Journal of Coastal Research	32	3	465–482	Coconut Creek, Florida	May 2016

The Environmental Implications of Sediment Transport in the Waters of Prince Rupert, British Columbia, Canada: A Comparison Between Kinematic and Dynamic Approaches

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ABSTRACT

McLaren, P., 2016. The environmental implications of sediment transport in the waters of Prince Rupert, British Columbia, Canada: A comparison between kinematic and dynamic approaches. *Journal of Coastal Research,* 32(3), 465–482. Coconut Creek (Florida), ISSN 0749-0208.

A Sediment Trend Analysis (STA®) was performed on 2474 grain-size distributions taken from the Port of Prince Rupert, British Columbia, Canada. The analysis was commissioned by the Lax Kw'alaams First Nations Band because of environmental concerns associated with future large-scale development plans, including a proposed liquefied natural gas (LNG) terminal associated with Flora Bank. Located at the mouth of the Skeena River, Flora Bank has long been considered an important nursery area for juvenile salmon. STA is an empirical technique to determine patterns of net sediment transport, which may provide a qualitative assessment of the possible environmental changes that could be expected following port construction. The patterns of transport revealed that sediments throughout the study area are derived from underlying till which is exposed in areas of strong currents. Flora Bank, a roughly 4 km^2 area of intertidal sand, contained the coarsest and most well sorted sand, which was not found elsewhere throughout the study area. Although derived from till, the sand did not form transport pathways from the other sediment types; in addition, pathways could not be determined on the bank itself. It is concluded that the surficial sediments of Flora Bank are a lag derived from underlying glacial deposits caused as coastal processes became active during a lowering sea level that reached its present position about 8000 years ago. They are, therefore, relict sediments held in place by the processes surrounding the bank. This suggests that the design plan for the proposed LNG terminal could disrupt the processes in such a way that sand could be lost from the bank. This finding is contrary to that derived from numerical modeling, which concludes that no environmental harm will be done. Efforts are presently underway for future collaboration in an attempt to resolve the discrepancy and to more accurately understand the risks to Flora Bank.

ADDITIONAL INDEX WORDS: *Sediment management, grain-size distributions, numerical modeling, Sediment Trend Analysis.*

INTRODUCTION

The coastal waters surrounding the Port of Prince Rupert (Figure 1) are under potential environmental pressure as a result of plans to build a number of large port developments. These include the construction of new terminals to accommodate for liquefied natural gas (LNG), potash, and other commodities. Such projects have the capability of altering the natural sea bed and the physical processes affecting sediment movement, with the result that undesirable erosion or deposition might alter important marine habitats or disturb previously contaminated deposits. In order to assess the probable impacts of each proposed development, it is essential to understand how the present environment is "working" with respect to the movement and behavior of sediments. With this goal in mind the Lax Kw'alaams First Nation, in conjunction with the Skeena Fisheries Commission, contracted a Sediment Trend Analysis (STA®) to cover the jurisdictional waters of the Port of Prince Rupert (Figure 2). The results of the STA were specifically applied to assess the implementation of an LNG terminal that is currently under environmental review (Figure 3).

Sediment Trend Analysis (STA®)[1]

STA is kinematic (*i.e.* empirical) model whereby patterns of sediment transport and sediment behavior are derived from relative changes in the grain-size distributions of sedimentary deposits. Its theory was first established in McLaren and Bowles (1985), and further discussions and refinements describing the technique are found in McLaren, Hill, and Bowles (2007). More recently, an up-to-date bibliography of research that has evolved since STA's inception was provided in McLaren (2014), which also described how it relates to other techniques in obtaining an understanding of sediment transport and how it can be implemented to make environmental and sediment management decisions.

DOI: 10.2112/JCOASTRES-D-15-00134.1 received 21 July 2015; accepted in revision 16 September 2015; corrected proofs received 25 October 2015; published pre-print online 24 November 2015.

[1] STA is a registered trademark owned by SedTrend Analysis Limited, which does not suggest ownership of the STA technique nor preclude any researcher or company from carrying out the STA technique as described by the author in a number of papers (*e.g.*, McLaren, Hill, and Bowles, 2007). The acronym refers only to the technique as described by McLaren (*e.g.*, McLaren, 1985, 2007); the letters *STA* cannot, however, be used by others when applying the technique.

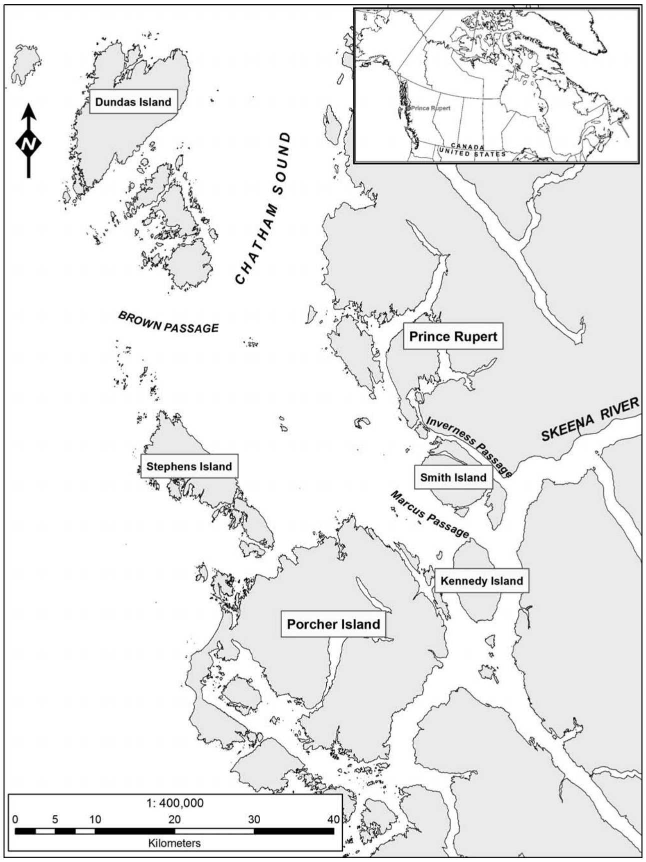

Figure 1. Regional map showing the waters and place names in the vicinity of Prince Rupert.

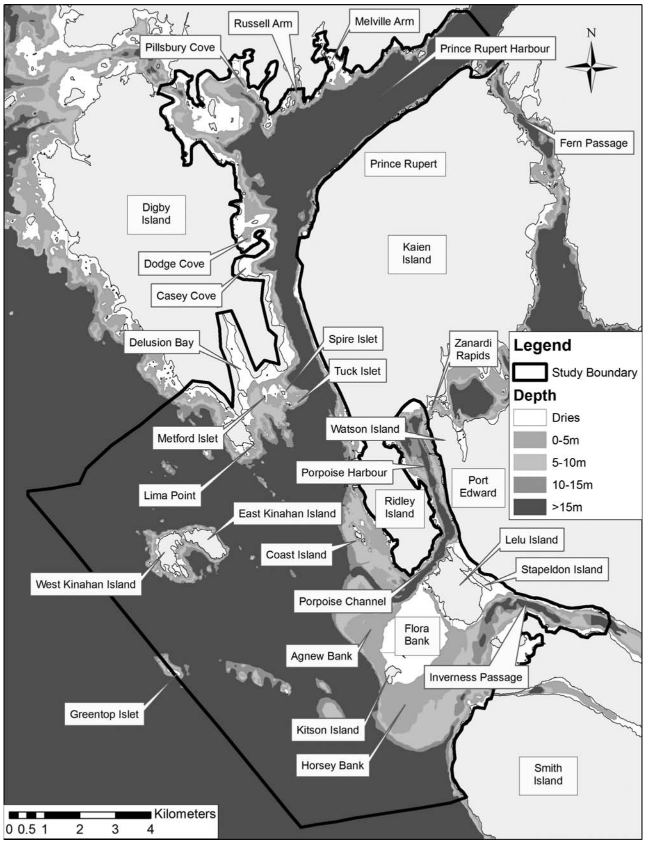

Figure 2. Study area and place names used in text.

Physical Setting

Prince Rupert and its port are situated inside a fjord that opens into Chatham Sound located on the NW coast of British Columbia, 50 km south of the Alaskan panhandle (Figure 1). Both the coast and nearshore shelf of this region were covered in ice during the last glaciation, resulting in a typical fjord coastline and, throughout the study area (Figure 2), a complex offshore bathymetry ranging from over 175 m deep to numerous exposed rocky islets. At the time of deglaciation, about 12,700 years BP, sea level was some 50 m higher than today, after which it dropped to its present position about 8000 years ago (Clague, 1984; Shugar *et al.*, 2014).

Sheltered somewhat from the open north Pacific Ocean by large islands and channels, Chatham Sound is about 1600 km^2 and is considered to be largely estuarine, being supplied with freshwater from the Nass and Skeena rivers and salt water entering from Dixon Entrance and Hecate Strait (Trites, 1952). Prevailing winds are from the SE, with stronger winds and storms able to generate wave heights from 1 to 3 m. According to Trites (1952), currents in the sound range from 0.06 to 0.10 m s^{-1}, with maximum currents reaching 0.50 m s^{-1} near the sea floor. The study area is also subject to large, semidiurnal tides of 7.5 m that generate significant currents and eddies in the passages and channels. At such places currents have been measured up to 2 m s^{-1} when river currents are combined with the ebb tide (Ages, 1995; Hoos, 1975).

Flowing a distance of 570 km from high up in the coastal mountains, the Skeena River (Figure 1), with a mean discharge of about 1750 m^{3}s^{-1}, drains a total area of 54,400 km^2. It is the second-largest river in the province and one of the longest undammed rivers in the world; it enters Chatham Sound at the southern portion of the study area, where its main channel is divided by several islands, Smith and Kennedy islands being the largest (Figure 1; Carr-Harris, Gottesfeld, and Moore, 2015).

The total amount of sediment load discharged by the Skeena River is roughly estimated to be 2–5 million t y^{-1}, and although deposits found in association with its mouth have been termed a delta (Conway, Bornhold, and Barrie, 1996), the division of the river into three principal channels has precluded the formation of an identifiable delta form. Significant sediment plumes emanate predominantly through Marcus and Inverness passages into Chatham Sound, where they can be traced NW over many kilometers depending on the state of river discharge.

