Using an anisotropic semivariogram of acoustic backscatter intensity to determine the effects of river and tidal forces on the spatial structure of the Gold River delta

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Abstract

River deltas are productive, fast changing landscapes that not only provide a habitat for marine life, but provide an ideal environment for researchers to study changing environmental conditions. This study will use the principle of autocorrelation and an anisotropic semivariogram to find a quantitative metric to describe the relative strength of river and tidal forces on the spatial structure of the Gold River delta. At the Gold River, tidal forces move perpendicular to the direction of river outflow. Because of this, comparing the major and minor ranges of an anisotropic semivariogram aligned parallel to the river outflow gives a measure of the relative strengths of these forces. The major range of the semivariogram was 139 m, while the minor range was 78 m, giving an anisotropy factor of 1.78 and showing that the river outflow is the more dominant force in shaping the river delta morphology. The error in this measurement is very small, with a mean standardized error of -2.37 e^{-5} and a root-mean-square standardized error of 1.022.

Introduction

River deltas are productive, fast changing landscapes that not only provide a habitat for marine life, but provide an ideal environment for researchers to study changing environmental conditions. In December 2014, a University of Washington student research cruise made a survey of the Gold River delta in Nootka Sound, Vancouver Island, Canada. The purpose of the survey was to study the spatial structure of the Gold River delta using acoustic backscatter intensity as a proxy for sediment grain size. Many studies have shown the importance of sediment grain size to chemical, biological, and geophysical processes on river deltas. Zhang et al. tested the grain size and total concentration of 49 elements in sediment samples taken from the Bohai Bay in China and found that grain size was a controlling factor in nearly all of the element concentrations (Zhang et al., 2002). Grain size is also shown to have a large effect on the morphology of river deltas, and helps to determine the delta structure as well as the mixing patterns and transport distance of sediments as they settle beyond the river mouth (Orton & Reading, 1993). Rippled scour depressions are a common but poorly understood phenomenon that leave large impressions on river deltas. They can be seen in the acoustic backscatter signal of multibeam sonar, as they are characterized by varying sediment grain sizes (Ferrini & Flood, 2005). Geostatistics is a valuable tool to characterizing these depressions due to their elongated nature and effects on river delta structure. Developments in multi-beam sonar technology has shown that sediment grain size can be remotely sensed and mapped using acoustic backscatter intensity, offering more extensive insight into sediment distribution than individual samples can provide (Sternlicht & de Moustier, 2003). Multibeam sonar is essential to analyzing spatial structure in particular because it is the only method available that provides continuous data over the entire study area.

The Gold River has the largest drainage area (1010 km^2) as well as discharge volume of any river within Nootka Sound, and also supports a town called Gold River which is located about 14 kilometers upstream with a population of 2100 people. Precipitation and river discharge is greatest in the month of December, when the Gold River releases around 133840 m^3 s^{-1}. In 1959, 48 snapper sediment grabs were taken throughout inlets on the ocean side of Vancouver Island, with 90% of the samples containing mud and 26% containing sand. In addition, 60% of the mud was soft enough that it did not keep its form (Pickard, 1963). This is the only study found about the sedimentary composition of Vancouver Island inlets, and it is generalized over all estuaries on the western side of Vancouver Island. Muchalat Inlet is unique because it is the deepest basin in this study site. The inlet is about 70 m deep above a sill at the entrance of the inlet before opening up to a more uniform basin between 250 and 365 m deep. This depth gradually decreases near the Gold River delta, and past the gold river the basin shallows to about 200 m and curves to a shallower sub basin. Near the output of the Gold River to Muchalat Inlet is a steep shelf which drops from a couple of meters deep at the river mouth to nearly 300 m about a km offshore. The mouth of the river opens to Muchalat Inlet facing south, while the tidal currents within the inlet move east in flood tides and west in Ebb tides. The major industries in the region include logging, fishing, bottled water production, mining as well as several tourist activities. The licensed water demands in the region are listed as conservation, industrial, waterworks, domestic, power and storage purposes (Jackson & Cook, 1997). The reliance of the local communities upon the Gold River for waste disposal shows the need to track where sediments accumulate in order to understand effects on the local ecosystem.

