Society for feasibility and accuracy.

2 Methods

2.1 Study Area and Site Selection

Douglas Channel is a large inlet on the northern coast of British Columbia, headed by the town of Kitimat and comprising more than 20 islands and 320 km of waterways. Channel widths range from 1.8 to 5 km across, depths from 18 to 365 m, and maximum surface currents from 90 to 100 cm/s (Enbridge 2010a). The fjord houses 19 parks, protected areas and conservancies, and the region overlaps with two First Nations territories, the Haisla and Gitga'at (BC Ministry of Environment 2015). Many high profile and valuable marine species utilize the Channel, including Pacific Salmon (*Oncorhynchus spp*.), Pacific Halibut (*Hippoglossus stenolepis*), Pacific Herring (*Clupea pallasi*), Killer Whales (*Orcinus orca*), Humpback Whales (*Megaptera novaeangliae*), and Sea Otters (*Enhydra lutris*) (Enbridge 2010a). Kitimat (population 8350) currently serves as a major producer of aluminum, and several new oil and gas export projects have been proposed for the region, each involving new pipelines and expanded marine traffic (District of Kitimat 2016). This includes the 1177 km Enbridge Northern Gateway Pipeline, which would transport up to 525,000 barrels of oil per day into the Kitimat Terminal, and 193,000 barrels of condensate out to Bruderheim, Alberta (Enbridge 2010b Vol. 3). This is projected to add approximately 190 to 250 tanker calls per year to terminal (Enbridge 2010b Vol. 8).

Six small islands within the channel were selected as study sites (Figure 1). These islands provide a discrete shoreline with 360˚ of exposure. They range from 2.7 to 30.7 km in perimeter and 20.1 to 139.3 km from the head of the fjord (Table 1). The three islands nearest Kitimat have shorelines similar in geomorphology to the surrounding fjord, comprised mainly of steep consolidated bedrock interspersed with small, steep coarse beaches. The three islands closer to the mouth of the fjord, particularly Rennison Island, are less precipitous with larger and more extensive beaches.

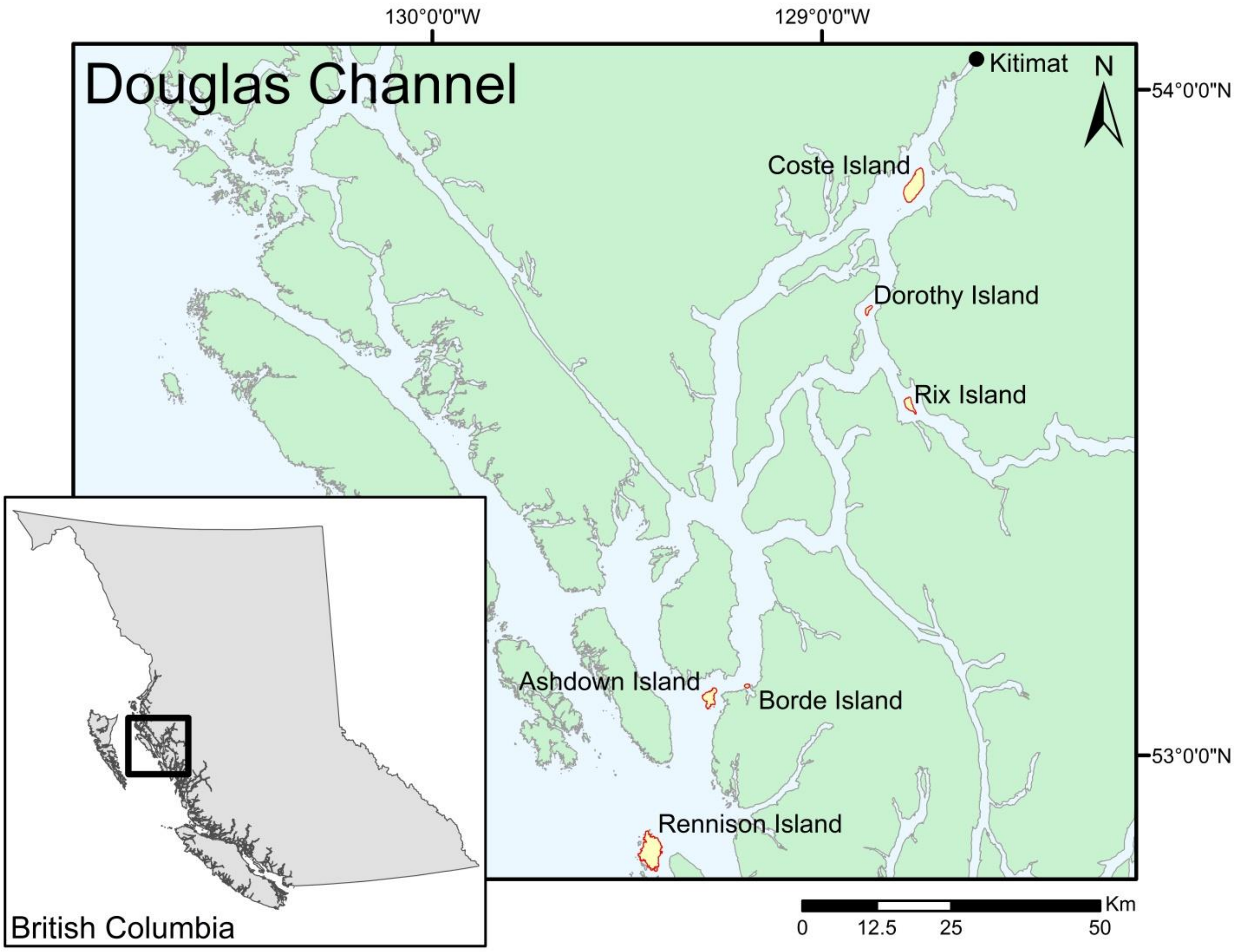

Figure 1. Map of the six study islands within Douglas Channel, British Columbia.

Table 1. Geographic size and location information for each of the six study islands.