METHODS

A number of steps are typically followed to collect the samples, obtain their grain-size distributions, and prepare the

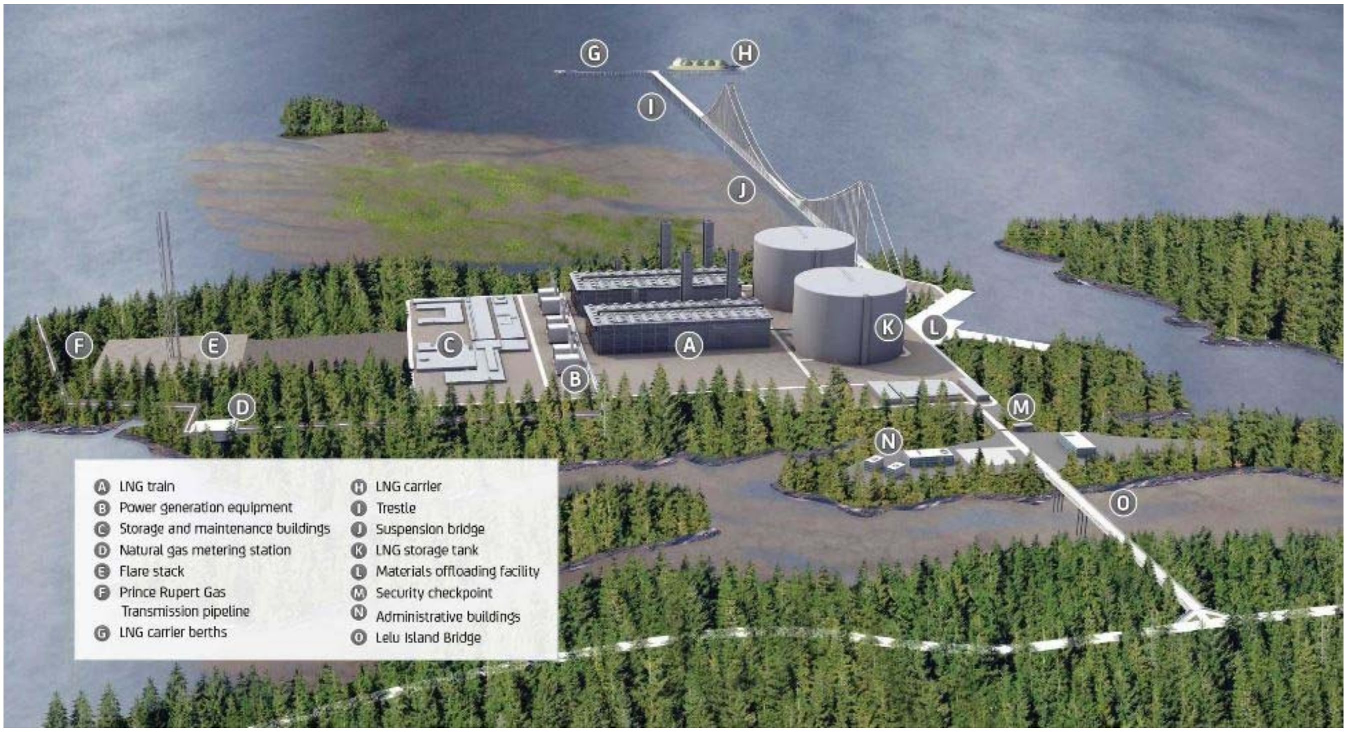

Figure 3. Artist's rendition of a proposed LNG facility on Lelu Island. View is looking SW across Flora Bank to Kitson Island (see Figure 2 for its location relative to the rest of the study area). The plan calls for a suspension bridge to avoid disturbing Flora Bank, followed by jetties supported on trestles to carry the LNG through pipes to waiting ships at the start of deep water (Pacific NorthWest LNG, 2015).

data for the STA. Specific details on sample collection, the laboratory technique, and utilization of a cluster analysis as a first step in organizing and understanding the grain-size data are described below. The STA technique itself is already presented in McLaren, Hill, and Bowles (2007).

Field Methods

Sediment grab samples were collected from 2 June to 12 July, 2014, using the Torrie Dawn, a small oceanographic workboat owned and operated by the Lax Kw'alaams First Nation. Samples were collected with a small Van Veen grab sampler, enabling the top 10 to 15 cm of sediment to be sampled. The sample design (see McLaren, Hill, and Bowles [2007] for a full discussion of criteria used to establish a sample design) was selected to cover as nearly as possible all the geomorphic environments present in the area. Spacing between samples was proposed at 500 m in the offshore, 250 m for the channels and exposed environments where coastal configurations and bathymetry are complex, and 125 m in areas where particular development concerns are focused, such as Porpoise Harbour, Ridley and Lelu islands, Flora Bank, and the Prince Rupert waterfront (Figure 2).

Navigation to and positioning of sample locations were carried out using differential GPS instrumentation to a nominal accuracy of 1.0 m. Observations of the sample were recorded. Representative samples from each grab were stored in plastic bags and shipped to the SedTrend laboratory in Brentwood Bay, British Columbia, for complete particle size analysis.

A total of 2601 sample locations were originally proposed, though samples were in fact attempted at 2647 sites, of which 162 could not be sampled due to "hard ground" (HG) (Table 1). A sampling site was designated HG after at least three drops of the grab failed to retrieve a sample. Figure 4 shows the sample locations used in the STA.

Grain-Size Analyses

All samples were analyzed at the SedTrend laboratory using a MasterSizer 2000 laser particle sizer (Malvern Instruments Ltd., Malvern, U.K.) combined with sieve distributions for sediments containing sizes greater than 1 mm. Size distributions provided the data to establish sediment trends and transport functions. For the purpose of brevity, position data, grain-size distributions, and sediment trend statistics are not provided, but they are available on request from the author

Table 1. *Summary of sample information used for the STA.*

Parameter	Number
Proposed number of sample sites	2601
Sample sites visited and sampler deployed (Figure 4)	2647
Hard ground (HG) sites where no sample could be obtained	162
Samples removed from the data base due to human errors (*e.g.*, missing or duplicated sample numbers)	11
Samples analyzed and used for the STA	2474

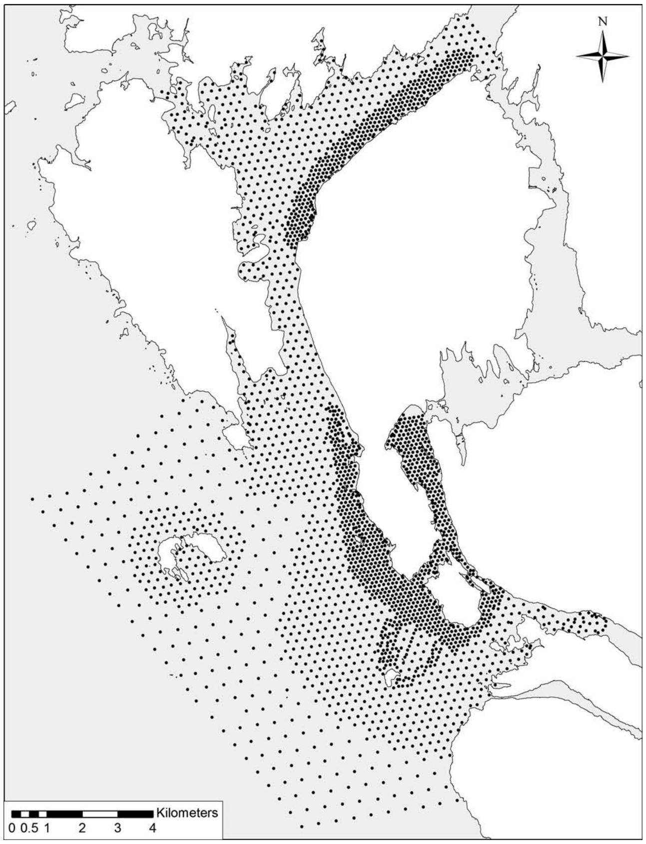

Figure 4. Sample locations visited (black dots), including sites where no sample could be obtained due to hard ground. The total number of locations is 2647.

together with a complete description of the grain-size analytical technique.

Cluster Analysis

A cluster analysis was used to find the optimum number of sediment types to describe the sediment size composition data for the 2474 sediment samples. Each sample record was a vector of 23 numbers corresponding to the percentage of the sample present at phi (ϕ) values, from minus 1.5 ϕ through plus 10.0 ϕ, at 0.5 ϕ intervals. The data were naturally scaled in that the numbers in each record must total 100%.

The data were partitioned into several classes, or "clusters," using k-means clustering (Hartigan, 1975). There are several variants of the k-means clustering algorithm, but most involve an iterative scheme that operates over a fixed number of clusters while attempting to satisfy the following properties:

(1) Each cluster has a center that is the mean position of all the samples in that cluster.
(2) Each sample is in the cluster whose center is closest.

The algorithm works by first selecting *N* samples randomly as cluster centers (where *N* is the chosen number of clusters). It then moves samples into the closest cluster, meanwhile recalculating the mean center of the cluster. This partition of samples into new clusters is repeated until any further movement of samples does not improve the mean square error of the partition. The space in which the classification takes place is that spanned by the 23 vector components, and the distance measure is Euclidean.

There is a practical limit to the number of clusters that can be reasonably represented in a region, based on the number of records, the area covered, and the assumed diversity of the environment. One method to determine the number of clusters is to keep track of the mean square error of the partition as the number of clusters increases, stopping when it is judged that the mean square error of the partition does not decrease significantly with the addition of another cluster. This approach allowed a classification of seven clusters, or sediment types that form the basis of the sediment classification scheme described in this report. The grain-size data sorted into the seven clusters are available from the author.

RESULTS

Based on the above description of the methods, the findings fall naturally into two categories. The first relates to the cluster analysis performed on the grain-size distributions of all 2474 samples, in which the sediments are divided into individual types (facies) and their interrelationships explored. The second describes the findings of the STA, which include the net sediment transport pathways and their behavior.

Sediment Types

The cluster analysis performed on the complete grain-size distributions of all samples revealed seven sediment types, making (with the inclusion of hard ground) a total of eight bottom classifications. These have been ordered by increasing mean grain-size (Table 2) and named according to the terminology described in the Wentworth grain-size scale (Wentworth, 1922). The principal features of the sediment types, as defined in Table 2 and mapped in Figure 5, are as follows:

(1) The grain-size distributions defined by the mean, sorting, and skewness indicate that cluster 4 (bimodal very fine sand) is the probable source for all the remaining sediment types. This is seen in Table 2, with clusters 1, 2, and 3 all finer, better sorted, and more negatively skewed than cluster 4; and clusters 5, 6, and 7 all coarser, better sorted, and more positively skewed than cluster 4. These observed changes in the grain-size distributions of the bottom types precisely follow STA theory (as shown in Figure 6) when determining source-deposit relationships. Figure 7 provides a summary plot of the average grain-size distributions of each cluster.
(2) The relative changes in the mean, sorting, and skewness values for each cluster (Table 2) also show that, as the sediment types become finer, the source-deposit relationship progresses from one cluster to the next. In other words, cluster 4 is the source for cluster 3, cluster 3 is the source for cluster 2, and cluster 2 is the source for cluster 1. The same is true for the coarsening sediment types: cluster 4 is the source for cluster 5, and cluster 5 is the source for cluster 6. However, cluster 7 is an exception. The skewness value (boldface in Table 2) is not more

Table 2. *Sediment types in the study area (see Figure 5). Note that clusters 1, 2, and 3 are all finer, better sorted, and more negatively skewed when compared with cluster 4, which is in boldface for easy reference. Similarly, clusters 5, 6, and 7 are coarser, better sorted, and more positively skewed when compared with cluster 4. These relationships indicate that cluster 4 is the likely source sediment for all the other sediment types. The skewness value in boldface for cluster 7 is more negative than the cluster 6 and cluster 5 values, indicating that cluster 7 cannot be derived from the medium and fine sand clusters (see text for full explanation).*

Sediment Type (cluster)	Mean Phi Size	Mean Sorting	Mean Skewness	Number of Samples	Percentage
1. Medium silt (fine)	5.79	1.62	−0.24	890	34
2. Medium silt (coarse)	5.23	1.74	0.04	514	19
3. Unimodal very fine sand	4.37	1.86	0.43	324	12
4. Bimodal very fine sand	**3.55**	**2.39**	**0.48**	235	9
5. Very fine sand	3.03	1.45	1.46	138	5
6. Fine sand	2.32	1.28	1.69	164	6
7. Medium sand	1.49	0.75	**0.66**	207	8
8. Hard ground				162	6
Totals				2636	100

positive than the skewness of clusters 6 or 5; therefore, cluster 7, though ultimately derived from cluster 4, has not followed the "pathway" through the preceding two clusters.