The purpose of this study is to create a map of acoustic backscatter intensity in order to analyze the spatial distribution of sediments on the Gold River delta. Specifically, this study will use the principle of autocorrelation and an anisotropic semivariogram to find a quantitative metric to describe the spatial distribution of Gold River sediments. Since the Gold River empties to the south, and the tidal forces in this part of Nootka Sound flow east/west, the principle of autocorrelation can be used to describe the relative strength of the two forces on river delta spatial structure by comparing the major and minor axis of an anisotropic semivariogram.

Methods

In order to find a metric to quantify the relative strength of river and tidal forces along the Gold River delta, a bathymetric survey of Muchalat Inlet was done in December 2014 on the University of Washington's R/V Thompson (Figure 1). Bathymetric data including depth and acoustic backscatter intensity was collected using a Kongsberg Simrad EM302 30 kHz multibeam sonar system. The survey passed by the Gold River delta twice at 2.5 knots with an equidistant beam angle of 70^{o}, and was segmented into fourteen lines based upon when the ship was turning. The ship used GPS to track its position throughout the entirety of the survey, to be used when georeferencing the data post-cruise. A sound velocity profile was taken at the very beginning of the survey in order to calibrate the speed of sound through the water column for the duration of the survey.

Results of the survey was analyzed using CARIS Hips and Sips software to create a 2.5 m resolution bathymetric layer of acoustic backscatter intensity over the Gold River Delta (Figure 1). In CARIS, each line was manually edited using the swath editor to remove erroneous pings before being compiled into an acoustic backscatter mosaic using the geocoder engine. The mosaic was then exported into ESRI's ArcGIS Suite, where it was georeferenced and analyzed using spatial statistics tools in ArcMap.

Spatial analysis was performed by creating an anisotropic semivariogram in the geostatistical wizard of ArcMap, used for the purpose of determining the directional orientation of acoustic backscatter variance (Figure 2). The semivariogram model relies on the principle of spatial autocorrelation to visualize the relationship between the spatial dependence between two points as a function of the distance between them (cite geostatistics text). The semivariance is defined as:

$$\gamma(\mathbf{h}) = \frac{1}{2N(\mathbf{h})} \sum_{\alpha=1}^{N(\mathbf{h})} \left[z(\mathbf{u}_\alpha + \mathbf{h}) - z(\mathbf{u}_\alpha) \right]^2$$

where h is the lag (distance between points), u_α is the vector of spatial coordinates, z is the backscatter intensity at the point in consideration, and N is the number of points analyzed (Bohling, 2005). The anisotropic (directional dependent) semivariogram is defined as:

$$\gamma(h_u, h_v) = \gamma_1(h_u) + \gamma_2(h_v)$$

where u and v represent the main directions of anisotropy (Deraisme, n.d.).

In this study the anisotropic semivariogram was used to compare the distance at which point two observations became statistically independent from each other, this distance is called the semivariogram range. The anisotropic semivariogram function in ArcMap takes direction into account, and calculates two ranges based upon the orientation of the semivariogram. The major range was the range measured in the direction of river outflow, or 25^{o} east of north, while the minor range was measured 90^{o} to this, or 115^{o} east of north. The relative sizes of these ranges was compared to show the relative strength of the river outflow versus tidal forces in sediment dispersal on the river delta.

Results

Figure 1 shows the backscatter intensity values overlaid on a satellite image of the Gold River, with a red line orientated 25^{o} east of north, parallel to the river mouth. This image is used to observe the spatial structure of the Gold River delta; clear patterns can be seen across the entire river delta, the most pronounced being the north to south bands of high backscatter intensity seen along the western edge of the river delta. The east to west trends hypothesized to be caused by tidal forces are less easily recognized, this suggests that the river outflow is likely the dominant process in Gold River sediment distribution, a claim supported by geostatistical analysis.

