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USE OF GIS TECHNIQUES FOR SEDIMENT DYNAMIC ANALYSIS OF THE MARTEL INLET, KING GEORGE ISLAND, SOUTH SHETLANDS

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ABSTRACT
This paper presents results of the sediment dynamic analysis of the Martel Inlet, King George Island, South Shetlands. As a consequence of the rising trend in study area mean surface air temperature, a rapid glacier front retreat occurred in the last decades, which has caused noticeable environmental changes, including impacts on sediment dynamics on the Martel Inlet. GIS techniques were applied for spatial and temporal changes analysis of suspended sediment concentration (SSC), using: (1) visible bands of SPOT HRV imageries obtained in February, 1988 and 2000, and in March, 1995; (2) TERRA ASTER imagery obtained in November, 2005. Furthermore, SSC sample data from subglacial frontal zone of the glacier were correlated with meteorological data. SSC data presented significant correlation with glaciers retreat that drain into the fjord, and thus they can be used as indicators of the consequences of climatic variability for the sedimentary dynamic in the study area. This methodology allowed us to obtain satisfactory results for the pattern analysis of SSC spatial and temporal changes in the Martel Inlet, during the months analyzed. By using GIS techniques, we could evaluate the intensity of the glacier sediment production in the study area and its meltwater runoff.
Keywords: Martel Inlet, suspended sediment concentration, GIS.

O USO DE TÉCNICAS DE SIG PARA ANALISE DA DINÂMICA SEDIMENTAR DA ENSEADA MARTEL, ILHA REI GEORGE, SHETLANDS DO SUL

RESUMO
Este trabalho apresenta resultados da análise da dinâmica sedimentar da Enseada Martel, ilha Rei George, Shetlands do Sul. Como consequência da tendência de aumento da temperatura média do ar superficial nessa região, ocorreu um rápido recuo da frente de geleiras nas últimas décadas, as quais promoveram mudanças ambientais perceptíveis, incluindo impactos na dinâmica sedimentar da Enseada Martel. Técnicas SIG foram aplicadas na análise da variação espacial e temporal da concentração de sedimentos em suspensão (SSC) dessa enseada, com bandas do visível de imagens SPOT HRV obtidas em fevereiro de 1988 e 2000, e março de 1995, além de imagens TERRA ASTER obtidas em novembro de 2005. Além disso, foram correlacionados dados de coletas de Concentração de Sedimentos em Suspensão (SSC) em canais glaciofluviais com dados meteorológicos. Esses dados apresentaram correlação significativa com a retração das geleiras que drenam para o fiorde, podendo assim ser usados como indicadores das consequências da variabilidade climática para a dinâmica sedimentar da área de estudo. A metodologia proposta possibilitou a obtenção de resultados satisfatórios na análise das modificações no padrão espacial e temporal da SSC na Enseada Martel durante os meses analisados. Com o uso de técnicas SIG, pôde-se avaliar a intensidade dos processos de produção de sedimentos pelas geleiras da área de estudo e o seu fluxo de água de derretimento.
Palavras-chave: Martel Inlet, Concentração de sedimentos em suspensão, GIS.

INTRODUÇÃO

The suspended sediment concentration (SSC) is one of the most important oceanographic parameters in glacial environments, since its spatial distribution and temporal changes can be used to infer the variability in the glacier ablation processes, due to its sensitive response to the meltwater runoff. The sediment supply indicates the glacier erosion action related with their thermal regimes (Ritchie and Schiebe, 1986). In respect to their thermal regime, glaciers can be classified as cold, temperate or polythermal. The ice temperature has an important control in several processes in the glacial environment, including basal melting and sliding and meltwater runoff, (Benn e Evans, 1998).

This paper aims to identify the SSC spatial and temporal variability in Martel Inlet glaciomarine environment (Figures 1, 2 and 3), King George Island (KGI), South Shetlands. It investigates the relationship between glacier retreat and the SSC contribution of the meltwater runoff in the Martel Inlet, and addresses suspended sediment production and transportation processes integration. The glacial sediment supply changes in Martel Inlet, resulting from the erosion action and from its transport to the glaciomarine environment, depend on several factors, including glacial retreat rate, glacier flow velocity and thermal basal conditions in the fjord.

Martel Inlet is classified as a fjord-like feature with proglacial front (such as Wanda glacier) and it is surrounded by outlet glaciers. Terrigenous sediment rate in South Shetland fjords is higher than those in the Antarctic Peninsula.

REVISÃO DE LITERATURA

The inorganic SSC in Admiralty Bay, measured by Pecherzewski (1980) in the summer, was 44.1m.g.dm^3 at 50 m depth; 13.6mg dm^3 in 50-100 m depth; and 5.5mg dm^3 under 100 m depth. Domack and Ishman (1993) estimated 12mg 1-^{1} for SSC in Admiralty Bay in 1993. SSC plumes were observed near the outlet glacier fronts in the Martel Inlet by Pilchemaier *et al.* (2004) and Rosa et al. (2010).