Name	Longitude	Latitude	Distance from Kitimat (km)	Area (km^2)	Perimeter (km)
Coste	128˚44’52” W	53˚50’42” N	20.1	11.3	15.5
Dorothy	128˚51’15” W	53˚39’23” N	42.2	0.9	4.5
Rix	128˚44’28” W	53˚30’55” N	56.1	2.6	16.1
Borde	129˚07’12” W	53˚04’58” N	107.8	0.5	2.7
Ashdown	129˚12’46” W	53˚03’42” N	112.4	4.5	13.3
Rennison	129˚20’26” W	52˚49’41” N	139.3	15.6	30.7

2.2 Ground Truth Data

Ground truth surveys were performed in July, 2014, for Coste and April, 2015, for all other islands. Surveys spanned a three hour period on either side the daily lower low tide. Islands were circumnavigated by boat with stops at all changes in substrate type from consolidated rock to unconsolidated forms, and vice versa. Unconsolidated forms include boulders and all smaller substrate size fractions (Table 2). Breaks were marked using a Global Positioning System (GPS; Lowrance HDS-7 Gen2 Fishfinder/Chart Plotter) and the boat was centrally positioned for measurement of beach length and width. At each site the location of the water's edge at zero tide was estimated using tide tables and extrapolating to five minute intervals. From this position, while standing in the bow of the boat or on shore, a laser rangefinder (Bushnell G-Force DX) was used to estimate the beach dimensions and the angle from the low to high tide line, with compensation for observer height. High water levels were taken as the lower margin of the supra-littoral zone, at the limit of stranded large woody debris, wrack and, when present, the distribution of *Vericaria sp.* Remaining on board allowed the development of a rapid survey methodology and the completion of entire island perimeter surveys in a single tidal window; however, on large and complex beaches and deeply indented bays, measurements for several locations were made on foot. Reference photos were taken of all unconsolidated beaches. Using ArcGIS (version 10.3.1, ESRI 2015), GPS point data were converted to a polyline vector layer and superimposed on the ShoreZone coastline map. Rangefinder data were used to determine the length of each line segment and to associate an estimate of the total beach area with each segment.

2.3 Shorezone

ShoreZone data were obtained from the Province of British Columbia (C. Ogbourne). The database includes a polyline vector map of the entire coastline of British Columbia. Each line segment represents a single Shore Unit – a continuous section of the shoreline with similar morphological and sedimentary characteristics (see Howes *et al.* 1994). Shore Units are divided into across-shore zones, which include the backshore, intertidal, shallow-subtidal and deep-subtidal. Each zone of each Shore Unit is classified based on form (morphological character) and physical materials (refer to Howes *et al.* 1994 for further detail). Shore units are also assigned a Repetitive Shore Type (Table 2), based on the dominant structuring process, morphology, and substrate of the unit as a whole (Harper and Morris 2014).

Table 2. List of Repetitive Shoreline Types as defined in the ShoreZone database. Each category was reclassified as "unconsolidated", "consolidated" or "none" to indicate the dominant substrate form.

Repetitive Shoreline Type	Consolidation
Channel	None
Estuary, Marsh or Lagoon	None
Gravel Beach	Unconsolidated
Gravel Flat	Unconsolidated
Man-Made	None
Mud Flat	Unconsolidated
Rock Cliff	Consolidated
Rock Platform	Consolidated
Rock with Gravel Beach	Unconsolidated
Rock with Sand Beach	Unconsolidated
Rock, Sand and Gravel Beach	Unconsolidated
Sand and Gravel Beach	Unconsolidated
Sand and Gravel Flat	Unconsolidated
Sand Beach	Unconsolidated
Sand Flat	Unconsolidated

2.3.1 Isolating Unconsolidated Segments

Using ArcGIS, the ShoreZone database was clipped to each of the six study islands. Repetitive Shoreline Types corresponding with unconsolidated materials (Table 2) were isolated into a single vector layer for each island. A separate analysis using form and material classifications was performed for each island. Codes including "Clastic", "Biogenic coarse shell" or "Biogenic fine shell hash" were isolated to create a new vector layer representing only unconsolidated shoreline segments. Backshore (Zone A) data were available for all study islands, while intertidal (Zone B) data were not available for Ashdown and Borde Islands. Therefore, separate unconsolidated segment vector layers were created for each of the two zones.

2.3.2 Beach Area Estimations

A vector layer of the lowest low water mark from the Canadian Hydrographic Service was used to define the lower boundary of the unconsolidated beaches, while the ShoreZone coastline was taken as the upper boundary. Polygon shapefiles were created for shoreline segments. Shoreline slopes are defined by ShoreZone as either <5˚, 5-20˚ or >20˚. Beach slopes were therefore averaged (3˚, 13˚ or 55˚, respectively) and the average slope and average polygon width were used to estimate the total area of each beach.

2.3.3 Ground Truth Comparison

Each unconsolidated shoreline vector layer created from the ShoreZone data was overlaid with the vector layer created from the ground truth data. Matched regions – those in which both ShoreZone and the ground truth data indicate the presence of unconsolidated shoreline – were isolated to reveal the total length of shoreline classified similarly or differently by each dataset. The area of beach associated with each matched or mismatched section of shoreline was calculated.

2.4 NWRC Geomatics Map (Eemap)

Shoreline classification data for Rennison Island were obtained from the National Wildlife Research Center Geomatics Lab at Carleton University. This project, in association with Environment Canada, used interpretation of aerial video and photos to classify shoreline segments, a method similar to that of ShoreZone (Laforest *et al.* 2015). Helicopter and ground truth surveys in the Douglas Channel were conducted during the summers of 2013 and 2014, and shorelines were classified as one of fourteen shoreline types (Table 3). Shoreline classification data were available for only one of the six study islands (Rennison Island). As with ShoreZone, the data are represented in a linear vector layer with shoreline segments indicating a continuous shoreline type. Shoreline type categories indicating unconsolidated substrates were isolated in a new vector layer (Table 3). This information was then superimposed onto the ShoreZone coastline and compared to the ground truth data.

Table 3. List of Shoreline Types as defined in the NWRC Geomatics Map database. Each category was reclassified as “unconsolidated”, “consolidated” or “none” to indicate the dominant substrate form.