Figure 3 shows a three dimensional trend analysis of the acoustic backscatter intensity values on the Gold River delta at 25 m resolution. When the gridlines are rotated parallel to the river outflow (red arrow), a linear trend is seen parallel to the river outflow while no clear trend is seen perpendicular to the river outflow.

A quantitative measure of the river structure is made by comparing the major and minor ranges of an anisotropic semivariogram (figure 2), a measure called the anisotropy factor. The major range of the semivariogram was 139 m, while the minor range was 78 m, giving an anisotropy factor was 1.78. The error in this measurement is very small, with a mean standardized error of -2.37 e^{-5} and a root-mean-square standardized error of 1.022.

Discussion

The three dimensional trend analysis (figure 3) provides a visual representation of influence of the river outflow on the backscatter intensity values, but it is not useful as a quantitative metric because trends in the direction perpendicular to the river outflow are undiscernible. The anisotropic semivariogram (figure 2) provides a quantitative but less visual metric to determine the relative strength of river and tidal forces. It analyzes the relationship between every pair of backscatter measurements within 150 m of each other and compiles the data into a single semivariogram, while the trend analysis displays the intensity values from a three dimensional plane in two separate two dimensional plots. Each are useful for displaying the spatial structure of the river delta, similar to the backscatter mosaic (figure 1), the trend analysis can be used to visualize how backscatter intensity varies spatially over the river delta. The semivariogram can be used to determine relative magnitudes of the forces that shape the delta landscape, but it does not display the physical characteristics of the landscape itself.

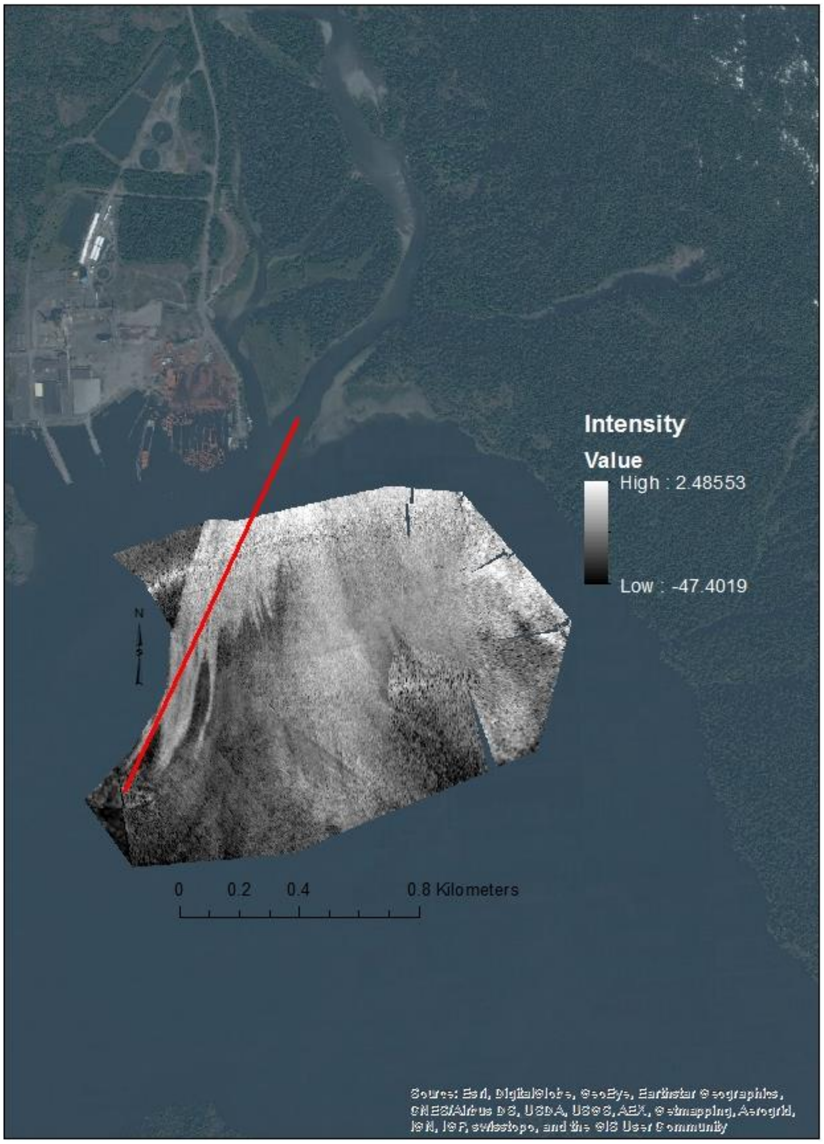
The greater range seen parallel to the river outflow describes the intensity gradient between the north and south ends of the river delta (figure 1). It can be seen that this gradient is smoother and more gradual, which leads to the increased distance at which two measurements are related to each other. Conversely, the shorter range perpendicular to the river mouth describes the alternating bands of high and low intensity clusters seen on the western edge of the study site; these bands add a lot of variance to measurements taken perpendicular to the river outflow. These relationships are the basis of how the semivariogram range can be used to describe the general shape of sediments on the river delta.