Figure 1 - Martel Inlet location on the King George lsland, and the Wanda Glacier.

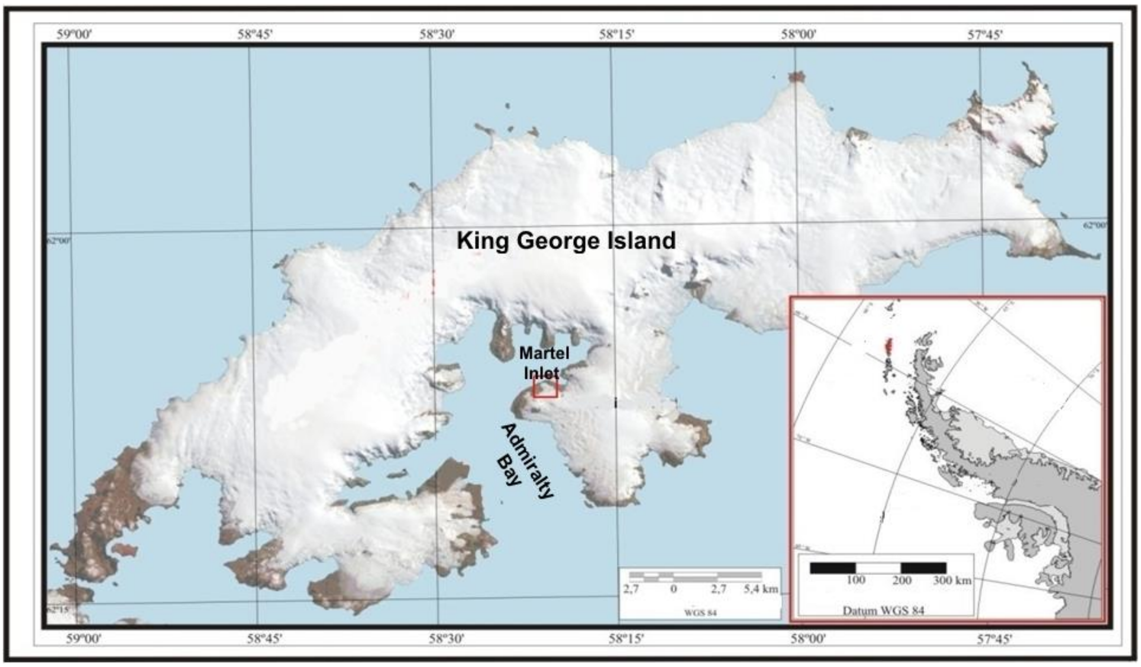


Figure 2 – Glaciers in Martel Inlet. Bathymetric contours and glacier drainage basin limits are also shown. Data provided by the Admiralty Bay Map Server prototype – Polar and Climate Center (2010).

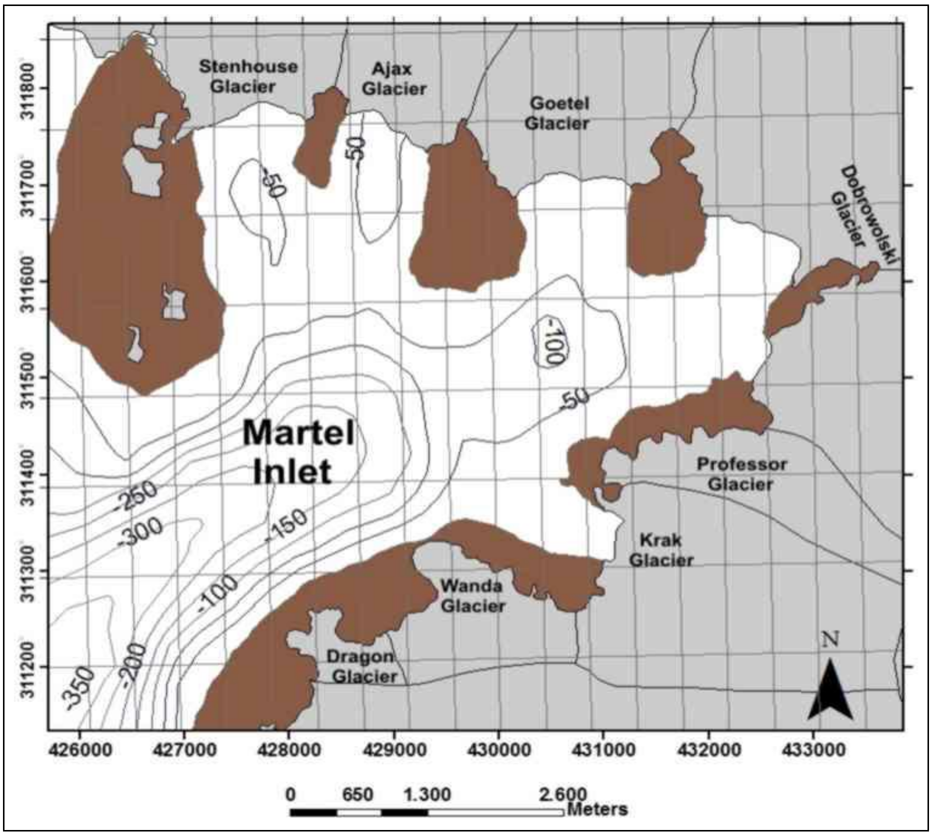


Figure 3 –Sediment plumes in Martel Inlet. (Photography taken by an Aerial Detachment onboard Ary Rongel vessel, during OPERANTAR XXVI – 2007/2008).