Shoreline Type	Consolidation
Bedrock Cliff/Vertical	Consolidated
Bedrock Platform	Consolidated
Bedrock Sloping/Ramp	Consolidated
Boulder Beach or Bank	Unconsolidated
Man-Made Permeable	None
Marsh	None
Mixed Sediment Beach or Bank	Unconsolidated
Mixed and Coarse Sediment Tidal Flat	Unconsolidated
Mud Tidal Flat	Unconsolidated
Pebble/Cobble Beach or Bank	Unconsolidated
Sand Beach or Bank	Unconsolidated
Sand Tidal Flat	Unconsolidated
Sediment Cliff	Unconsolidated
Vegetated Bank	None

2.5 Satellite Imagery

High resolution satellite imagery for the study sites was obtained from the WorldView satellite series (DigitalGlobe™). WorldView imagery offers 8 spectral bands ranging from 400 to 1040 nm. WorldView-2 imagery provides 0.46 m panchromatic and 1.85 m multi-spectral resolution, while WorldView-3 imagery provides 0.31 m panchromatic and 1.24 m multi-spectral resolution. As intertidal visibility is necessary for shoreline identification, we sought images taken during the lowest low tides with minimal cloud cover. Specifications for each image are given in Table 4.

Two methods were used to isolate unconsolidated shoreline segments in satellite images. Unconsolidated beaches were first identified manually by examining the high resolution images and mapping the locations of suspected unconsolidated substrates. Beach locations were then superimposed onto the ShoreZone coastline for ease of comparison with ground truth data. The process was then automated using rule-based feature extraction in the remote sensing software ENVI™ (version 5.1, Exelis 2013). Multi-spectral images were classified by restricting the spectral range of the coastal blue (400-450 nm) and green (510-580 nm) bands and panchromatic images were classified by restricting features by area, texture and brightness to isolate unconsolidated substrates. Regions positively identified in both the multi-spectral and panchromatic images, consisting of more than three pixels, and below the high tide mark were taken as unconsolidated shoreline segments. These locations were then mapped onto the ShoreZone coastline.

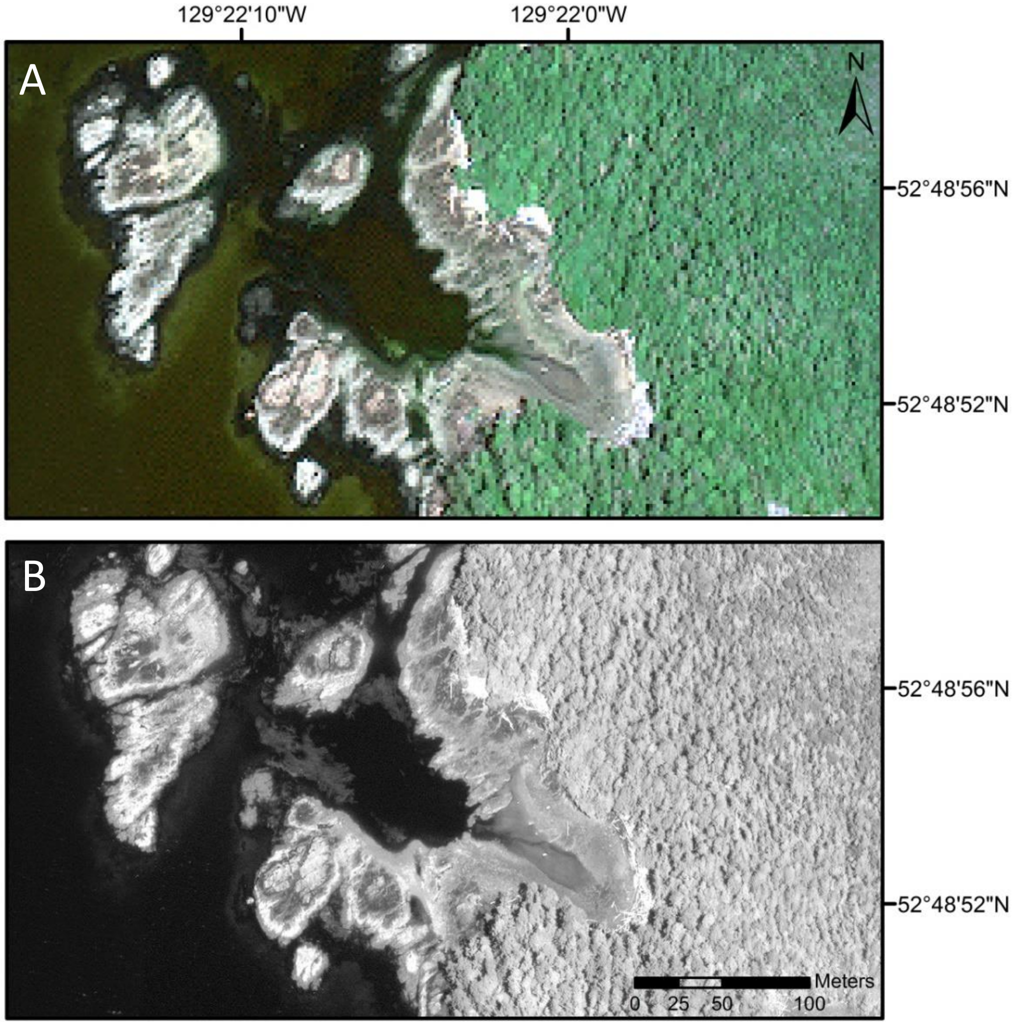

Figure 2. Example of multi-spectral (A) and panchromatic (B) WorldView-3 satellite imagery from Rennison Island. Image was taken June 23, 2015, at 24˚ off-nadir. Approximate tidal height is 1.8 m above chart datum.

Table 4. Image specifications for WorldView satellite imagery.