(3) The bimodal very fine sand (cluster 4) comprising only 9% of all the samples is typically found in two distinct areas. The first is where tidal current velocities are likely to be higher than elsewhere, such as the narrow channels entering Prince Rupert Harbour, Porpoise Harbour, Inverness Passage, and the outflow area where the Zanardi Rapids enter the northern end of Porpoise Harbour (Figure 5; see Figure 2 for place names). In each of these regions, HG areas are also prevalent (Figure 5), supporting the concept of high currents, which can result in the removal of sediment altogether or produce an armored surface layer unable to be penetrated by the grab sampler. Secondly, cluster 4 is also found in association with channel sides and rock outcrops. An examination of Figure 5 shows scattered cluster 4 samples along the shoreline of both sides of Prince Rupert Harbour and parts of the Porpoise Harbour shoreline, as well as adjacent to the predominantly rocky shores of the Lima Point area and the Ridley, Coast, East Kinahan, and West Kinahan islands. In addition, the small, rocky islets of Metford, Spire, Tuck, and Greentop all provide nearshore areas where cluster 4 sediments were sampled.

(4) Apart from the anomalous bimodality of cluster 4, the remaining sand clusters are unimodal and range from very fine to medium (Table 2). These are found most often in association with shallow bays and inlets, with the exception of the Flora Bank region, which is almost uniquely composed of medium sand (cluster 7) and is

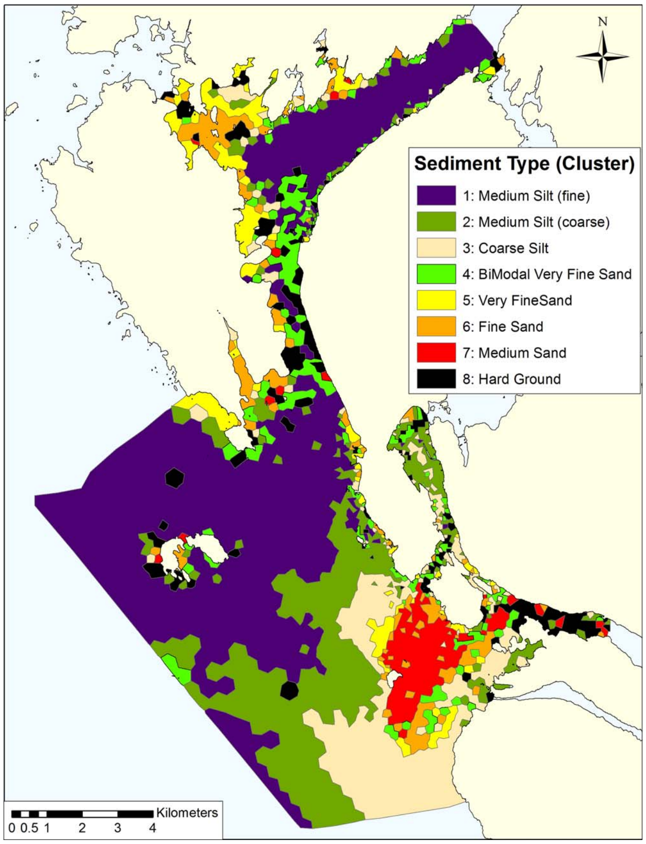

Figure 5. Sediment types as determined by cluster analysis. The clusters are ordered by increasing grain size, as in Table 2.

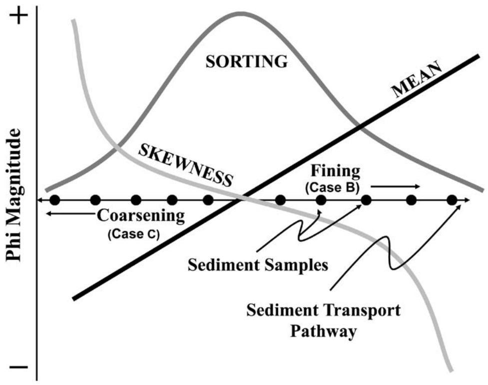

Figure 6. Diagrammatic summary of STA theory showing the sequential changes in mean grain size, sorting, and skewness that must occur when sediments are related to each other by transport (McLaren and Bowles, 1985). The distribution of cluster 4 (Table 2) would lie on the x-axis in close proximity to the maximum sorting value and where the mean and skewness values intersect. Fining sediment types are to the right and coarsening sediment types are to the left, which can be observed in the average grain-size distributions of all the clusters, as shown in Table 2 and Figure 7.

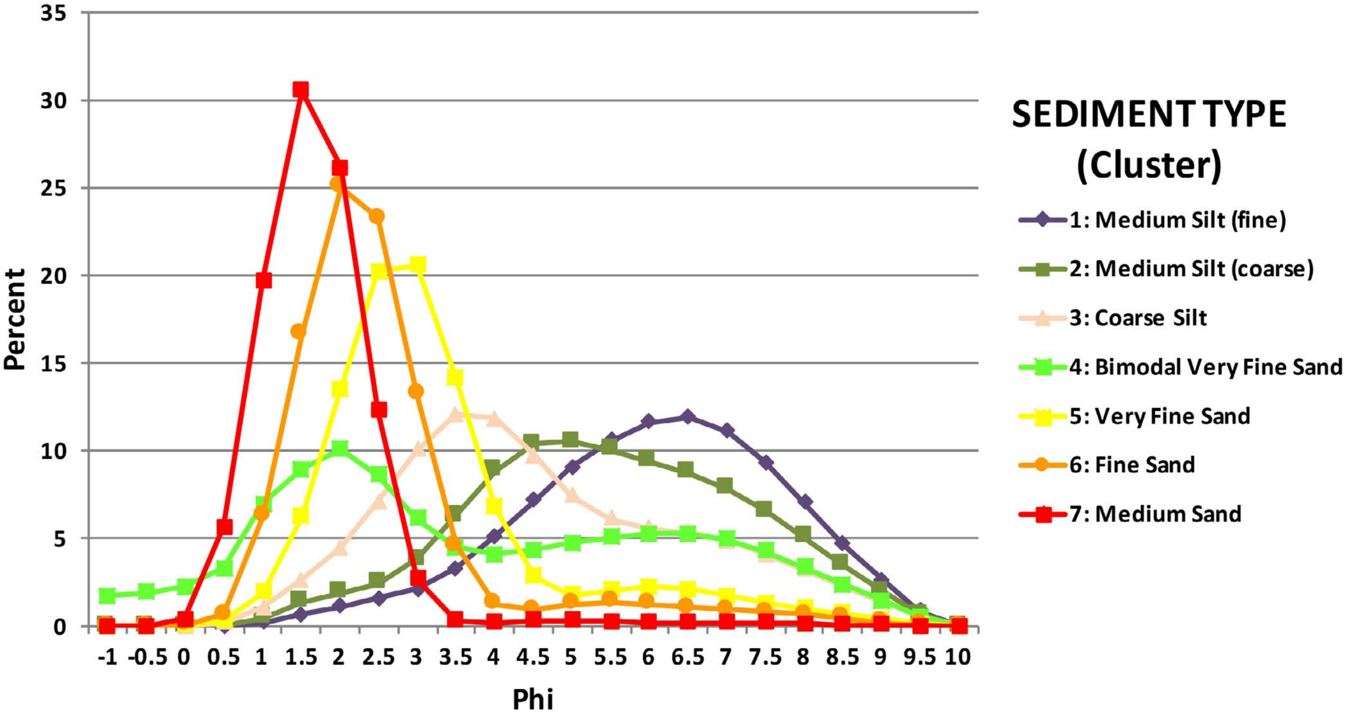

Figure 7. Average grain-size distributions of each cluster mapped in Figure 5. Note that the modes of clusters 3, 2, and 1 move progressively to the right (*i.e.* the sediment types are becoming finer); conversely the modes of clusters 5, 6, and 7 move progressively to the left, indicating that the sediment types are coarsening. Cluster 4 is the only bimodal sediment and is the source sediment for all the other sediment types.

surrounded by varying amounts of clusters 6, 5, and 3 (Figure 5). As will be discussed later, it is significant that cluster 7 is principally confined to Flora Bank and has not, as described in paragraph (2) above, been derived from either clusters 6 or 5. The sand clusters found in the subtidal area surrounding Flora Bank in turn grade into the silt facies (defined by clusters 2 and 1) seen to the NW of the bank and which dominate the offshore region of the study area. Inside Prince Rupert Harbour, the bottom is characterized with cluster 1, whereas cluster 2 forms much of the bottom of Porpoise Harbour.

Patterns of Sediment Transport

Following the procedures described in McLaren, Hill, and Bowles (2007) to obtain patterns of sediment transport, it was found that, with the notable exception of the cluster 7 sand found only on Flora Bank, nearly all samples could be accounted for in 540 lines (*i.e.* sample sequences in which statistically acceptable trends were obtained). The trend lines and samples making up each line, their locations, and statistics can be provided by the author on request. The net sediment transport pathways and their behavior as derived from the trend lines are shown in Figure 8. For ease of discussion, the transport lines are grouped into 13 transport environments (TEs) (Figure 9). A TE is defined as an area containing a number of transport lines that share a common source. The trend statistics break down if transport lines are taken beyond the TE boundary, and therefore pathways cannot be continued from one TE into another. A summary of the line numbers and dynamic behavior within each TE is provided in Table 3.

DISCUSSION

Despite the simplicity of the STA results (illustrated in their entirety in Figures 5, 8, and 9), a large number of both geologic and practical issues can be elucidated from such a conceptual understanding of the sediments and their behavior. This section is an attempt to progress through these issues in a logical sequence, commencing with the geology to the serious environmental concerns presently affecting the region.

Primary Sediment Source

As discussed above, cluster 4 (bimodal very fine sand) is, according to STA theory, the initial or primary source sediment for all the other clusters. During the sampling program (and therefore independent of the classification of sediment types as defined by the clusters), notes were taken describing various characteristics of each sample. Samples that were particularly loose and unconsolidated, often containing abundant broken shell debris as well as a large size range of clasts (from mud to gravel and larger sizes), were described as "lag" deposits. Such characteristics are interpreted as the products of erosion and likely reflect an active sedimentary layer overlying a deposit capable of supplying the full range of grain sizes that make up the remaining six clusters. The latter is most probably composed of till or glacial marine sediments derived from glaciers that retreated from this region about 12,700 years BP (Clague, 1984). Although

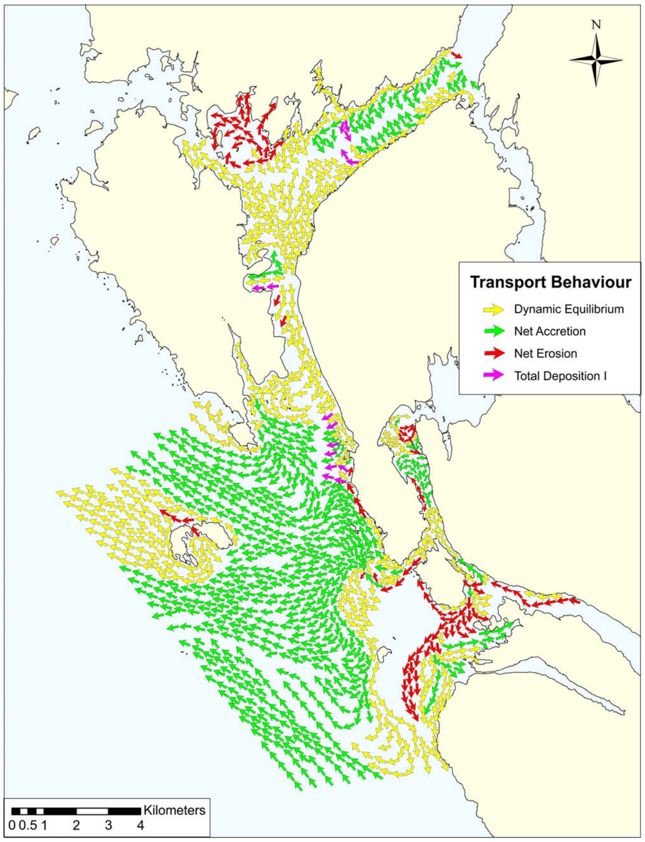

Figure 8. Pathways of net sediment transport.