An advantage of this method of river delta analysis is that it is dependent only upon the river delta structure. Since river deltas are generally far less dynamic systems than their overlying water columns, short term processes related to conditions at the time of data collection will have nominal effects on measurements compared to methods that rely on water column measurements such as ADCP, CTD profiles, and transmissometer measurements.

The Gold River discharge clearly has a stronger role in shaping the river delta than tidal forces. This is important because logging and development along the Gold River could potentially change the strength of the river discharge. Understanding the role of river discharge in the structure of river deltas is vital to predicting how changes in river dynamics will affect related delta environments. While the remoteness of the Gold River makes it unlikely to see large anthropogenic changes in river dynamics, the same method can be applied to rivers in more varying landscapes to predict the effects of changing river dynamics. The addition or removal of dams in particular can have drastic effects on both river outflow strength and sediment supply. This same method can be applied to any river whose outflow is perpendicular to tidal flow, and can be invaluable to not only determine relative strength of river and tidal forces, but to track changes in river delta structure through repeated measurements.

The largest source of error in this study is the choice of sample area. The ordinary kriging algorithm takes all chosen data points into account, so accurately limiting the study area to the river delta is very important. The Gold River study area was chosen after analyzing the depth and backscatter mosaics of the survey and choosing an area extending from the river mouth until the seafloor either flattened out or looked like other processes were involved in shaping the backscatter mosaic. Unfortunately this is a very subjective method, and future studies should formalize a method to determine the study area through set guidelines.

Figures



Sources: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Figure 1. Mosaic of acoustic backscatter intensity (dB) in a 2.5 m resolution raster and projected on a base map of the Gold River. The red line shows the direction of river outflow used in geostatistical analyses, equal to 25° east of north.