Island	Satellite	Image Date	Time (PDT)	Approximate Tide Height (m)	Cloud Cover (%)	Off-nadir angle (˚)
Coste	WorldView-2	12/05/2012	12:25	1.3	0.0	18.0
Dorothy	WorldView-2	06/09/2012	13:14	3.2	1.0	2.0
Rix	WorldView-2	12/05/2012	12:25	1.3	0.0	18.0
Borde	WorldView-3	23/06/2015	12:47	1.8	5.0	9.0
Ashdown	WorldView-3	23/06/2015	12:47	1.8	1.0	24.0
Rennison	WorldView-3	23/06/2015	12:47	1.8	1.0	24.0

2.6 Terrestrial Laser Scanning Data

Terrestrial laser scanning provides accurate point locations as well as a relative estimate of surface reflectance. These data have previously been used to map rock faults and surface geometry of vertical cliff faces (Humair *et al.* 2015; Matasci *et al.* 2015). Terrestrial laser scanner (ILRIS-HD, Optech Inc.) data for Rennison Island were collected by the Canadian Hydrographic Service on June 4 and 5, 2015. Data points were collected around the perimeter of the island by boat during low tides. Each point indicates a three dimensional location on the shoreline, as well as the intensity of the return signal. Points falling between 0 and 6 MASL in elevation were isolated. Points associated with known locations for six unconsolidated and six consolidated shoreline segments were selected as training samples. The histograms of the intensity data for the unconsolidated and consolidated points were used to assign a probability to each intensity value. Each point in the dataset was then assigned a binary value to indicate whether the intensity value of that point has a greater probability of being consolidated or unconsolidated. These binary values were then mapped onto the ground truth vector layer to assess the level of agreement with known unconsolidated beach locations. This method was not successful in accurately distinguishing between consolidated and unconsolidated shoreline, and the results are therefore not presented here.

3 Results

3.1 Ground Truth Survey

Based on the ground truth data, the number of unconsolidated beaches on each island ranges from 9 to 89, with a total of 191 individual segments and 16462 meters of shoreline (Table 5). The length of unconsolidated beaches ranges from 5 to 1196 m, with a mean of 86 m, indicating that they are predominantly small pocket beaches. Beach width varied both within and between islands, indicating that beach area cannot be approximated from beach length.

Table 5. Amount of unconsolidated shoreline on the six study islands, based on ground truth surveys.

Island	Unconsolidated Shoreline					
	Total Segments (#)	**Total Length (m)**	**Mean Length (m)**	**Total Width (m)**	**Total Area (m^2)**	**Mean Area (m^2)**
Coste	31	3813	123	44	167062	5389
Dorothy	17	424	25	25	10549	621
Rix	21	1957	93	27	53307	2538
Borde	9	309	34	22	6825	758
Ashdown	24	2087	87	45	94594	3941
Rennison	89	7872	88	58	458193	5148

3.2 Accuracy Assessments

3.2.1 ShoreZone

Overall, ShoreZone identifies more than twice as much unconsolidated shoreline as the ground truth survey, with fewer, longer segments (Table 6). The error of inclusion is very high, meaning that ShoreZone often misidentifies consolidated shoreline as unconsolidated. In many instances, the geographical location of an unconsolidated beach matches that of the ground truth survey, but ShoreZone assigns a much greater beach length (Figure 3). Most (60/99) of the segments totally or partially misidentified as unconsolidated shoreline are in the Repetitive Shore Type category 'Rock with Gravel Beach'. ShoreZone has the lowest error of exclusion of all the assessed methods for all islands except Coste, meaning that it omits fewer unconsolidated beaches. Despite this, ShoreZone also fails to identify many small beaches on all of the study islands. The omitted beaches range from 4 to 544 m, with a mean of 50 m, and are wrongly identified as 'Rock Platform' or 'Rock Cliff'. The overall accuracy of ShoreZone is greatest for Rix and Rennison Islands, and least for Dorothy Island.

A summary of results from the separate analyses of ShoreZone's Zone A and Zone B data is given in Appendix A. Where Zone A data identify all shoreline as consolidated (Coste, Dorothy and Rix Islands), the results of the Zone B and Repetitive Shoreline Type analyses are identical (Appendix A). However, where Zone B data are unavailable (Ashdown and Borde Islands), the Repetitive Shoreline Type analysis does not match the Zone A analysis, suggesting that information from Zone B was incorporated in the assignment of Repetitive Shoreline Types.

Shoreline area estimations for ShoreZone were largely unsuccessful due to inaccuracies in the CHS Low Water Mark map, which frequently crossed the CHS High Water Mark and the ShoreZone coastline, and the imprecision of the ShoreZone slope estimates. Area estimates for ShoreZone greatly exceed those of the ground truth surveys (Appendix A).

3.2.2 NWRC Geomatics Map (EEMAP)

The accuracy assessment of the NWRC Geomatics Map produced the greatest errors of inclusion and exclusion of all the methods assessed, though data are only available for Rennison Island (Table 6). Overestimated shorelines (errors of inclusion) are typically classified as 'Boulder Beach or Bank', 'Mixed Sediment Beach or Bank', or 'Pebble/Cobble Beach or Bank', and are almost entirely immediately adjacent to a ground truth survey beach. This suggests that inclusion errors are mostly the result of overestimating the length of beaches, rather than assigning beaches where none exist. Underestimated shorelines (errors of exclusion) are mostly classified as 'Bedrock Cliff/Vertical' and 'Bedrock Sloping/Ramp', and the length of the omitted beaches ranges from 2 to 682 m, with a mean of 58 m.

3.2.3 Satellite imagery

The manual classification of the satellite imagery resulted in fewer errors of both inclusion and exclusion than the automated classification (Table 6). The poor performance of the automated satellite image classification is related to the inability of the program to distinguish between unconsolidated and consolidated shorelines, given the methods and parameters used in this study. The manual classification of satellite imagery produced the lowest error of inclusion of all the assessed methods, suggesting that the interpreter was more conservative. The manual classification also has the lowest error of exclusion for Coste Island, and is second to ShoreZone for all other islands.

Use of high resolution satellite imagery revealed substantial inaccuracies in the location of the high water marks in the ShoreZone and CHS vector layers. However, the shoreline visible in the satellite imagery matched well with the CHS terrestrial laser scanner data. Beach area could not be accurately measured from the satellite imagery without a reliable digital elevation model (DEM) to indicate shoreline slope, and an accurate low water mark. The time required to complete the classifications was 2.8 minutes per kilometer of shoreline for the manual classification, and 10.8 minutes per kilometer for the automated classification.

Table 6. Comparison of the total number of beach segments, total beach length and associated error for each of the classification methods for each island. Accuracy of methods is tested against the ground truth survey. Error calculations are provided in Appendix B.