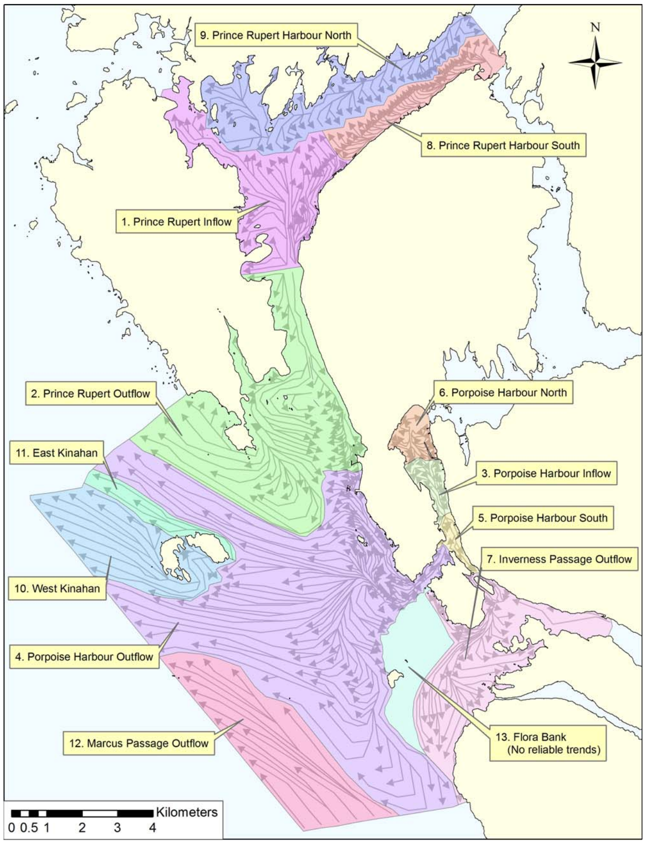

Figure 9. Transport environments (TEs) as determined from the STA.

glacial deposits are relatively rare on land, three till samples were collected on nearby Kaien Island (Figure 2). Plots of the average grain-size distributions of the lag samples, the cluster 4 samples, and the till deposit from Kaien Island were all about 70% similar to each other (Figure 10) and clearly support the concept that glacial deposits not only underlie the marine sediments sampled for this study but are their dominant source.

When mapped, the lag samples are found in similar localities as the cluster 4 sediment type (Figure 11), which, as described earlier, is largely confined to areas of high tidal currents (*e.g.*, the narrows into Prince Rupert Harbour and Porpoise Harbour) and adjacent to channel sides and rocky outcrops (*e.g.*, around the south end of Digby Island and the Kinahan Islands). Till, therefore, is to be expected immediately underlying the lag deposits in the

Table 3. *Summary statistics of the dynamic behavior in each of the transport environments (TEs).*

TEs (Figure 9)	Line Numbers	Total Number of Lines	Behavior			
			Total Deposition 1	Net Accretion	Equilibrium	Net Erosion
1. Prince Rupert inflow	385–434	50		2	48	
2. Prince Rupert outflow	265–344	80	7	32	39	2
3. Porpoise Harbour inflow	345–364	20		18		2
4. Porpoise Harbour outflow	16–173	158	3	93	50	12
5. Porpoise Harbour south	174–182	9			9	
6. Porpoise Harbour north	365–384	20		3	12	5
7. Inverness Passage outflow	206–264	59		13	17	29
8. Prince Rupert Harbour south	435–484	50	3	23	24	
9. Prince Rupert Harbour north	485–540	56	2	25	18	11
10. West Kinahan	183–201	19			18	1
11. East Kinahan	202–205	4			3	1
12. Marcus Passage outflow	1–15	15		15		
13. Flora Bank	No reliable trends					
Totals		540	15	224	238	63
Percent		100	3	41	44	12

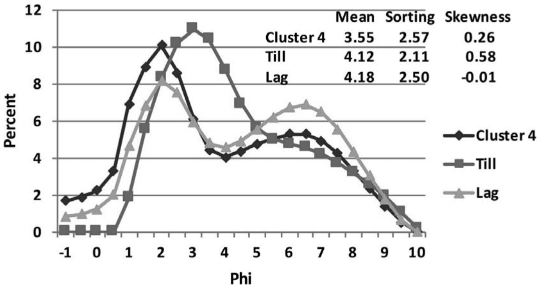

Figure 10. Average grain-size distributions of the samples described as "lag" at the time of collection (Figure 11), nearby till from Kaien Island, and cluster 4 sediments. Their similarity both in shape and grain-size measures (mean, sorting, and skewness) supports the concept that glacial deposits underlie the sediments throughout the study area.

high-current areas where erosion is likely to be occuring. Till can also be expected along the sides of fjords such as Prince Rupert Harbour, where it was likely deposited as subglacial moraine, and rocky islets, where the interaction of glaciers against such obstructions would favor till deposition.

Parting Zones and Constricted Channels (TEs 1–7)

The term *sediment parting zone* was first introduced by Stride (1963). Found commonly in estuaries and high-energy environments, a parting zone is an area of bottom out of which sediments may be transported in different directions. STA has identified parting zones in many environments (*e.g.*, the Bristol Channel and Carmarthen Bay in the U.K. [Cooper and McLaren, 2007; McLaren *et al.*, 1993] and in the St. Lawrence River estuary [McLaren and Braid, 2009]), and in all cases parting zones were supplied by the erosion of underlying deposits. The narrows of Prince Rupert Harbour and Porpoise Harbour each contain sediment parting zones where sediment derived from the lag/underlying glacial deposits is transported both into the harbors (Prince Rupert Harbour and Porpoise Harbour inflows [TEs 1 and 3; Figure 9]) and out of the harbors (TEs 2 and 4; Figure 9). In Prince Rupert Harbour, the parting zone is found in the vicinity of Casey Cove; however, the location of the parting zone in Porpoise Harbour is somewhat less precise, as Porpoise Harbour south (TE 5) lies in between

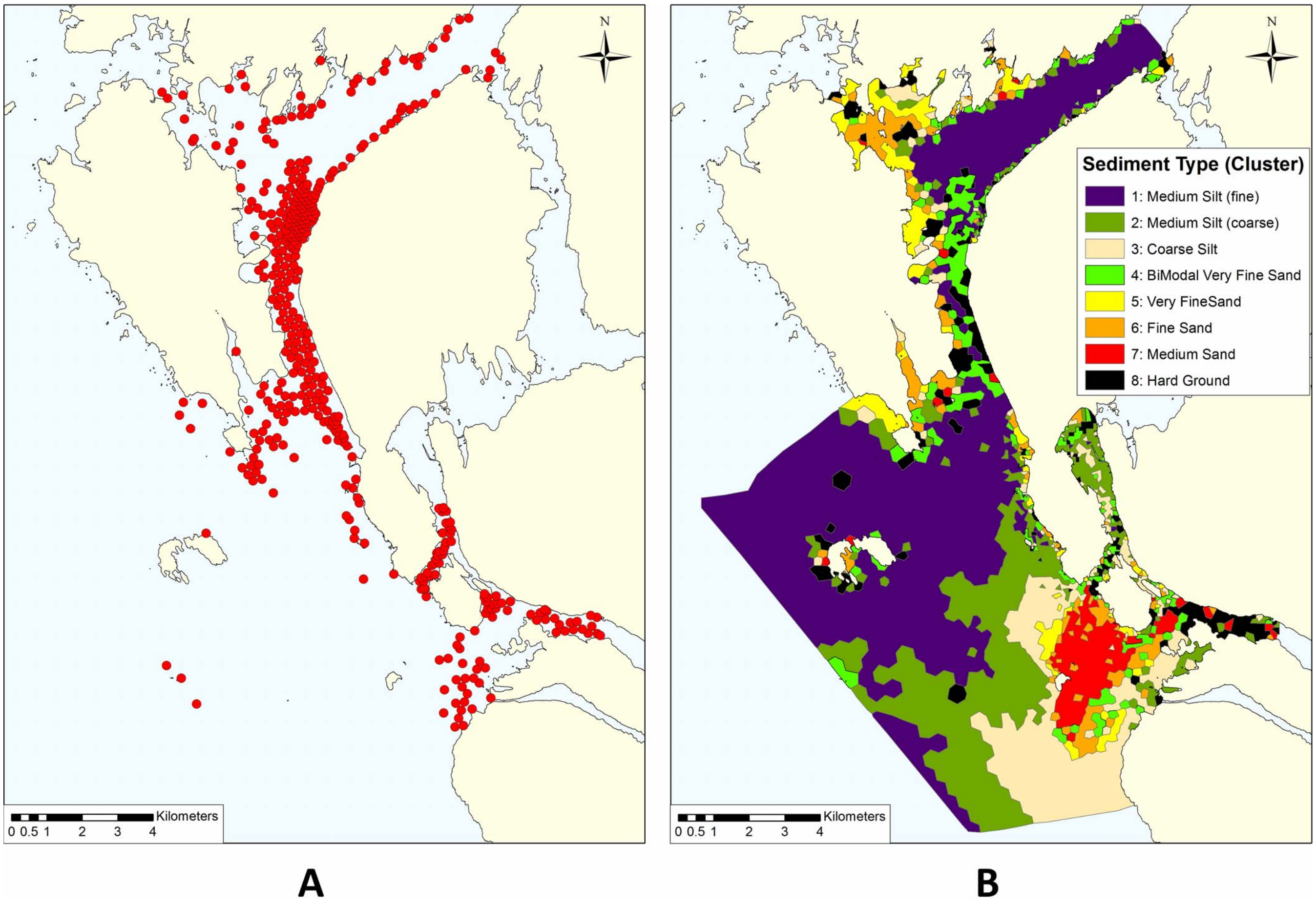

Figure 11. (A) The red dots are samples described as "lag" deposits at the time of sampling. (B) Similar to the locations of cluster 4 samples, lags were most often described from samples collected along the sides of Prince Rupert Harbour, associated with rocky outcrops and in narrows where tidal currents are strongest.

the principal inflow and outflow environments (TEs 3 and 4; Figure 9). The Porpoise Harbour south TE is, in reality, part of the outflow regime, and its separation from TE 4 may simply reflect the variability in the grain-size distributions of the underlying glacial deposits, causing complexities in the source sediments in this area.

The parting zones observed in the two harbors are likely the result of an increase in current velocities as the flood tide becomes constricted in the narrows, causing sediment to be dispersed into the wider and more central areas of the harbors, where it deposits as velocities decrease with the approach of slack water. The ebb current, however, is not sufficient to return the sediments back to the narrows, but its velocity once again becomes enhanced by the constriction in the parting zone area, where more of the bottom sediments are able to be eroded and transported out into Chatham Sound.

Two of the transport environments (Porpoise Harbour north [TE 6] and Inverness Passage outflow [TE 7]) also obtain their sediments from the underlying substrate as a result of constricted currents. However, no parting zone was determined for either of them. In the case of the Porpoise Harbour north TE, the Zanardi Rapids (Figure 2) provide turbulent currents into the harbor, resulting in HG and an eroding substrate at the head of Porpoise Harbour. Sediments are transported southward from the mouth of the rapids to form circulatory clockwise and counterclockwise gyres. The southward progression of these sediments is limited by their meeting with the northward trending sediments contained in the Porpoise Harbour inflow regime (TE 3). An inflow transport regime might well be taking place from the Zanardi Rapids into Wainwright Basin (Figure 1) to the east, but no samples were collected from this area.