The sediment plumes identified on the bay surface are linked mainly to meltwater contribution from subglacial and proglacial channels (Figure 4) (Pecherzewski, 1980; Gruber, 1989; Griffth and Anderson, 1989; Domack et al., 1989; Domack and Ishman, 1993; Yoon et al., 1997; Yoon et al., 1998; Aquino 1999, Pilchemaier et al., 2004). Sediments are also transported by icebergs from tidewater glacier fronts (Pecherzewski, 1980). However, there are not any studies about the rate of sediment supply from icebergs in the study area.

Interflows are formed near the tidewater glacier fronts (Anderson and Molnia, 1989). According to Syvisky (1989), 70% of the sediments total discharge released by glacial action will be deposited up to about 500 m from glacier fronts. The sediments flow within the Martel Inlet form a turbidity plume, with maximal concentrations at about 40 m depth. The mechanisms of the plume generation are attributed to upwelling flows from the subglacial meltwater channels (Gruber, 1989). Domack and Ishman (1993) and Rakfusa-Suszczewski (1993) observed that a surface layer of low saline water can be formed as a consequence of the snowmelt runoff and by liquid precipitation in fjords. Its influence can reach at about 75 m depth.

Aquino (1999) considered the weather as a major factor that control the sedimentation processes in the study area.

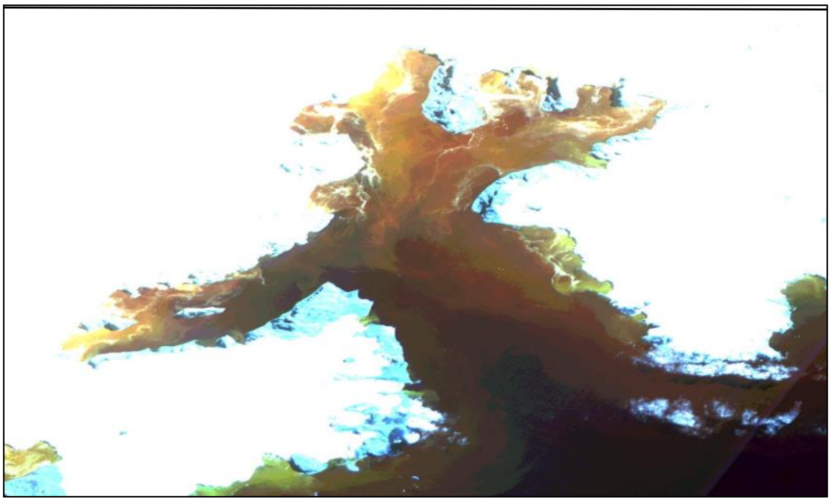
Temperature and precipitation changes affect the meltwater generation and influence the terrigenous sediment supply. Additionally, the maritime subpolar climate causes more meltwater runoff, contributing to glacier erosion processes and the erosion product transportation to the glaciomarine environment. The SSC spatial distribution has great variability, in response to the meteorological and oceanographic conditions in the inlet (Vogt e Braun, 2004).

Other studies showed a strong relationship between glacial erosion processes and rapid glacier retreat in fjords. Over the past 60 years, was observed a rising trend in Antarctic Peninsula mean surface air temperature, between 2.5 and 3.0°C (Blindow et al., 2010). Several studies observed a glacier front retreat on the Martel inlet since 1950 (Park et al., 1998; Bremer, 1998; Simões and Bremer, 1995; Simões et al., 1999; Aquino, 1999; Braun and Gossmann, 2002; Vieira et al., 2005; Rosa et al., 2006; Rosa et al., 2009). Over the past 30 years, the number of days with liquid precipitation has increased in the summer. This process accelerated the snowmelt and increased the negative mass balance of the local glaciers (Braun et al., 2001; Ferrando, 2009). As a result of regional warming, the expansion of deglaciarized areas and meltwater runoff were evident. This increased erosion processes and suspended sediment supply to the Martel Inlet. To understand such processes it is important to investigate the influences of the climate variability for sediment dynamic in the study area.