	Island					
	Coste	**Dorothy**	**Rix**	**Borde**	**Ashdown**	**Rennison**
Unconsolidated Segments (#)						
Ground Truth	31	17	21	9	24	89
*ShoreZone***	15	6	6	3	21	63
NWRC	NA	NA	NA	NA	NA	27
Manual Satellite	21	3	11	4	39	100
Auto Satellite	NA	40	17	20	105	262
Unconsolidated Length (m)						
Ground Truth	3813	424	1957	309	2087	7872
*ShoreZone***	8038	812	5387	838	5023	20959
NWRC	NA	NA	NA	NA	NA	9452
Manual Satellite	8424	63	1518	242	2041	6535
Auto Satellite	NA	998	348	379	3719	10943
Underestimate (Error of Exclusion %)						
Ground Truth	0	0	0	0	0	0
*ShoreZone***	31.9	*80.7	*5.6	*8.1	*20.3	*6.1
NWRC	NA	NA	NA	NA	NA	59.8
Manual Satellite	*0.1	85.1	24.0	65.0	32.4	20.6
Auto Satellite	NA	86.3	86.4	74.8	63.3	39.2
Overestimate (Error of Inclusion %)						
Ground Truth	0	0	0	0	0	0
*ShoreZone***	67.7	89.9	65.7	66.1	66.9	64.8
NWRC	NA	NA	NA	NA	NA	66.5
Manual Satellite	*54.8	*0	*2.0	*55.4	*30.9	*4.4
Auto Satellite	NA	94.2	23.6	79.4	79.4	56.2

*Indicates the method of best performance

**Repetitive Shoreline Type used for ShoreZone comparison.

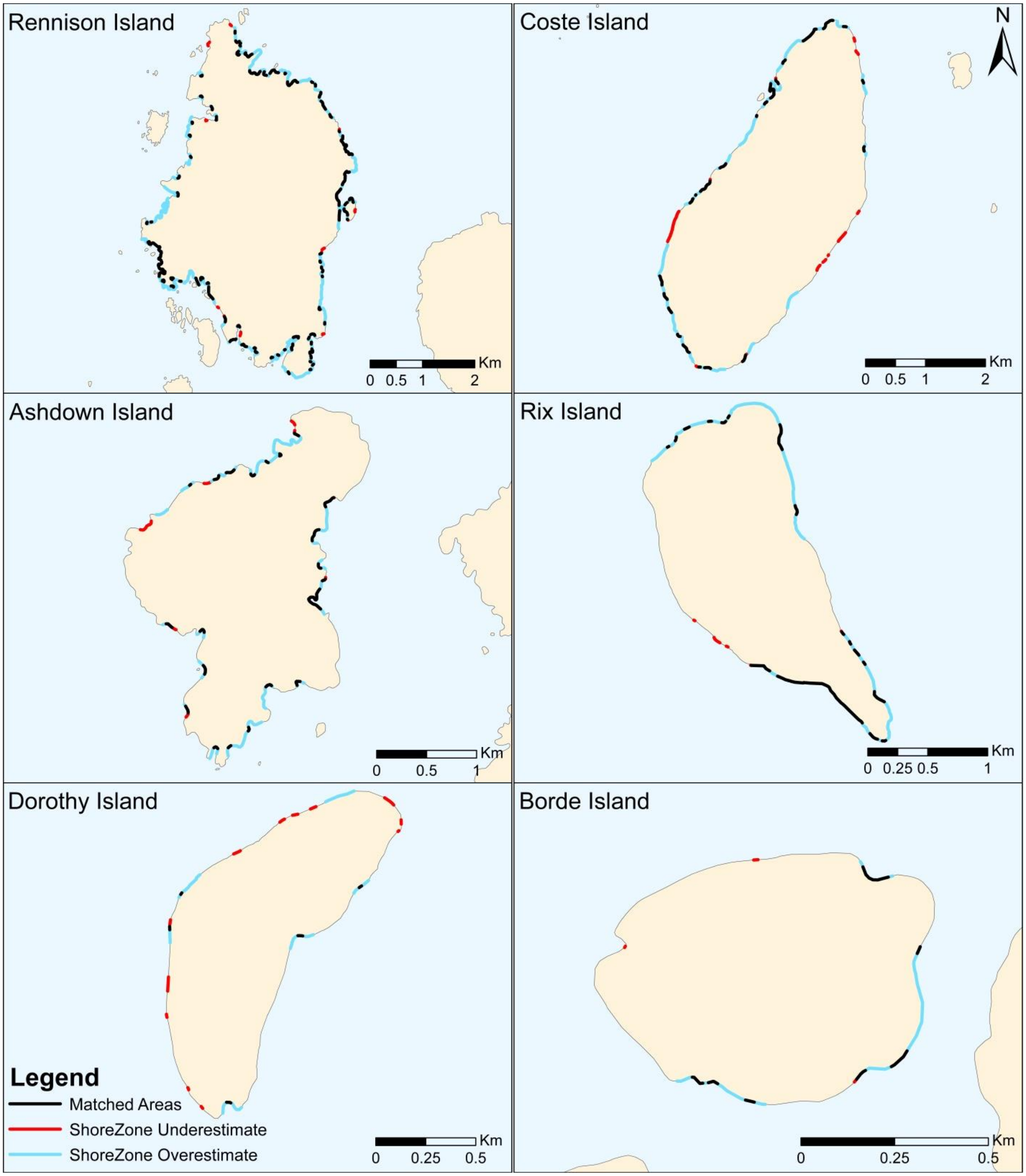

Figure 3. Maps of study islands comparing unconsolidated shoreline segments from Fisheries and Oceans Canada (DFO) ground truth data to ShoreZone Repetitive Shoreline Types. 'Matched Areas' refers to regions where both the ShoreZone and DFO datasets identify unconsolidated substrates. 'ShoreZone Underestimate' refers to regions classified as unconsolidated segments in the DFO dataset but are classified as consolidated in the ShoreZone dataset. 'ShoreZone Overestimate' refers to regions classified as unconsolidated in the ShoreZone dataset, but identified as consolidated segments in the DFO dataset. Grey lines indicate regions which both datasets identify as consolidated shoreline. Note changes in scale.