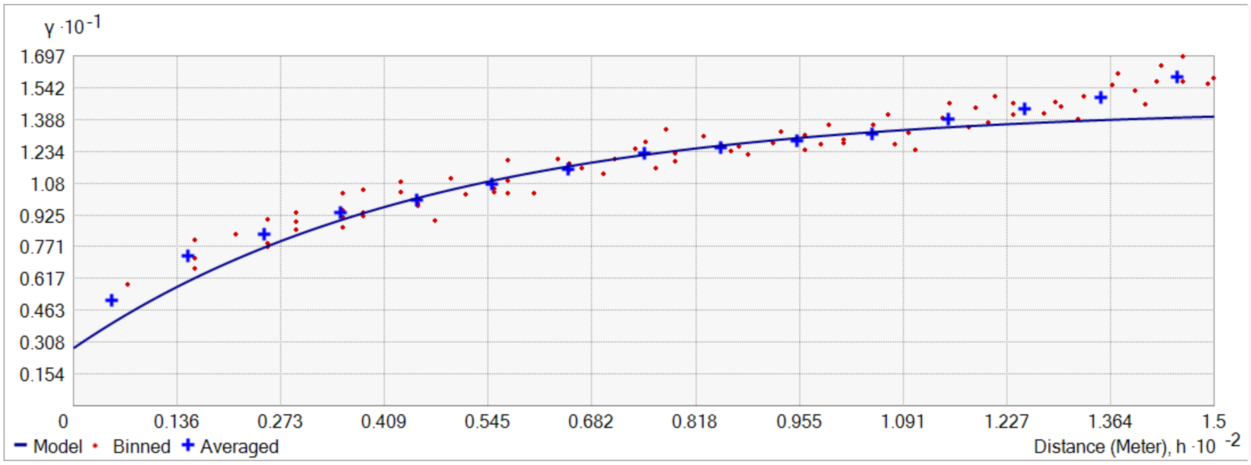


Figure 2. Anisotropic semivariogram used to show directional trends in acoustic backscatter intensity.

The major axis is measured along the path of river outflow, 25° East of North.

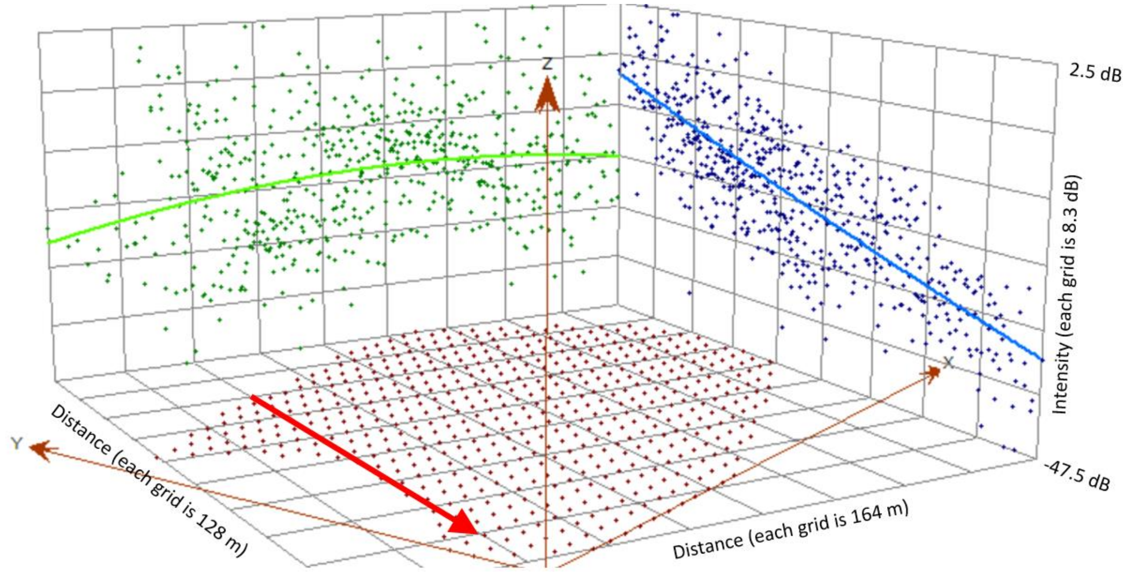


Figure 3. 3D Directional Trend Analysis of the acoustic backscatter mosaic at 25 m resolution. The x and y axis show direction (E and N respectively) while plotted on the z axis is acoustic backscatter intensity (points not shown for clarity). The red arrow shows the direction and approximate location of the Gold River outflow. The gridlines are rotated 25^{o} east from north to show the backscatter intensity trends along the direction of river outflow (blue) and perpendicular to river outflow (green).

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