MATERIAL E MÉTODOS

The monitoring of SSC seasonal variability was performed by processing satellite images from different years (1988, 1995, 2000 e 2005) and by using meteorological data. The application of a linear contrast stretch in the SPOT color composite image used in this study enhanced the SSC (Figure 4). Through this operation it was possible to detect the suspended sediment plumes on the water and quantify their spatial distribution and concentration. The remote sensing products can be considered as a potential instrument for mapping the SSC in waterbodies with estuarine circulation. However, applications of remote sensing data in these areas depend on access to time series of images. In subpolar maritime climates, characteristic of the KGI, there is an extensive cloud cover during most of the year and low sunlight conditions in a few months of the year. These conditions can influence significantly the temporal data coverage from optical sensors. Additionally, the differences of the reflectivity in surface water as consequence of cloud cover, presence of shallow water, ice and wind action on surface water can complicate the comparison of satellite data from different years for the SSC quantification in the study area (Vogt and Braun, 2004).

Figure 4 – SPOT color composite (RGB 123), processed by a linear contrast stretch, shows the spatial distribution and concentration of the suspended sediment in Admiralty Bay - February, 2000.



Digital processing was performed in multispectral scenes acquired by SPOT (HRV), on a Quickbird (October, 2006) and TERRA (ASTER) platforms. The SPOT imageries were obtained in February, 1988, March, 2000 and in 1995, with 20 m spatial resolution. The ASTER imagery was obtained in November, 2005, with a 15 m spatial resolution. The methodology proposed in this study was developed in three stages:

Data pre-processing:

Data pre-processing consisted on the ASTER image georeferencing by ENVI software (ITT VIS), using a polynomial model with second order and data resampling by a nearest neighbor interpolation. Control points were collected from the SPOT images geometrically corrected, in UTM projection, with data referenced to WGS-84.

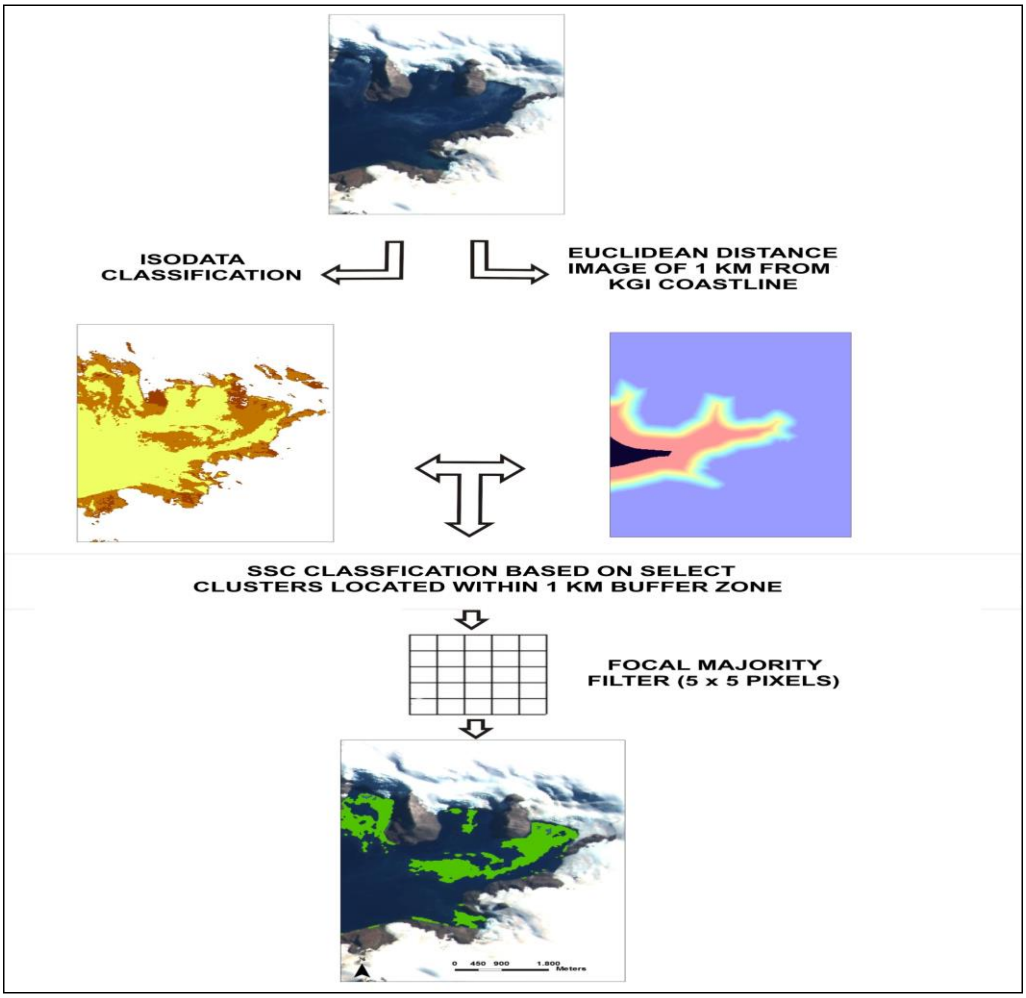
Suspended sediment classification by using an unsupervised method and a knowledge-based algorithm (Figure 5):

The SSC classification was carried out using visible bands of the HRV and ASTER sensors, due to the high SSC reflectivity in the water in these wavelengths (Vogt and Braun, 2004;

Lorenzzetti et al., 2007). The image classification was performed by using the Isodata unsupervised method.