4 Discussion

Shoreline substrate properties dictate the degree of environmental damage incurred by contact with spilled petroleum products, as well as the mitigation measures that can and should be applied. As such, reliable, accurate and precise maps of both the location and area of coastal substrates are critical for preparing marine response plans, both to protect sensitive shorelines and biota from encountering oil and to efficiently allocate clean-up effort and resources. While shoreline classification maps do exist, it is important for users to be aware of accuracy of these maps and the limitations imposed by the classification methods. A ground-truth process is therefore a crucial component of any landscape classification, but particularly in very large and important datasets.

4.1 Shorezone Accuracy Assessment

Based on our analysis, ShoreZone has a tendency to overestimate both the number and size of unconsolidated beaches. This is largely influenced by the length of shoreline segments (*i.e.* low spatial resolution) and the use of mixed substrate categories, such as 'Rock with Gravel Beach' and 'Rock, Sand and Gravel Beach'. Despite this propensity to be highly inclusive, the ShoreZone database still misses 25 to 1218 m of unconsolidated shoreline per island, and most of the omitted beach segments are less than 50 m in length. This finding suggests that, in its current form, the ShoreZone database is not precise enough to locate sensitive pocket beaches.

This assessment is unique from previous ShoreZone verification studies, in that we applied a methodology specifically designed to address the needs of oil-spill responders. The overall accuracy attained by the ShoreZone database in this analysis fell between that of Harper and Morris (2008) and Harney *et al.* (2009), with overall accuracies ranging from 54% to 78%, though the reduction of Repetitive Shoreline Types into only two broad categories (consolidated and unconsolidated) necessarily improved ShoreZone's performance. This further illustrates that the accuracy of the ShoreZone data varies from one region to the next. This study does, however, highlight many of the same ShoreZone weaknesses identified by Schoch (2009). The lack of a high resolution basemap on which to situate interpreter classifications means that errors in the size and location of beaches will occur, as observations are forced to conform to the existing vector layer, and the lack of a minimum mapping unit causes many small shoreline segments to be overlooked or lumped into broader, mixed substrate categories.

Our assessment also differs from previous studies in that we attempt to specifically address the issue of beach area. Because of the oblique nature of the ShoreZone aerial imagery, and the lack of a reliable map of the low water mark, it is not possible to accurately estimate beach area from the ShoreZone data. Further, our ground survey measurements illustrate that beach width varies substantially from one beach to another, and from one island to another, so the length of unconsolidated shoreline cannot be used as an adequate proxy for area. This is a major drawback of the current ShoreZone database that restricts its utility for oil-spill response programs.

4.2 Study Limitations

This study suffers from several constraints which may contribute to errors in the analysis or limit the applicability of the results. First, the sample consists of only six small, non-randomly selected islands in one region of British Columbia. These islands may not adequately represent the geomorphology of the surrounding mainland or larger islands in the Douglas Channel, and definitely not represent the entire BC coastline. Similarly, the accuracy of the ShoreZone data on these islands may not be representative of the accuracy of the entire ShoreZone database. In fact, comparison with other ShoreZone verification studies suggests that the accuracy may vary substantially from on area to another. Second, the methodology used for the assessment introduces some error into the analysis. Shifting the ground truth survey data onto the ShoreZone coastline causes discrepancies in the geographic location of beaches, and, as previously mentioned, dividing ShoreZone into a binary classification system in which mixed substrate categories are classified as ‘Unconsolidated’ causes the ShoreZone database to be overly inclusive.

4.3 Additional Classification Methods

The NWRC Geomatics Map uses a methodology similar to that of ShoreZone. As such, it suffers from many of the same weaknesses related to subjective interpretation of oblique aerial imagery. The NWRC Map has similar qualitative mixed-substrate categories that create ambiguity in the classification and leave room from subjective interpretations. Shoreline segments range from 150 to 1991 m, with a mean of 410 m, which demonstrates low spatial resolution similar to that of ShoreZone. Although the coastline basemap of the NWRC Map is much closer to the true coastline observed from the satellite imagery, it is not yet available for most of the BC coast, limiting its utility.

The manual satellite imagery classification performed well in our analysis, though it showed a tendency to omit more unconsolidated shoreline than ShoreZone. The satellite imagery is beneficial in that shoreline features can be accurately mapped, as they are clearly visible and the images are properly georeferenced. Visually distinguishing unconsolidated from consolidated beaches proved relatively straightforward, although the process is not perfect and is still subject to the bias of interpreters. The automated satellite imagery classification took much longer than the manual classification, and produced worse results. It would be possible to further refine the process using different software and algorithms, or a more powerful computing unit capable of processing larger amounts of imagery at one time, but based on our experience it may not be a worthwhile pursuit.

Satellite imagery interpretation also suffers from many setbacks. It is not possible to differentiate between sand, pebble and gravel beaches from the imagery, so a more specific classification is not an option. Shadows and clouds can impede interpretation, particularly in a Northern region that has limited sunlight and frequent rain. Locating images with suitably low tides for analysis is also a major challenge, and the cost of high resolution imagery is substantial (approximately \$17.50 USD/km^2). These issues could possibly be addressed by tasking a commercial or federal satellite if this method is preferred.

The analysis of the CHS intensity data was not successful in separating consolidated and unconsolidated shoreline. Intensity is a relative measure of the laser return signal strength, which varies with atmospheric conditions, target reflectivity, and distance to the target (Teledyne Optech, personal communication). These factors may have interfered with our ability to distinguish between different substrates, and further analysis would be necessary to determine if this metric could be used to successfully classify shorelines. This dataset, however, is important for improving existing CHS high and low water mark maps, and could be used in tandem with a shoreline classification system to accurately determine beach slope and area.

4.4 Recommendations

The ShoreZone database, in its current form, has several limitations that the user should be aware of prior to use. While it is useful for providing general information about shoreline geomorphology, it certainly does not provide an exact inventory of all beaches. Coastal and Ocean Resources Inc., the creator of ShoreZone, is currently engaged in updating and improving the database, including developing digital elevation models which will enable users to measure shoreline slope and area. There are also efforts to establish a minimum mapping unit to help standardize interpretations and improve repeatability (Coastal and Ocean Resources, personal communication). These developments have great potential to drastically improve the precision and accuracy of ShoreZone, and certainly could be used along with other classification systems and methods, including the NWRC Map and high resolution satellite imagery, to further advance the database. The ShoreZone project is an incredible effort that deserves commendation, but verification and accuracy assessments should always be conducted to continually improve upon existing data.