It is unlikely that the Inverness Passage outflow (TE 7) has a corresponding inflow environment, as its behavior is significantly different from the two harbors as a result of the outflowing Skeena River. It is commonly stated that 25% of the Skeena River flow into Chatham Sound goes through Inverness Passage, and the remaining 75% is equally divided between Marcus and Telegraph passages (*e.g.*, Conway, Bornhold, and Barrie, 1996; Hoos, 1975). The reference generally given is Trites (1956), although such a statement does not occur in this paper. It would seem unlikely that, given the shallow depths and small cross-sectional area of Inverness Passage when compared with those of Marcus and Telegraph passages, that such a large amount of the Skeena flow could pass through it. Nevertheless, whatever the actual amount of river flow coming through the passage, it will undoubtedly lessen the effect of the flood tide and enhance the effect of the ebb, reducing the likelihood of an inflow transport regime in this area.

Valley Sides and Rocky Outcrops (TEs 8–11)

Unlike TEs 1–7, which owe their origin to the constriction of tidal currents, resulting in erosion of the substrate, a number of TEs are derived from the exposed till along valley sides and rocky outcrops. TEs 8 and 9 on the south and north sides of Prince Rupert Harbour originate from samples collected nearest to the shorelines, where sufficient numbers of cluster 4 sediments were available to identify their glacial source. Under the influence of both tidal and wave processes, the nearshore sediments on both sides of the harbor are transported seaward until they are halted by the Prince Rupert inflow (TE 1) regime. It is these nearshore sediments that provide the "trunk" lines (*i.e.* the "root" lines from which all other transport lines in the two TEs are derived; McLaren, Hill, and Bowles, 2007). As seen in the maps of sediment pathways (Figures 8 and 9), the trunk lines supply the finer sediment that accumulates toward the center of the harbor (cluster 1; Figure 5). On the north side where bays and inlets are present, sediment from the same trunk lines is transported under higher-energy conditions (the result of shallow waves and tidal currents) in coarsening sediment sequences to produce the very fine and fine sands (clusters 5 and 6) that are commonly found there (Figure 5).

The influence of random exposures of glacial deposits associated with valley sides, rocky shorelines, and outcrops frequently results in the influx of new sediments into the transport lines. For this reason occasionally transport lines could not be extended past a new sediment source, and a new line was required to continue the path at that point. Examples of line breaks are especially common where rocky outcrops are present (*e.g.*, along the rocky shoreline between Russell Arm and Pillsbury Cove, Spire, Tuck and Metford islets, Lima Point, and Coast Island). In general, such breaks were not deemed sufficient to identify separate transport environments. An exception was made in the identification of TEs 10 and 11 (West and East Kinahan), where glacial deposits near the shoreline required new transport lines to be constructed. As is apparent from the maps of transport pathways (Figures 8 and 9), the two Kinahan TEs could really be considered environmental subsets of TE 4 (Porpoise Harbour outflow). The influence of new sediment joining the Porpoise Harbour outflow sediments from the Kinahan Islands has, however, clearly changed the dynamic behavior from dominantly net accretion to equilibrium (Figure 8), possibly the result of local velocity increases around the sides of the islands.

Marcus Passage Outflow (TE 12)

Only the Marcus Passage outflow (TE 12) resulted in a TE that could not be directly related to the underlying glacial deposits. Composed of cluster 1 and cluster 2 sediments, this TE appears to be the only environment that originates from the load carried by the Skeena River (Figure 12). Although the Skeena River outflow may be responsible for the general NW movement of sediment in all the TEs associated with Chatham Sound, it clearly has not supplied sufficient sediment to produce its own sedimentary signature throughout the study area. Most likely the sediment contained in the seemingly impressive plume that spreads out from the channels separated by Smith and Kennedy islands is too fine to remain in the high-energy environments typical of the Prince Rupert coastal waters. Such a finding, however, is contrary to the generally accepted view that the sediments found in the Chatham Sound portion of the study area are deltaic in origin, having been derived entirely from the

Figure 12. Aerial view of the Skeena River plume emanating through Marcus Passage toward the NW into Chatham Sound. The plume likely accounts for TE 12 (Marcus Passage outflow; Figure 9, Table 3). Photo taken by Brian Huntington and reproduced here courtesy of Ocean Ecology (2014).

Skeena River and its plume[2] (Conway, Bornhold, and Barrie, 1996), though it is consistent with the observation of Hoos, (1975, p. 55), that "strong tidal currents" result in "little deposition of Skeena River sediments in the estuarine channels."

Sediment Behavior

For each of the 540 lines of samples that generated the trend statistics, the derived X-function[3] was examined and the dynamic behavior was interpreted. For the study area as a whole, most of the lines divided roughly equally into net accretion and equilibrium (Figure 13). Total deposition 1 and net erosion are, in comparison, extremely minor.

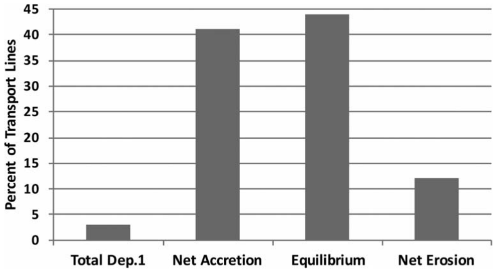

Figure 13. Relative proportions of the dynamic behavior of all sample lines used in the STA (data from Table 3).

Sediment behavior depends not only on the relative strength of the processes responsible for erosion, transport, and deposition, but it is also greatly dependent on the amount of sediment that is actually available in the sedimentary environment. For any particular process capable of eroding, transporting, and depositing sediment, net erosion, equilibrium, or net accretion will occur preferentially as the amount of sediment available for transport increases (*i.e.* with an increase in abundance of available sediment comes a greater probability of accretion; the converse being that as sediment supply decreases, the probability of net erosion increases. Equilibrium falls in between the two extremes).

As seen in Figure 8, most of the transport pathways in dynamic equilibrium are associated with the tidally driven parting zones found in the narrows and along shorelines (waves and tidal currents). Equilibrium occurs when the probability of any one size of particle being deposited is equal to the probability that a particle of the same size will be removed by erosion. Such behavior can only occur when the sediment available for transport is small, although *small* is used only in a qualitative sense relative to the transport processes involved. The lack of sediment available for transport is entirely consistent with the paucity of cluster 4 sediments found throughout the study area. Other sediment sources, such as the Skeena River or small creeks and land runoff, have left no sedimentary signature to qualify as being significant. The equilibrium interpretation is also supported through examination of sequential charts, which show no measurable erosion or deposition occurring inside any of the constricted channel areas.

As sediments are transported from areas of erosion through areas of dynamic equilibrium into deeper water, the trends change to net accretion. Although the sediment loads are not large, the declining energy of tidal currents in the central parts of both Prince Rupert Harbour and Porpoise Harbour and in the unrestricted waters of the offshore areas in Chatham Sound allows for deposition and accretion to take place.

Conditions for Eel Grass

Given the importance of eel grass as a critical habitat for many species, including juvenile salmon, notes were made at the time of sampling when eel grass was present in the grab sampler. A total of 88 samples were observed to contain eel grass (Figure 14A). When its presence is compared with

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[2] The Skeena River is a macrotidal estuary (*i.e.* an estuary with a tidal range of greater than 6 m; Coleman and Wright, 1975), which technically can be thought of as an extreme end point in various classification schemes for deltas. Such estuaries typically have elongated sand bodies paralleling the axis of the estuary at its mouth. The Skeena River estuary is unique in that its mouth is broken up by large bedrock islands (Smith and Kennedy Islands being the two main ones), which have completely changed the sedimentary dynamics that might have been capable of producing the bar forms associated with this type of estuary. For this reason the Skeena River has not produced an identifiable delta form, and the term *delta* provides a misleading concept of how the sediments might be behaving in Chatham Sound.

[3] The X-function, which is fully described in the presentation of STA theory (McLaren, Hill, and Bowles, 2007), is a distribution relating the average grain-size distributions of the "source" sediments with the average grain-size distributions of the "deposit" sediments that make up a particular sample line. It is exactly like a grain-size distribution in its content, but in this case it represents the relative probability of each particle size being eroded from the source sediments, transported, and deposited further down the pathway. It is the shape of the X-function relative to the shapes of the grain-size distributions that makes up the source-deposit sediments in the line, which determine the dynamic behavior of the sample line.

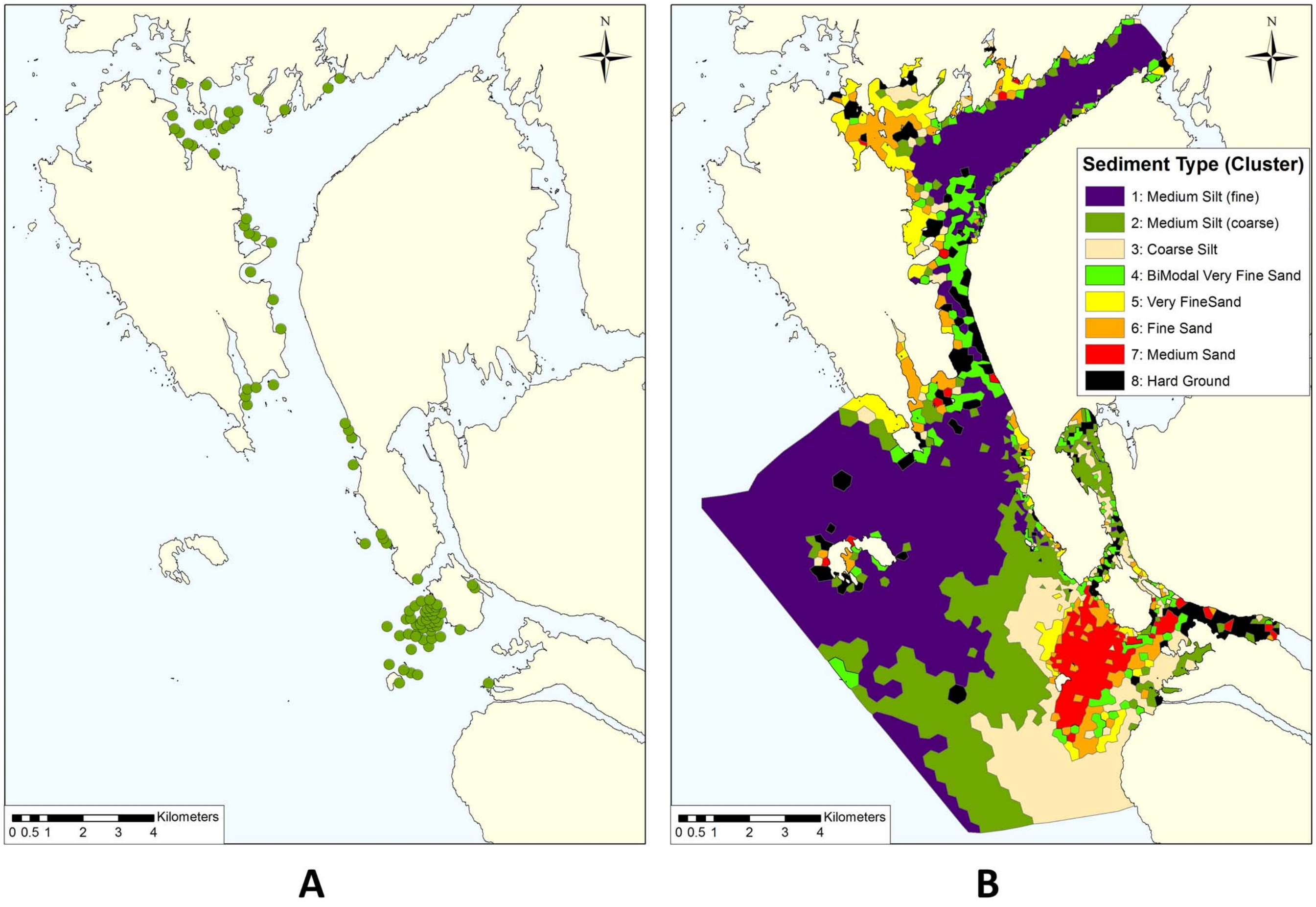

Figure 14. (A) Locations where eel grass was present in the grab samples. When compared with (B), it can be seen that the eel grass is predominantly associated with nearshore sandy deposits.

sediment type (Figure 14B), one can clearly see a strong association with nearshore sandy deposits (clusters 5, 6, and 7). In particular, cluster 6 appears to be the preferred sediment type (Figure 15), which also suggests that eel grass has difficulty growing in sediments finer than cluster 5, which has a mean grain size of 3.03 ϕ (very fine sand; Table 2). There is also a clear relationship between eel grass habitat and the percent of mud contained in the sediment. In over 90% of samples containing eel grass, the mud content was less than 25% (Figure 16), which may provide some understanding of the requisite sedimentological conditions required to remediate or

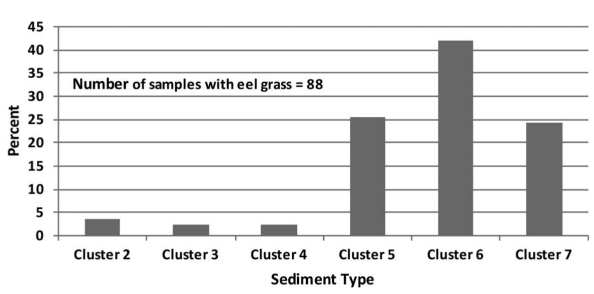

Figure 15. The relationship between eel grass habitats and sediment types as defined by clusters.