The Isodata unsupervised method assigns classes based on statistical parameters of spectral properties and on cluster analysis, considering the image gray levels. Thus, the spectral pattern recognition occurs without the provision of spectral parameters of each class in the scene and this algorithm identifies the classes within the whole data (Crosta, 1992).

Figure 5 – Data processing chain used for SSC classification.



The SSC classification was carried out by using the selected clusters and it was also based on a buffer zone image derived from Euclidean distance images generated in ArcGIS™ (ESRI, Inc.). The latter consisted on a 1 km buffer zone from KGI coastline in the Martel Inlet (Figure 5), that was considered an area of maximum occurrence of meltwater plume sedimentation. In general, its rates decrease exponentially with distance of 1 km from the tidewater glacier fronts (Syvitski, 1989)..

Classification by decision rules were implemented in ArcGIS™ to detect SSC pixels from the selected clusters located within 1 km from KGI coastline. A focal Majority filter, with 5 x 5 pixels window, was used to data post-classification, to remove pixels and groups of pixels that did not meet the minimum requirement, generating more continuous and consistent classes and thus improving the accuracy of classification.

(a) Analysis and interpretation of the classified maps

The SSC dispersion pattern observed in the classified maps (Figure 7) were correlated to glacier flow velocity data (Figure 6), glacier area, degree of glacier retreat (data provided by the Admiralty Bay Map Server prototype) and even the weather conditions**,** during the acquisition of HRV and ASTER images used in this study (meteorological data obtained by INPE - National Institute for Space Research – Antarctic Station Comandante Ferraz - KGI, 62 ° 05 '07"S, 58 ° 23' 33"W).

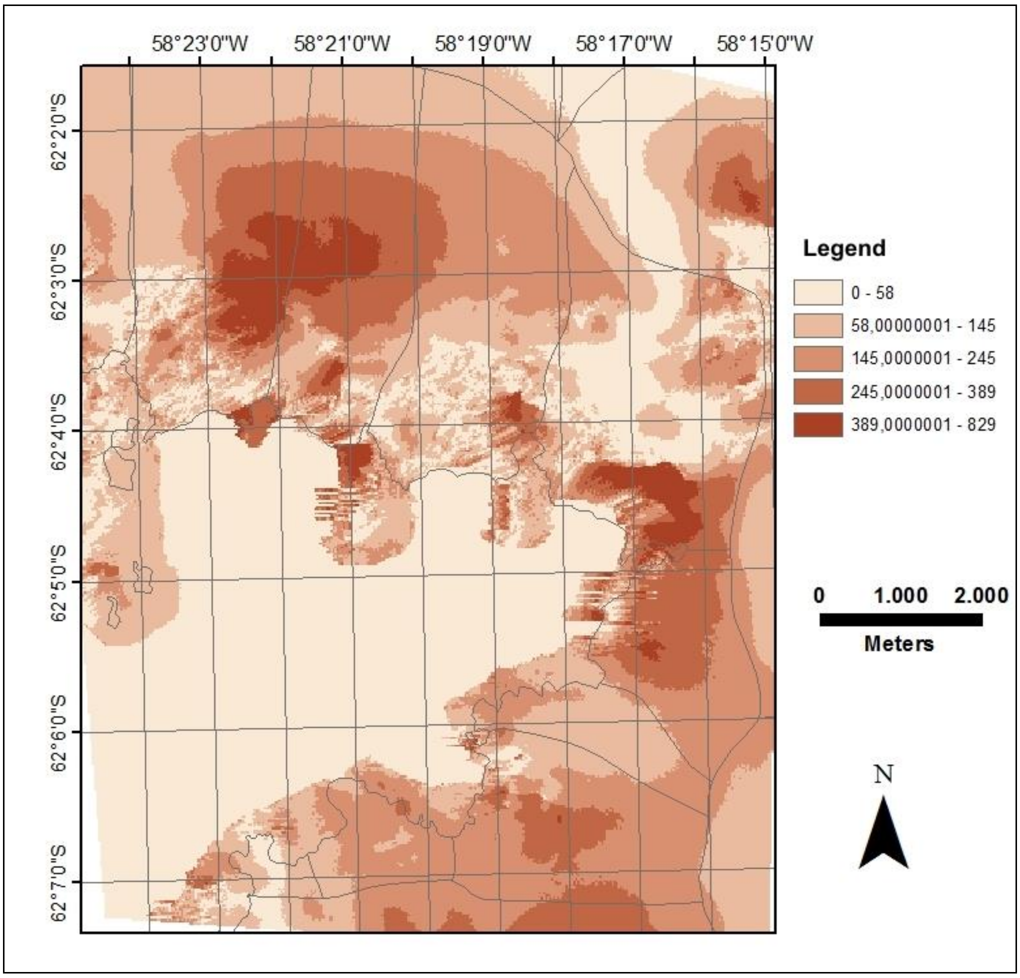
The monitoring of the SSC dispersion pattern by *in situ* collection is inaccessible for most of the year. SSC samples in the ablation channels of the Wanda Glacier (which drains into the Admiralty Bay, through a proglacial lagoon) (Figure 2) were made daily during January and February, 2010 and 2011 (ablation season), to estimate the sediment supply and the variability of its contribution to the bay. These fieldwork activities were conducted during the Brazilian Antarctic Operations XVIII and XXIX.