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Appendix A: Shorezone Measurements

Island	**Unconsolidated Shoreline**					
	Total Segments (#)	**Total Length (m)**	**Mean Length (m)**	**Total Width (m)**	**Total Area (m^2)**	**Mean Area (m^2)**
Coste						
Zone A	0	0	0	0	0	0
Zone B	15	8038	536	25	202272	13485
RST	15	8038	536	25	202272	13485
Dorothy						
Zone A	0	0	0	0	0	0
Zone B	6	812	135	26	21034	3506
RST	6	812	135	26	21034	3506
Rix						
Zone A	0	0	0	0	0	0
Zone B	6	5387	898	21	110473	18412
RST	6	5387	898	21	110473	18412
Borde						
Zone A	2	722	361	9	6482	3241
Zone B	NA	NA	NA	NA	NA	NA
RST	3	838	279	9	7672	2557
Ashdown						
Zone A	22	5676	258	20	110750	5034
Zone B	NA	NA	NA	NA	NA	NA
RST	21	5023	239	19	95050	4526
Rennison						
Zone A	36	10795	300	44	474664	13185
Zone B	71	25097	353	37	934506	13162
RST	63	20959	333	37	780786	12393

Appendix B: Error Matrices

Example Table. Illustration of calculations of Error and Accuracy in an Error Matrix.

Example		**Ground Truth**		Total (m)	User's Accuracy	Error of Inclusion
		Consolidated (m)	Unconsolidated (m)			
Test Case	Consolidated (m)	w	x	$(w+x)$	$w/(w+x)$	$x/(w+x)$
	Unconsolidated (m)	y	z	$(y+z)$	$z/(y+z)$	**$y/(y+z)$**
	Total (m)	$(w+y)$	$(x+z)$	$(w+x+y+z)$		
	Producer's Accuracy	$w/(w+y)$	$z/(x+z)$		$\frac{(w+z)}{(w+x+y+z)}$	
	Error of Exclusion	$y/(w+y)$	**$x/(x+z)$**			$\frac{(x+y)}{(w+x+y+z)}$

Table B1. Error Matrix for ShoreZone Coste Island classification.

Coste Island		**DFO Ground Truth**		Total (m)	User's Accuracy	Error of Inclusion
		Consolidated (m)	Unconsolidated (m)			
Shore Zone	Consolidated (m)	6256	1218	7474	83.7%	16.3%
	Unconsolidated (m)	5443	2595	8038	32.3%	**67.7%**
	Total (m)	11699	3813	15512		
	Producer's Accuracy	53.5%	68.1%		57.1%	
	Error of Exclusion	46.5%	**31.9%**			42.9%

Table B2. Error Matrix for Manual Satellite Coste Island classification.

Coste Island		**DFO Ground Truth**		Total (m)	User's Accuracy	Error of Inclusion
		Consolidated (m)	Unconsolidated (m)			
Manual Satellite	Consolidated (m)	7083	5	7088	99.9%	0.1%
	Unconsolidated (m)	4616	3808	8424	45.2%	**54.8%**
	Total (m)	11699	3813	15512		
	Producer's Accuracy	60.5%	99.9%		70.2%	
	Error of Exclusion	39.5%	**0.1%**			29.8%

Table B3. Error Matrix for ShoreZone Dorothy Island classification.

Dorothy Island		**DFO Ground Truth** Consolidated (m)	Unconsolidated (m)	Total (m)	User's Accuracy	Error of Inclusion
Shore Zone	Consolidated (m)	3357	342	3699	90.8%	9.2%
	Unconsolidated (m)	730	82	812	10.1%	**89.9%**
	Total (m)	4087	424	4511		
	Producer's Accuracy	82.1%	19.3%		76.2%	
	Error of Exclusion	17.9%	**80.7%**			23.8%

Table B4. Error Matrix for Manual Satellite Dorothy Island classification.

Dorothy Island		**DFO Ground Truth** Consolidated (m)	Unconsolidated (m)	Total (m)	User's Accuracy	Error of Inclusion
Manual Satellite	Consolidated (m)	4087	361	4448	91.9%	8.1%
	Unconsolidated (m)	0	63	63	100%	**0%**
	Total (m)	4087	424	4511		
	Producer's Accuracy	100%	14.9%		92.0%	
	Error of Exclusion	0%	**85.1%**			8.0%

Table B5. Error Matrix for Automated Satellite Dorothy Island classification.

Dorothy Island		**DFO Ground Truth** Consolidated (m)	Unconsolidated (m)	Total (m)	User's Accuracy	Error of Inclusion
Auto Satellite	Consolidated (m)	3147	366	3513	89.6%	10.4%
	Unconsolidated (m)	940	58	998	5.8%	**94.2%**
	Total (m)	4087	424	4511		
	Producer's Accuracy	77.0%	13.7%		71.0%	
	Error of Exclusion	23.0%	**86.3%**			29.0%

Table B6. Error Matrix for ShoreZone Rix Island classification.

Rix Island		**DFO Ground Truth** Consolidated (m)	Unconsolidated (m)	Total (m)	User's Accuracy	Error of Inclusion
Shore Zone	Consolidated (m)	10611	110	10721	99.0%	1.0%
	Unconsolidated (m)	3540	1847	5387	34.3%	**65.7%**
	Total (m)	14151	1957	16108		
	Producer's Accuracy	75.0%	94.4%		77.3%	
	Error of Exclusion	25.0%	**5.6%**			22.7%

Table B7. Error Matrix for Manual Satellite Rix Island classification.

Rix Island		**DFO Ground Truth**				
		Consolidated (m)	Unconsolidated (m)	Total (m)	User's Accuracy	Error of Inclusion
Manual Satellite	Consolidated (m)	14121	469	14590	96.8%	3.2%
	Unconsolidated (m)	30	1488	1518	98.0%	**2.0%**
	Total (m)	14151	1957	16108		
	Producer's Accuracy	99.8%	76.0%		96.9%	
	Error of Exclusion	0.2%	**24.0%**			3.1%

Table B8. Error Matrix for Automated Satellite Rix Island classification.