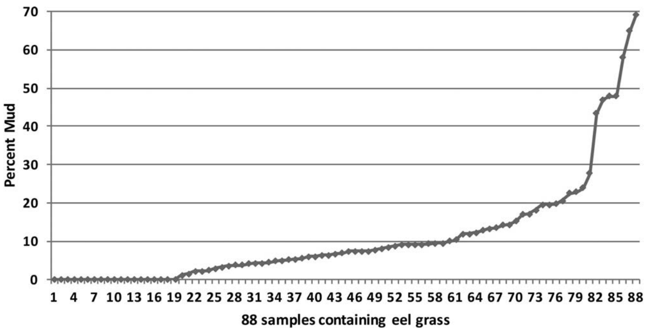

Figure 16. The relationship between percent mud contained in the sediments and the presence of eel grass. Only about 10% of the 88 samples in which eel grass was observed contained more than 20% mud in the substrate.

Figure 17. An aerial view of Flora Bank taken at low water on 17 June 2014. The number of different groups of sand waves and their orientations attest to the complexity of processes that are operating on the bank to hold it in place. (Photo supplied by Pacific NorthWest LNG to the Skeena Fisheries Commission.)

replace eel grass habitats destroyed in future development activities.

The Origin and Dynamics of Flora Bank (TE 13)

Flora Bank has been recognized since at least the 1970s as a critical habitat for juvenile salmon (Higgins and Schouwenburg, 1973). Recent work reinforces this view (Carr-Harris, Gottesfeld, and Moore *et al.*, 2015). For this reason, it is of particular importance to understand its origin and possible fate in light of present development plans associated with the area. Measuring about 4 km^2, Flora Bank can be considered a unique geomorphic feature composed of intertidal sand lying between Kitson Island and Lelu Island (Figure 17). The term *unique*, which is frequently overused, is completely valid in this instance, even with no understanding of either Flora Bank's origin or dynamics, for a number of reasons: There is, for example, no geomorphological term or name that can be easily applied to the feature as a whole. It carries no characteristics of a delta and does not appear to be associated with the Skeena River. Although Kitson Island may be helping to anchor Flora Bank, the island is not large enough to offer protection for such a large sand body in its lee (*i.e.* there are no features to suggest that it might be a tombolo). Above all, there is no comparable feature, to the author's knowledge, anywhere on the British Columbia coast.[4] Perhaps most curiously, even without knowledge of how it has formed, is the fact that it is there at all, given that the sand body is literally sticking out into an apparently high-energy environment. There appears to be no particular reason for the sand to remain in such an environment, as evidenced by the very small amounts of intertidal sand present on the coastline throughout the rest of the study area (Figures 2 and 5).

Prior to the initiation of the STA, it was expected that the transport pathways would reveal the source of the sand making up Flora Bank, perhaps from Inverness Passage or the surrounding Agnew and Horsey banks (Figure 2). It was also expected that the pathways would demonstrate sand not only coming onto Flora Bank but also being removed in trends indicative of dynamic equilibrium. That would provide an explanation of how the bank maintains itself.

Instead, as has been described earlier, not only did the Flora Bank sand define its own sediment cluster (cluster 7; Table 2 and Figure 5), but the grain-size characteristics (mean, sorting, and skewness) indicate that its origin cannot be from the surrounding sand contained in clusters 5 or 6. Furthermore the cluster 7 sand does not support evident transport pathways, which, outside of the bank's area, are seen to terminate at its low-water edge on its NW side or simply parallel the low-water edge on its SE side (see the pathways of TE 4 and TE 7 on either side of the bank in Figure 9).

It appears that only one explanation can account for these observations. If the sand has not been transported onto Flora Bank, it must have formed *in situ* or be a remnant from a preexisting environment. The findings of the STA demonstrate that till or other glacially derived sediments are likely underlying and are the source for the present sediments throughout essentially the whole study area. Although Flora Bank sand cannot be derived from surrounding sand deposits, they can come from cluster 4, the distribution that most closely reflects glacial sediments (Table 2). Flora Bank's sand, therefore, can be explained by Case A as defined in STA theory (McLaren and Bowles, 1985), in which a lag deposit develops from underlying source sediments (*i.e.* the observed grain-size distributions are not the result of sediment transport from one locality to another, but have developed *in situ*). It is suggested that Agnew, Horsey, and Flora banks are cored with glacial deposits, possibly a moraine reflecting a pause in the advance or retreat of the late Wisconsin ice cover, or a medial moraine formed between ice tongues preferentially coming down the valleys of Prince Rupert Harbour, between Kaien Island and the mainland (*via* Morse and Wainwright Basins) and Inverness Passage.

Recent work suggests that, at the time of deglaciation, sea level was about 50 m higher than today and fell to its present position about 8000 years ago (Shugar *et al.*, 2014). As sea level fell, submarine glacial deposits would have become increasingly exposed to littoral processes as they shallowed to form part of the nearshore and intertidal environment. The result would be to remove all the fines, leaving only the coarsest sediments to make up the Flora Bank sand, which can now be correctly termed relict sediment and which is likely to be about 8000 years old. At the same time sea level dropped to allow marine and coastal processes (waves and tidal currents) to produce the present Flora Bank, the Skeena River flow through Inverness Passage and the tidal dynamics associated with Porpoise Harbour also became "activated." These processes, together with wave action, have served to hold the Flora Bank sand in place, and it is suggested that, as a result, Flora Bank has had little change to its morphology since its formation.

The concept that the processes acting on Flora Bank are instrumental in holding the relict sand in place is also

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[4] The author aerially photographed nearly the whole British Columbia coast in 1982 while working for the Geological Survey of Canada as part of a coastal geomorphic mapping program.

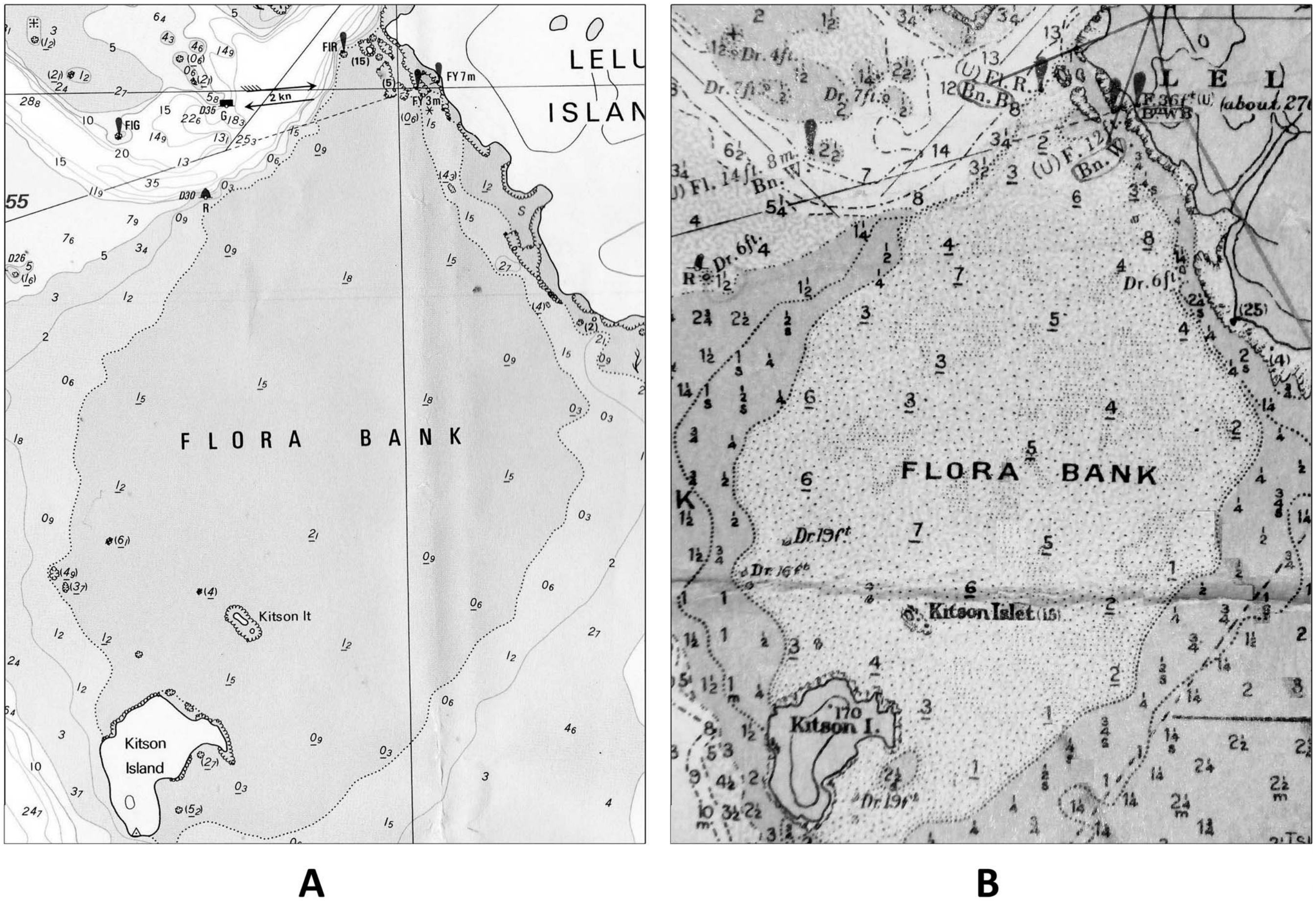

Figure 18. A comparison of (A) the shape of Flora Bank in 1991 compared with (B) its shape in 1907. Note that the outline of the low-water line has changed very little. Any minor differences are more likely the result of significantly improved surveying techniques in the construction of the 1991 chart than any geomorphological change.

reinforced by its apparent stability. If, in fact, the sand is actually part of a larger transport regime in which it is both arriving and leaving the bank, thereby keeping it maintained, a constantly shifting position of the bank could be expected, as the availability of arriving sand could never be constant and the processes to remove it would also be variable. Sand banks in macrotidal estuaries, for example, are continually shifting position in response to variability in the processes and changing supplies of sediment. However, the photo of Flora Bank (Figure 17) shows a complexity of bedforms, none of which are oriented in a direction that would remove sand from the bank. In an examination of marine charts through time, the definition of the low-water line on Flora Bank remains consistently in the same position (Figure 18). Also, the drying elevation of the bank (about 2 m) stays identical throughout the length of time represented in all charts and field sheets archived at the National Hydrographic Service of the Institute of Ocean Sciences (Sidney, British Columbia). This can be understood only when it is considered that the amount of sand on the surface of Flora Bank has remained constant, and, to date, there has been little possibility for the complex interaction of river, tide, and wave processes responsible for holding the sand in place to have changed since sea level reached its present position 8000 years ago.

