HEADLAND-BAY BEACH PLANFORM STABILITY OF SANTA CATARINA STATE AND OF THE NORTHERN COAST OF SÃO PAULO STATE

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A B S T R A C T

This paper presents the results of the planform stability classification for the headland-bay beaches of the State of Santa Catarina and of the Northern Coast of São Paulo, based on the application of the Parabolic Bay-Shape Equation (PBSE) to aerial images of the beaches, using the software MEPBAY®. For this purpose, georeferenced mosaics of the QuickBird2® satellite imagery (for the State of Santa Catarina) and vertical aerial photographs (for the northern coast of São Paulo State) were used. Headland-bay beach planform stability can be classified as: (1) in static equilibrium, (2) in dynamic equilibrium, (3) unstable or (4) in a state of natural beach reshaping. Static equilibrium beaches are the most frequent along the coast of the State of Santa Catarina and the Northern Shore of São Paulo, notably along the most rugged sectors of the coast and those with experiencing lower fluvial discharge. By comparison, dynamic equilibrium beaches occur primarily on the less rugged sectors of the coast and along regions with higher fluvial discharge. Beaches in a state of natural beach reshaping have only been found in SC, associated with stabilized estuarine inlets or port breakwaters. However, it is not possible to classify any of these beaches as unstable because only one set of images was used. No clear relation was observed between a beach's planform stability and other classification factors, such as morphodynamics or orientation.

R E S U M O

Este trabalho apresenta resultados da classificação da estabilidade da forma em planta das praias de enseada do Estado de Santa Catarina e do Litoral Norte de São Paulo, realizada através da aplicação do modelo parabólico a imagens aéreas utilizando o software MEPBAY®. Para isso foram construídos mosaicos georeferenciados com imagens do satélite QuickBird2® (para o Estado de Santa Catarina) e com fotografias aéreas verticais (para o Litoral Norte de São Paulo). Quanto à estabilidade de sua forma em planta, as praias de enseada podem ser classificadas como: (1) equilíbrio estático, (2) equilíbrio dinâmico, (3) instável e (4) remodelamento natural. No Estado de Santa Catarina e no Litoral Norte de São Paulo foi observado o domínio de praias em equilíbrio estático, predominantemente nos setores do litoral que são mais recortados e apresentam menor aporte fluvial. As praias em equilíbrio dinâmico, por outro lado, são mais freqüentes nos setores menos recortados e com maior influências do aporte sedimentar por via fluvial. Praias em remodelamento natural ocorrem apenas em SC, associadas à desembocadura de rios retificados ou a quebra-mares de portos. Como foi utilizada apenas uma série de imagens, não foi possível enquadrar praias no estado instável. Não foi observada uma clara relação entre o estado de equilíbrio da forma em planta com outras classificações de praias, como morfodinâmica e orientação.

Descriptors: Headlands, Wave diffraction, Parabolic Bay-Shape equation.
Descritores: Promontórios, Difração de ondas, Equação parabólica.

INTRODUCTION

Most of the world's coastlines (approximately 80%) are classified as rocky coasts, containing headlands, coastal mountains and cliffs (EMERY; KUHN, 1982). Beaches adjacent to such headlands tend to exhibit a curved shape due to the effects of the sheltering and diffraction of waves; *i.e.* they generate headland-bay beaches. Despite the abundance of headland-bay beaches on the southern/southeastern coasts of Brazil (e.g. in Rio de Janeiro, São Paulo, Paraná and Santa Catarina States), few studies of these beaches have incorporated planform stability analysis (KLEIN, 2004).

Several empirical models have been developed to mathematically represent headland-bay beach planform. The log spiral equation (KRUMBEIN, 1944; YASSO, 1965), the hyperbolic tangent model (MORENO; KRAUS, 1999; MARTINO et. al., 2003) and the parabolic bay-shape equation (HSU; EVANS, 1989; SILVESTER; HSU, 1993, 1997; HSU et. al., 2000, 2008) all seek to fit the planform shape of headland-bay beaches, based on different coordinate systems and variables. However, the only model that incorporates as direct parameters the geometry of the bay and shoreface dynamics (e.g. diffraction point and the prevailing wave direction) is the parabolic model (HSU et al., 2008). Hence, this represents the only model capable of predicting changes in the shoreline due to changes of the diffraction point (e.g. coastal engineering structures) or in the direction of the most energetic waves (swell).