Rix Island		**DFO Ground Truth**				
		Consolidated (m)	Unconsolidated (m)	Total (m)	User's Accuracy	Error of Inclusion
Auto Satellite	Consolidated (m)	14069	1691	15760	89.3%	10.7%
	Unconsolidated (m)	82	266	348	76.4%	**23.6%**
	Total (m)	14151	1957	16108		
	Producer's Accuracy	99.4%	13.6%		89.0%	
	Error of Exclusion	0.6%	**86.4%**			11.0%

Table B9. Error Matrix for ShoreZone Borde Island classification.

Borde Island		**DFO Ground Truth**				
		Consolidated (m)	Unconsolidated (m)	Total (m)	User's Accuracy	Error of Inclusion
Shore Zone	Consolidated (m)	1787	25	1812	98.6%	1.4%
	Unconsolidated (m)	554	284	838	33.9%	**66.1%**
	Total (m)	2341	309	2650		
	Producer's Accuracy	76.3%	91.9%		78.2%	
	Error of Exclusion	23.7%	**8.1%**			21.8%

Table B10. Error Matrix for Manual Satellite Borde Island classification.

Borde Island		**DFO Ground Truth**				
		Consolidated (m)	Unconsolidated (m)	Total (m)	User's Accuracy	Error of Inclusion
Manual Satellite	Consolidated (m)	2207	201	2408	91.7%	8.3%
	Unconsolidated (m)	134	108	242	44.6%	**55.4%**
	Total (m)	2341	309	2650		
	Producer's Accuracy	94.3%	35.0%		87.4%	
	Error of Exclusion	5.7%	**65.0%**			12.6%

Table B11. Error Matrix for Automated Satellite Borde Island classification.

Borde Island		**DFO Ground Truth**		Total (m)	User's Accuracy	Error of Inclusion
		Consolidated (m)	Unconsolidated (m)			
Auto Satellite	Consolidated (m)	2040	231	2271	89.8%	10.2%
	Unconsolidated (m)	301	78	379	20.6%	**79.4%**
	Total (m)	2341	309	2650		
	Producer's Accuracy	87.1%	25.2%		79.9%	
	Error of Exclusion	12.9%	**74.8%**			20.1%

Table B12. Error Matrix for ShoreZone Ashdown Island classification.

Ashdown Island		**DFO Ground Truth**		Total (m)	User's Accuracy	Error of Inclusion
		Consolidated (m)	Unconsolidated (m)			
Shore Zone	Consolidated (m)	7827	423	8250	94.9%	5.1%
	Unconsolidated (m)	3359	1664	5023	33.1%	**66.9%**
	Total (m)	11186	2087	13273		
	Producer's Accuracy	70.0%	79.7%		71.5%	
	Error of Exclusion	30.0%	**20.3%**			28.5%

Table B13. Error Matrix for Manual Satellite Ashdown Island classification.

Ashdown Island		**DFO Ground Truth**		Total (m)	User's Accuracy	Error of Inclusion
		Consolidated (m)	Unconsolidated (m)			
Manual Satellite	Consolidated (m)	10556	676	11232	94.0%	6.0%
	Unconsolidated (m)	630	1411	2041	69.1%	**30.9%**
	Total (m)	11186	2087	13273		
	Producer's Accuracy	94.4%	67.6%		90.2%	
	Error of Exclusion	5.6%	**32.4%**			9.8%

Table B14. Error Matrix for Automated Satellite Ashdown Island classification.

Ashdown Island		**DFO Ground Truth**		Total (m)	User's Accuracy	Error of Inclusion
		Consolidated (m)	Unconsolidated (m)			
Auto Satellite	Consolidated (m)	8233	1321	9554	86.2%	13.8%
	Unconsolidated (m)	2953	766	3719	20.6%	**79.4%**
	Total (m)	11186	2087	13273		
	Producer's Accuracy	73.6%	36.7%		67.8%	
	Error of Exclusion	26.4%	**63.3%**			32.2%

Table B15. Error Matrix for ShoreZone Rennison Island classification.

Rennison Island		**DFO Ground Truth**		Total (m)	User’s Accuracy	Error of Inclusion
		Consolidated (m)	Unconsolidated (m)			
Shore Zone	Consolidated (m)	9210	484	9694	95.0%	5.0%
	Unconsolidated (m)	13571	7388	20959	35.2%	**64.8%**
	Total (m)	22781	7872	30653		
	Producer’s Accuracy	40.4%	93.9%		54.1%	
	Error of Exclusion	59.6%	**6.1%**			45.9%

Table B16. Error Matrix for NWRC Geomatics EEMAP Rennison Island classification.

Rennison Island		**DFO Ground Truth**		Total (m)	User’s Accuracy	Error of Inclusion
		Consolidated (m)	Unconsolidated (m)			
NWRC Map	Consolidated (m)	16493	4708	21201	77.8%	22.2%
	Unconsolidated (m)	6288	3164	9452	33.5%	**66.5%**
	Total (m)	22781	7872	30653		
	Producer’s Accuracy	72.5%	40.2%		64.1%	
	Error of Exclusion	27.5%	**59.8%**			35.9%

Table B17. Error Matrix for Manual Satellite Rennison Island classification.

Rennison Island		**DFO Ground Truth**		Total (m)	User’s Accuracy	Error of Inclusion
		Consolidated (m)	Unconsolidated (m)			
Manual Satellite	Consolidated (m)	22494	1624	24118	93.3%	6.7%
	Unconsolidated (m)	287	6248	6535	95.6%	**4.4%**
	Total (m)	22781	7872	30653		
	Producer’s Accuracy	98.7%	79.4%		93.8%	
	Error of Exclusion	1.3%	**20.6%**			6.2%

Table B18. Error Matrix for Manual Satellite Rennison Island classification.

Rennison Island		**DFO Ground Truth**		Total (m)	User’s Accuracy	Error of Inclusion
		Consolidated (m)	Unconsolidated (m)			
Auto Satellite	Consolidated (m)	16627	3083	19710	84.4%	15.6%
	Unconsolidated (m)	6154	4789	10943	43.8%	**56.2%**
	Total (m)	22781	7872	30653		
	Producer’s Accuracy	73.0%	60.8%		69.9%	
	Error of Exclusion	27.0%	**39.2%**			30.1%