Kinematic Modeling (STA) *vs.* Dynamic Modeling in Environmental Decision Making

The following is an attempt to describe the present struggle for various government departments, the proponents, and stakeholders to arrive at an acceptable environmental solution (if it exists) to utilize the Flora Bank region for a new LNG terminal (Figure 3).

Predicted Fate of Flora Bank Based on STA Results

As described in McLaren (2014), STA is a kinematic model in which the movement and behavior of sediments are determined without regard to the processes that may be responsible. In that article it was argued that such an understanding is instrumental in making rational sediment management decisions and could be used to direct and validate dynamic models should quantitative analyses be required. The article provided two examples of port construction where dynamic modeling had failed to predict correctly the consequences of altering the sediment transport regime. In one, a tourist beach and coastal road were lost to erosion following the start of construction (McLaren and Fleming, 1988); in the other, a breakwater built to shelter a small craft harbor produced a sediment trap of such effectiveness that the harbor was never used for its purpose (Hughes, 2005). In both examples, STA provided an explanation as to why the development activities resulted in their unexpected consequences. It was argued that, had an understanding of the patterns of sediment transport and the sources and behavior of sediment been available prior to construction, the designs could have been altered to avoid the costly mistakes that occurred.

In the case of Flora Bank, there are plans, presently subject to the Canadian government's environmental review process, to construct an LNG terminal across the bank (Figure 3). Efforts are focused on the potential effects of the terminal on fisheries and fisheries habitat. The latter is primarily concerned with sediment issues—will Flora Bank sand and its eel grass beds that are known to be important for juvenile salmon be deleteriously affected by altering the sediment transport regime, potentially resulting in erosion or deposition? With no construction having yet started, there is now an opportunity to apply the STA results to predict the probable consequences of the development.

The principal finding of the STA is that the sand on Flora Bank is not maintained by sediment that has come from elsewhere; rather it is a lag deposit that was formed *in situ* and is held in place by the surrounding processes. This conclusion dramatically alters the perspective on the possible effects the development may have on the bank. There is no longer a concern, as was originally thought, that the development might result in a change of transport patterns affecting the movement of sand onto or off of the bank. Rather the findings demand an assessment of how the processes that hold the relict sediment in place might be affected. If they are altered, or more specifically, reduced in magnitude, their ability to hold the sand in place could be jeopardized. Should such a change result in a loss of sand from the bank, it will not be returned, and there is no outside source to enable it to be replenished. Once gone, the habitat it supported will also be lost, and it is unrealistic to suggest that future mitigation could satisfactorily restore an area of such magnitude. If, instead of losing the sand, a decrease in energy levels over the bank increases the deposition of fine sediments, there is a danger of losing the eel grass should the mud content mixed with sand increase to more than 25% (Figure 16).

The present design of the docking facility consists of a 1.6 km clear-span suspension bridge over Flora Bank from Lelu Island to Agnew Bank, followed by a 1.1 km conventional pipe pile trestle to the LNG carrier berths, which form the final section of the marine terminal (Figure 19). The design of the trestle and berthing jetties calls for 448 pilings, each with a diameter of 1.22 m (Hatch, 2014a). Ignoring, for simplicity, the complexity of their positions and their interactive effects on currents, the combined width of barrier produced by the pilings will be 547 m, nearly 75% of the length of the low-water line defining Flora Bank that is in direct shelter of the pilings (740 m; Figure 19). Given the variability of directions from which currents might approach the trestle, it is suggested that its zone of influence would realistically extend all the way to Kitson Island, a complete distance of 1.6 km.

In order for Flora Bank sand to remain in place, the net effect of the processes (*i.e.* the energy produced by the combined action of tidal, river, wave, and wind-driven currents) must be equal on both the NW and SE sides of the bank. If this were not so, the sand would be unable to remain and Flora Bank, as it is seen today, would not exist. For this reason, it is believed that a reduction of energy along any portion of the perimeter of the bank caused by the pilings obstructing the currents (regardless of which process or combination of processes are responsible for generating the currents) will result in an inability for the sand to continue being held in place. The suggested loss of sand is illustrated and explained in Figure 20.

This prediction is favored over the suggestion that the reduction in energy might result in an increase of fine-grained sediment being deposited over Flora Bank. This is because the STA has demonstrated that suspended sediment from the Skeena River is unable to produce its own sedimentary signature throughout the study area, indicating that processes are too strong to allow its deposition in sufficient amounts to produce a unique facies. Given the strength of tidal currents and the significant wave action that can occur during each flooding and ebbing tide, it is unlikely that the reductions in energy over Flora Bank would be of sufficient magnitude to allow the deposition of suspended sediment.

Predicted Fate of Flora Bank Based on Modeling Results

Data collection and subsequent dynamic modeling associated with sediment transport have been undertaken since 2012 by Pacific NorthWest LNG as part of the environmental review process, using a two-dimensional Coastal Modeling System flow model (U.S. Army Corps of Engineers, 2015), a particle tracking model (U.S. Army Corps of Engineers, 2012), and, more recently, the Delft3D model (Deltares, 2012). Unlike the kinematic approach of STA, dynamic models determine particle transport and behavior in response to the driving processes. It is, therefore, critical not only that the process data adequately describe the environments but that all processes are accounted for in the model. Although the modeling is discussed throughout a large number of reports, many of the essential findings can be found in Hatch (2014a,b,c), which in turn are contained within the Canadian Environmental Assessment Agency website (CEAA, 2014). Occasional statements in these reports appear to provide some agreement to the STA findings with respect to how the environment is "working." For example, there is a description of how the tidal currents help to maintain both sides (edges) of Flora Bank (Pacific NorthWest LNG, 2014; p. 4/9), which certainly parallels the STA-derived concept that the processes on either side of Flora Bank must be holding the sand in place. It is not clear from the report, however, if this finding is actually a conclusion made from the modeling or is merely an observational description.

With respect to the fate of Flora Bank, only numerical results from one model have any real importance (Hatch, 2014a). At 6 locations on either side of the proposed trestle structure (T_1 to T_6; Figure 20), average and maximum currents are modeled for

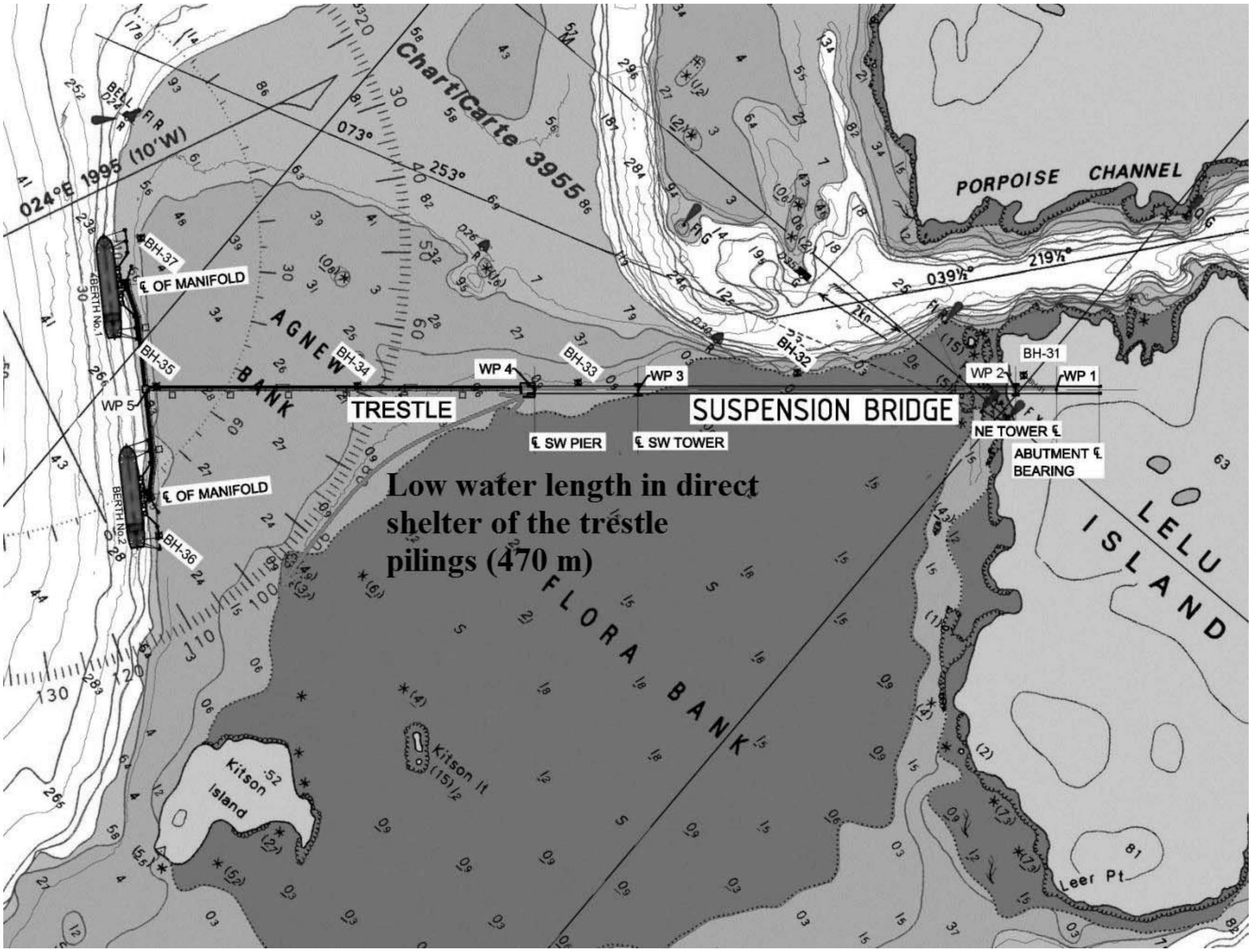

Figure 19. Proposed docking facility for an LNG plant, to be located on Lelu Island (taken from Hatch, 2014a).

the conditions before and after its construction. The report does not identify the source of the currents (tides, waves, wind driven, or fluvial) or whether the currents from all processes have been integrated. An examination of the modeled current velocities before and after the trestle installation reveal a number of discrepancies that provide cause for concern. One such discrepancy is a modeled current reduction of 91% at T_1, a finding that, at first sight, largely supports the STA conclusion that such a drop in energy so close to the edge of Flora Bank could indeed lead to a loss of sand. However, about 500 m away, at T_2 and T_5, the reduction, according to the model, has been reduced to no change at all (0%). No explanation is provided in the report as to why there might be such a large discrepancy in the reduction of current velocities.

Throughout the modeling reports, although clearly stated and unambiguous results are not provided, the oft-repeated overriding conclusion is that there will be no effects on Flora Bank following construction of the terminal. One reads instead statements such as, "Changes in tidal current velocities and sediment re-suspension and deposition patterns are not expected to alter or destroy fish habitats in proximity to the project marine terminal structures," (Pacific NorthWest LNG, 2014; p. 5/9) and throughout the reports are frequent suggestions that there will be "no significant effects" or "residual effects will be minimal."