RESULTADOS E DISCUSSÃO

The SSC classification, resulted from the application of the knowledge-based algorithm elaborated in this study, allowed us to identify satisfactorily the pattern of the SSC spatial and temporal distribution in the Martel Inlet, during the months analyzed (Figure 7).

However, the presence of clouds in the study area affected the application of classification methods. In this methodology, there were difficulties to estipulate digital number thresholds for SSC detection in visible bands, due to its spectral characteristic changes, as well as the type and areas of clouds in the study area.

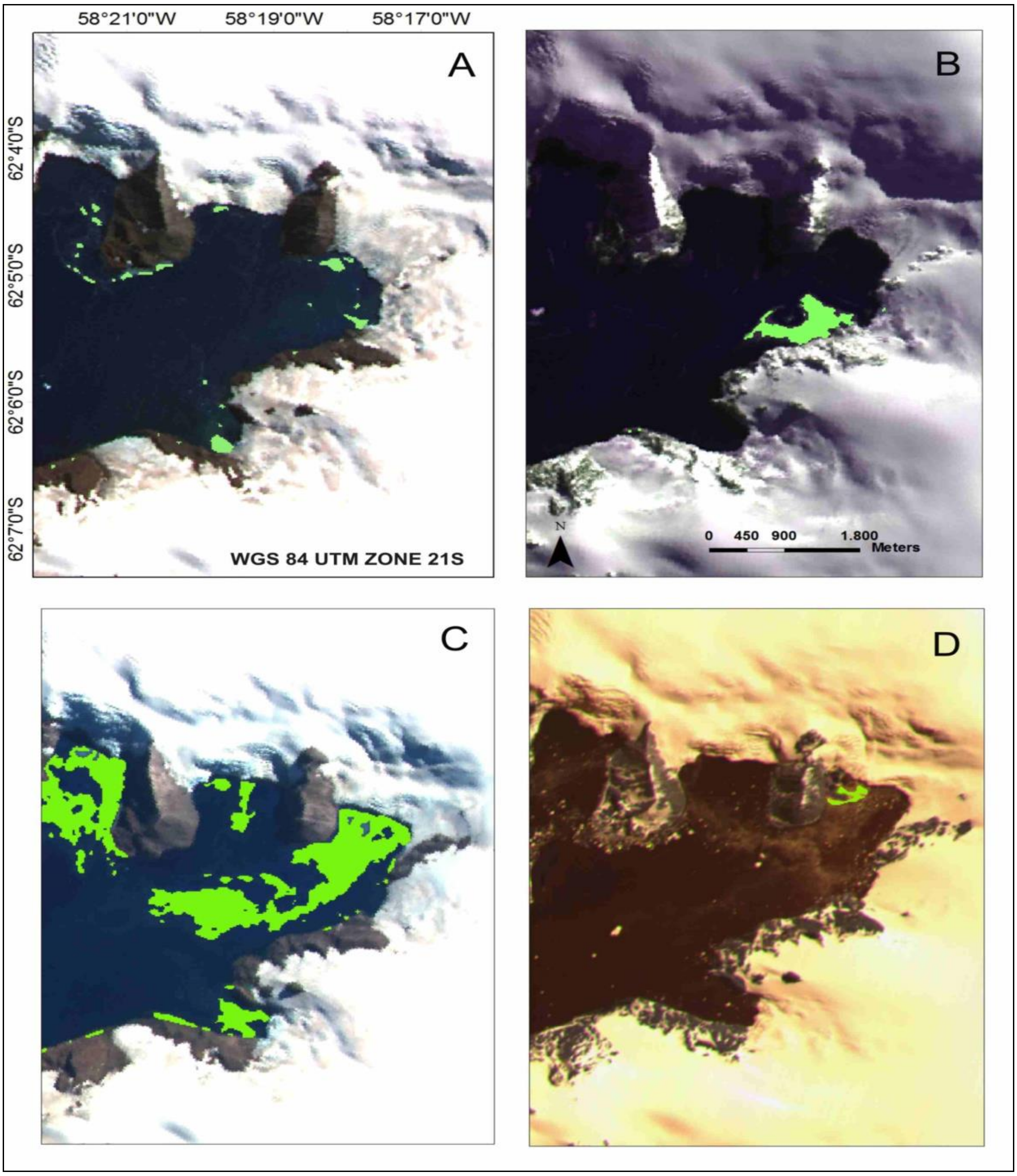
Figure 6 – Flow velocity map of glaciers located at the Martel Inlet. Data provided by Mathias Braun (Moll et al, 2006).