Difficulties in Reconciling the Conclusions Determined by the Two Techniques

Clearly the two approaches have produced exactly opposite assessments of the fate of Flora Bank. The discrepancy has serious economic, social, and environmental implications that encompass the First Nations, local communities, and "environmentalists" on the one hand, and the LNG developers and the British Columbia provincial and Canadian federal governments on the other. The Canadian Environmental Assessment Agency has halted the review process three times with the request for further work to resolve the discrepancy in the opposing conclusions. To this end, the Delft3D model was instigated, which arrived at the same finding as the previous

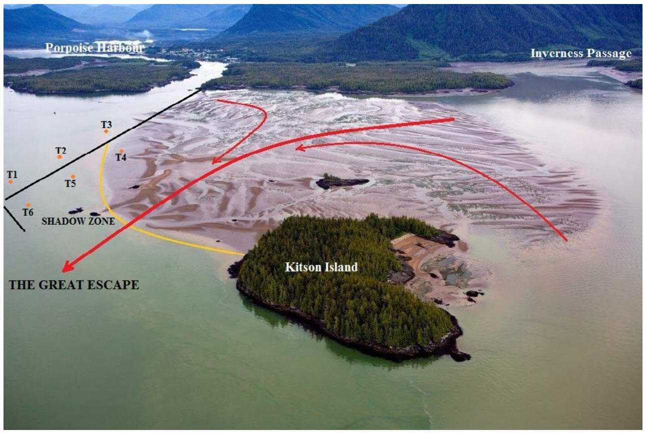

Figure 20. Based on the interpretation provided by the STA, it is predicted that sand will be lost from Flora Bank (the Great Escape) following construction of the trestle portion of the terminal jetty. Because the energy of the processes affecting Flora Bank will be reduced between the start of the trestle and Kitson Island (the shadow zone), inequality of the energy between the two sides of the bank will allow sand waves to advance, causing a seaward loss of sand in the approximate directions of the red arrows. T_1 to T_6 are the approximate locations where current velocities have been modeled before and after trestle emplacement (discussed in text).

models—namely, there will be no environmental harm as a result of the LNG terminal development.

It is the author's belief that (1) there is a significant and possibly widening gap between the more qualitative discipline of coastal geology and those involved in the dynamic modeling of coastal systems, and (2) it is important to try to close the gap for the benefit and progress of coastal science. On the geologic/empirical side, there has been criticism of the use of numerical models to make predictions, one of the most notable being the book *Useless Arithmetic: Why Environmental Scientists Can't Predict the Future* (Pilkey and Pilkey-Jarvis, 2009). McLaren (2014) strove to assess the fundamental differences between the kinematic and dynamic approaches, suggesting, "To adopt dynamic modeling without taking into account or accepting observations that are easily available and can produce demonstrably correct conclusions without regard to the processes is pointless and counterproductive." In a later discussion, Little and Bullimore (2015) state, "The kinematic approach used by STA in coastal studies has often been greeted with intransigence by those who see it as a disruptive challenge to the incumbent approach, as represented by dynamic modeling."

In the case of the Flora Bank controversy, the latter statement is distressingly true. Since the release of the STA report, the modelers have seemingly refused to acknowledge its findings or even to respond to questions concerning their models' assumptions or conclusions (*e.g.*, the wide discrepancies in current velocities at localities T_1, T_2, and T_5, as discussed above). By simply ignoring the STA, the modelers are now choosing to rely only on the presentation of the three-dimensional model to convince the relevant regulatory authorities that no environmental harm will happen. It must be realized, however, that such an approach not only weakens the defensibility of using the model as an effective predictive tool but actually strengthens the prediction of the STA's kinematic approach. As a result, the public perception is, on balance, weighed strongly against trusting the modeling claims that no environmental harm will occur.

The modelers did, however, release a scathing review of the STA, which followed a completely familiar format. As in numerous similar reviews in which STA has been applied, the comments were negative, the first point usually being (as in this case) that the environment is simply too complex for STA to work. Perceived errors are often alluded to but never specified. Inevitably the final comment constitutes a plea that more modeling must be done to resolve the discrepancies between the two techniques. What is consistently absent from all reviews concerning STA is (1) a scientific discussion to show that the findings of the STA are incorrect by providing an alternative explanation for the statistically significant sequential changes in grain-size distributions that define transport pathways, and (2) an examination of the original McLaren and Bowles (1985) article to demonstrate that the fundamental theory of STA is wrong. In all reviews the actual STA results are never mentioned, let alone rationally refuted. Furthermore, despite many invitations to write a discussion paper on the inadequacies of the STA approach, thereby enabling a scientific dialogue to occur, such an article has never been published.

The inescapable conclusion is that the results (although not necessarily the predictions) of STA cannot be challenged without either finding fault with the theory or offering an explanation other than sediment transport to account for the nonrandom changes in grain-size distributions found in the sediments. The validity of this statement was recently supported by the outcome of a highly public lawsuit filed by the United States Department of Justice (United States and Wisconsin *v.* NCR Corp. *et al.*, 2013), in which STA was conducted in the Superfund site of the lower Fox River in Green Bay, Wisconsin. The judgment rejected the findings of numerical modeling, which were unconvincing to the court in establishing reasonable liability allocations for cleanup costs in favor of the conceptual model provided by the STA (Singer and McLaren, 2015).

At present the "gap" is far from closed, and possibly the only solution will be a genuine effort, encouraged by all parties, to undertake further and collaborative research. Although it is possible that the findings of the STA cannot easily be challenged, the prediction whereby the sand will be lost is based simply on the conceptual understanding of how the sediments appear to behave. No prediction can ever be considered foolproof. Flora Bank is quintessentially paradoxical. The STA concludes that the sand is relict and is held in place by what are thought to be high-energy processes operating equally around the bank. But if this is so, how is it that, according to careful examination of aerial photos from 2007 to the present, the existing bedforms and drainage channels appear never to move? Conversely, modeling suggests that the process energy around the bank is sufficiently dissipated that the coarse sediments are simply unable to be transported, and that is why the bank remains so stable. Therefore it follows that, because the energy is so low, there can be no changes to the hydrodynamics and sediments after the terminal and its trestle structure are installed, a finding evidently confirmed by the model. If this is so, it is hard to explain why the sediments on the bank do not reflect less energy than the surrounding waters. There are certainly all sizes of sediment particles abundantly plentiful in the nearby underlying till and in the Skeena River plume. The STA would be expected to find pathways from the surrounding areas fining up onto the bank, possibly showing total deposition. Instead, Flora Bank is uniquely characterized by the coarsest and best-sorted sand in the whole study area; this sand shows no transport relationship to any of the sediments that surround it.

CONCLUSIONS

The empirical technique of Sediment Trend Analysis was applied to 2474 grain-size distributions taken from sediment samples collected throughout the jurisdictional waters of Prince Rupert Harbour. A cluster analysis performed on the distributions divided the samples into seven sediment types defined by the mean grain size of each, which ranged from medium silt to medium sand (Wentworth classification). An eighth category constituted hard ground, where the grab sampler was unable to capture any sediment. Cluster 4 produced the only bimodal distribution and closely resembled the distribution of an onshore till deposit. The average mean, sorting, and skewness of the clusters exactly followed sediment trend theory when compared with cluster 4; the finer clusters (1, 2, and 3) all became progressively finer, better sorted, and more negatively skewed, while the coarser clusters (5, 6, and 7) became coarser, better sorted, and more positively skewed, indicating cluster 4 (the underlying till) as the primary source for all the sediment types found in the area. Furthermore, the clusters themselves showed transport relationships whereby cluster 3 could be the source for cluster 2, which in turn could be the source for cluster 1. Similarly, cluster 5 could be the source for cluster 6 in the coarsening direction. Cluster 7 (the coarsest sand), however, was an exception; although derived from cluster 4 (the till), it was uniquely separate from the preceding finer clusters (6 and 5). The cluster 7 sand was also confined essentially entirely to Flora Bank and was not found elsewhere except in isolated outliers.

Cluster 4 samples were commonly exposed as lag deposits in areas of high tidal currents such as in the narrows to both Prince Rupert Harbour and Porpoise Harbour and Inverness Passage. They were also found adjacent to the fjord sides and rocky islets, where till was likely to be present and exposed on the bottom. Following the STA, transport pathways were divided into 13 transport environments, all except one showing their origin from areas of cluster 4 sediments. The pathways demonstrated the importance of parting zones in the narrows, where sediment from the lag can be transported landward to be deposited in Prince Rupert Harbour and Porpoise Harbour, as well as transported seaward into Chatham Sound. Other TEs were found originating along the fjord sides and in the nearshore of the numerous rocky islets, where till was commonly exposed. Only TE 12 (Marcus Passage) contained sediments that likely originated from the Skeena River; otherwise the Skeena was not a major source of sediment throughout the area, despite its highly visible plume. The behavior of the sediments was dominated by equilibrium in the areas associated with high energy (*e.g.*, the narrows), suggesting that the amount of sediment available for transport and deposition is not large. Net accretion was confined to the deeper portions of the harbors and Chatham Sound.

Transport pathways could not be determined using only the cluster 7 sediments on Flora Bank, and their source could not be discovered from any of the surrounding sediments. It was concluded that these sediments are relict, having formed as a lag from the underlying glacial deposits as sea level fell to its present position about 8000 years ago. With this interpretation, it follows that the sand composing the bank, rather than being part of an active transport regime in which sand moves on and off the bank, is held in place by the surrounding processes. It was concluded that the quantity of sand is fixed; comparisons of charts and photographs through time suggest that it remains essentially immobile. If it were lost, there could be no source or transport regime capable of replacing it.

If the processes surrounding the bank are holding the sand in place, it is suggested that their energy must be equal on both the NW and SE sides. Were it not, it is unlikely that the sand could remain, and the sedimentology would undoubtedly be considerably different than that presently found. For this reason, it is suggested that development plans to construct an LNG terminal and trestle dock structure adjacent to Flora Bank could have the effect of reducing the energy along a portion of Flora Bank's perimeter, enabling sand to be lost to deep water. Numerical modeling undertaken by the proponent of the terminal, however, indicates that energy levels are already low, thereby accounting for the observed stability of Flora Bank. From the models, it is argued that the future development will not have any adverse effects on the present habitat that is of high importance to the Skeena River salmon fishery.

The opposing conclusions produced by the STA and numerical modeling emphasize the paradoxical nature of Flora Bank, which remains, at least in detail, unexplained. The unique sediment type, coarser and better sorted than any sand found throughout the region, suggests that processes acting on the bank preclude any finer sediment from being deposited. Yet there is a large range of grain sizes easily available from glacial outcrops in nearby Inverness Passage, which is known for exceptionally high currents, as well as the fine sediments contained in the ubiquitous Skeena River plume. For this reason, if sufficiently energetic processes are required to maintain coarse, well-sorted sand, the complete immobility of the bank is difficult to explain. If, as determined by the numerical model, the processes are too low in energy to move the sand, thereby accounting for the bank's stability, finer and more-poorly sorted sediments together with easily defined transport pathways would be expected. Future collaboration is a possibility in order to more accurately determine the risk of placing the marine docking structures so close to Flora Bank.

ACKNOWLEDGMENTS

The author is grateful to Mayor Garry Reece of the Lax Kw'alaams First Nations Band, who instigated this project. The work was carried out in close association with the Skeena Fisheries Commission, and thanks are extended to Mark Duiven, who managed the project, and Dr. Allen Gottesfeld and Davide Latremouille, who provided expertise in both the logistical and scientific aspects of the work. Bill Shepert, Lax Kw'alaams fisheries resource manager, managed the vessel used during the field portion of the project. Wade Helin, as skipper of the *Torrie Dawn*, provided superb vessel and navigation skills to achieve the collection of an unprecedented number of sediment samples. The help of Brandon Ryan, James Henry, Jr., James Russel, and Jen Gordon in their various roles during the field program is gratefully acknowledged. Dr. Steven Hill (SH Scientific Systems Ltd.) undertook data quality control and the GIS mapping and performed the cluster analysis. Gary Langstaff (SedTrend) provided office support and carried out the grain-size analyses.

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