According to Mendes and Cirilo (2001), classification problems may occur due to changes in reflected energy in relation to time of day and season. Therefore, the SSC spectral signature can change from one image to another and there can also be differences among classes within the pixel, generating uncertainties in the classifications.

We observed in the classified images that sediment plumes are well distributed in proximal zone of the tidewater glaciers in the Martel Inlet. The high SSC agreed with data obtained by Vogt and Braun (2004). The absence of sediment plumes near the exposed areas indicated that there was little SSC contribution. The SSC data can be correlated with meltwater runoff from tidewater glacier fronts. These sediments were product of the glacial erosion action and were transported by a possible developed subglacial drainage system.

Figure 7 – SSC spatial distribution on images obtained in (A) 1988, (B) 1995, (C) 2000 e (D) 2005.



Besides, they can evidence warm thermal basal conditions for these glaciers. According to Vogt and Braun (2004), the strong fresh water and sediment inputs to the Martel Inlet have relevant impact on marine ecosystem. Rakusa-Suszczewski et al. (1993) observed that the nutrients availability and seasonal variations are more controlled by the dynamics of hydrological processes than biological processes in the study area.

There was a significant contribution to SSC supply from some glaciers, which have recorded the most rapid retreat process (e.g., Krak, Dobrowolski, Stenhouse and Ajax glaciers - Figures 8 and 9). Additionally, it was observed that the highest concentration of SSC occurred at the proximal zone of the glaciers that have greater extension (Figure 2) and ice flow speed (Figure 7), and therefore a higher sediment transport capacity.

Meteorological and satellite image acquisition data presented strong correlation. Images of February, 1988 and 2000 were obtained during days with positive air temperatures and high solar radiation conditions, and showed higher SSC than images of March, 1995 and November, 2005, which were obtained during days with greater snowfall, more negative air temperatures and low solar radiation conditions.

There was a considerable SSC temporal fluctuation due to weather conditions. The highest concentrations were associated with days of liquid precipitation. According to Pilchmaier et al. (2004), the SSC temporal changes in the Martel Inlet can also be attributed to storm and rainfall events. These changes were associated with increased freshwater discharge and erosion processes. Furthermore, resuspension by wind of material previously deposited on the fjord bottom is also linked to high SSC found in the Martel Inlet. Processes involved in SSC spatial and temporal distribution in fjord environments may also be influenced by tidewater changes and hydrodynamic characteristics of the bay (Drewry, 1986).

The proglacial discharge and SSC time series monitored during the two periods analyzed from the Wanda glacier meltwater channel, during January, 2010 and 2011, indicated that the subglacial meltwater discharge with suspended sediment had great alteration during the melt season and it represented a fraction of total sediment discharge to the Martel Inlet. SSC measurements in subglacial meltwater channels, presented in the Glacier Wanda proglacial area, demonstrated the prevalence of probable subglacial origin of suspended sediment in the bay, thus indicating great influx of basal meltwater from these glaciers, with accelerated and continuous retreat process.

Figure 8 – SSC spatial distribution from Krak (A) and Dobrowolski glaciers (B) (February, 2000).

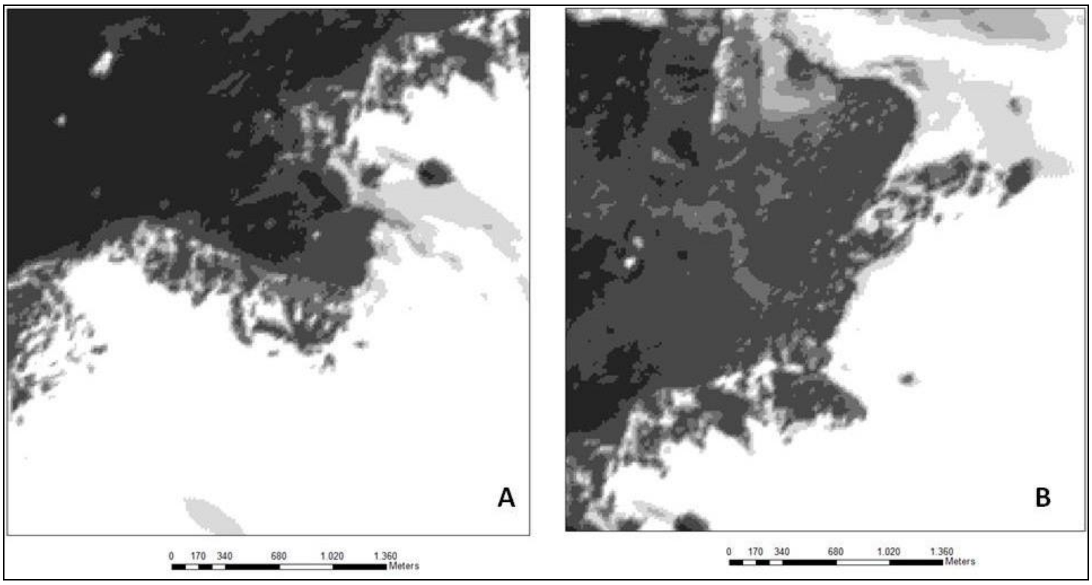
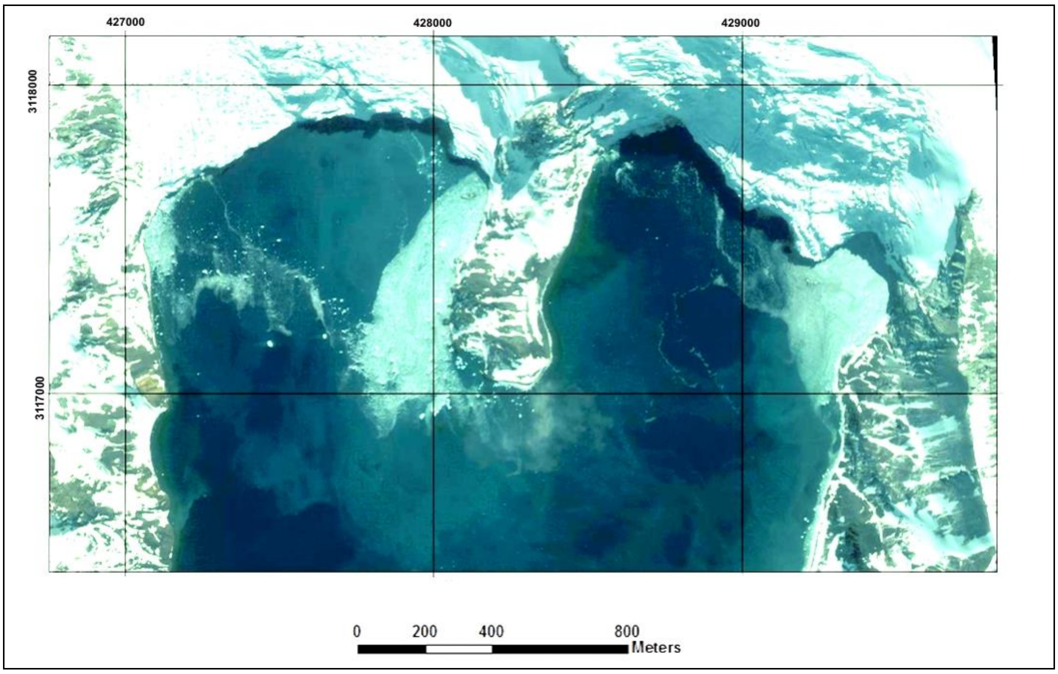


Figure 9 – SSC spatial distribution from Stenhouse and Ajax glaciers, as seen on a Quickbird image color composite (RGB 321) processed by a linear contrast stretch, obtained in October, 2006.



The higher SSC from subglacial origin may be related to an effective rate of sediment removal due to intense glacier meltwater runoff, thus providing indicators to quantify the rate of sediment production, which is related to the degree of glacier basal sliding (i.e., represents the proportion of subglacial meltwater and is also linked to local precipitation). Additionally, the high concentration of sediment plumes in the proglacial area can indicate a high sediment production and indicates a warm basal thermal regime for local glaciers.

CONSIDERAÇÕES FINAIS

The proposed knowledge-based classification algorithm could be applied successfully for monitoring the SSC spatial and temporal variability and the glacial erosion processes. These processes could be associated with climate variability and glacier retreat, evidenced in the study area in the latest six decades.

The use of GIS techniques allowed us to evaluate the intensity of glacier sediment production processes in the Martel Inlet, related to glacier retreat and increased meltwater runoff. It could be used for the development of conceptual and numerical models of the processes involved in glacial dynamics and estuarine circulation related to the climate changes evidenced in the study area.

Differences in SSC spatial changes related to the month in which the image were obtained and measurements of meltwater discharge data showed strong seasonal and weather condition control in these processes.

We highlighted some difficulties in obtaining optical images without cloud cover in the study area, which could affect the analysis of temporal processes associated with glacier retreat. In addition, it was difficult to quantify more accurately the SSC, because the sensor signal was integrated with the entire water column. Thus, the samples collected in fieldworks became essential to check the classification accuracy and to estimate quantitatively the SSC in the fjord.

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