The parabolic equation created by Hsu and Evans (1989), is a second order polynomial based on polar coordinates, designed to curve-fit the shape of 14 prototype and 13 natural bays that are believed to be in static equilibrium.

$$R_N/R_0 = C_0 + C_1 (\beta/\theta_N) + C_2 (\beta/\theta_N)^2$$

In the equation, the main parameters are the angle β (angle formed by the wave crest direction and the control line, which joins the diffraction point to the point where the straight section of the beach starts) and the length R_0 (length of the control line cited above – Fig. 1). The wave direction is assumed to be parallel to the straight section of the beach. Based on the given input parameters, the model calculates, for the desired range of the angle θ_N, the corresponding length R_N that generates the stable form of the beach. The three constants C are derived by regression analysis and are dependent on β. In the equation, the parameters are used as ratios (e.g. R_N/R_0, β/θ_N), allowing the model to be dimensionless.
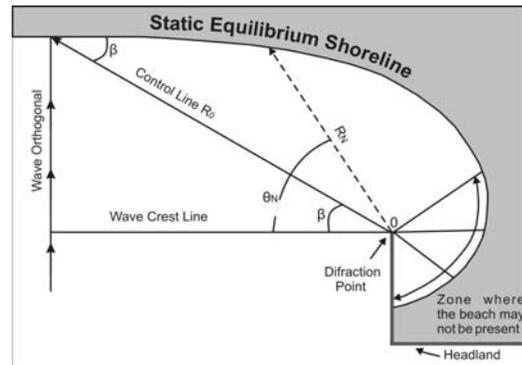

Fig. 1. Schematic sketch of the parabolic bay-shape equation parameters (modified from HSU and EVANS, 1989).

Control points are cautiously determined and based on the interpretation of the coastal morphology presented in aerial images (BENEDET et. al., 2004). The diffraction point, defined as the last point where the incoming swell interacts with the headland before propagating to the beach, is determined in a straightforward manner. . The distal location of headland influence is given as either the proximal end of the straight section of beach or, in cases where no straight section of beach exists, the distal terminus of the beach. The wave direction is defined as tangent to the straight section of the beach. Based on that input, the model generates the stable planform of the beach, defined by the effect of the given wave direction in a situation of a balanced sediment budget. The model can only be used on wave dominated, micro-tidal coasts (HSU; EVANS, 1989).

Based on the planform stability Hsu et al., (2008) classified the headland bay beaches as belonging to four states: (1) static equilibrium, (2) dynamic equilibrium, (3) unstable and (4) natural beach reshaping. Beaches in static equilibrium exhibit net longshore transport close to zero; waves that diffract on the headland proceed to break simultaneously along the entire bay (Fig. 2A). Therefore, these beaches tend to keep a stable planform, regardless of the sediment budget (a notable exception occurs during storm events). The shape modeled using the parabolic equation coincides with the shape of beaches in static equilibrium. For beaches in a state of dynamic equilibrium, waves break at an angle to the shoreline, generating longshore currents capable of transporting sediment (Fig. 2B). In this case, planform stability is dependent on the sediment budget. The planform of a dynamic equilibrium beach does not coincide with the shape dictated by the parabolic equation. If the sediment input of those beaches decreases or ceases, the shoreline tends to move toward the static equilibrium position, possibly causing erosion and, on populated beaches, damage to infrastructure. Beaches where the displacement of the

shoreline is verified are classified as unstable. Assigning this classification requires the verification of the shoreline displacement with field data or a time-series of aerial images. Beaches that have coastal engineering structures (e.g. jetties, breakwaters and dykes) are classified as being in a state of natural beach reshaping (Fig. 2C). In such locations, sediment tends to be transported to the sheltered area, causing down drift erosion. Since static equilibrium beaches are the most stable under the action of the prevailing waves, the construction of coastal structures that provide for that equilibrium state is highly recommended to stabilize the shoreline of eroding beaches (HSU et. al., 2000).

Prior to the classification system defined by Hsu et al., (2008), the most commonly used classification system was that given by Hsu and Evans (1989). This scheme, which presents only the static and dynamic equilibrium states, was adopted by Klein et al. (2003a) to analyze the planform stability of 63 beaches along the coast of Santa Catarina State, Brazil. This was accomplished using 1:12.500 scale images and applying the model manually. These authors also proposed an additional intermediate equilibrium state between the static and dynamic states, which was called close-to-static equilibrium.

Although it is simple, the manual application of the parabolic equation is laborious and time consuming; this method requires the calculation and manual drawing of each increment of the angle, θ, or the verification of the R_N/R_0 ratio values for a range of angle θ in accordance with tables published by Silvester and Hsu (1993, 1997). Seeking a solution to these deficiencies, Vargas et al. (2002) and Klein et. al. (2003b) developed the MEPBAY® software, which allows a fast and efficient application of the model. The software was developed for educational purposes, allowing undergraduate and graduate students to actively apply the parabolic model, through a simplistic graphical user interface (GUI, Fig. 3). In MPEBAY®, a digitized aerial image is projected; the user can then determine the position of the control points and observe the shape generated by the equation. The result is a dynamic and straightforward application of the model.
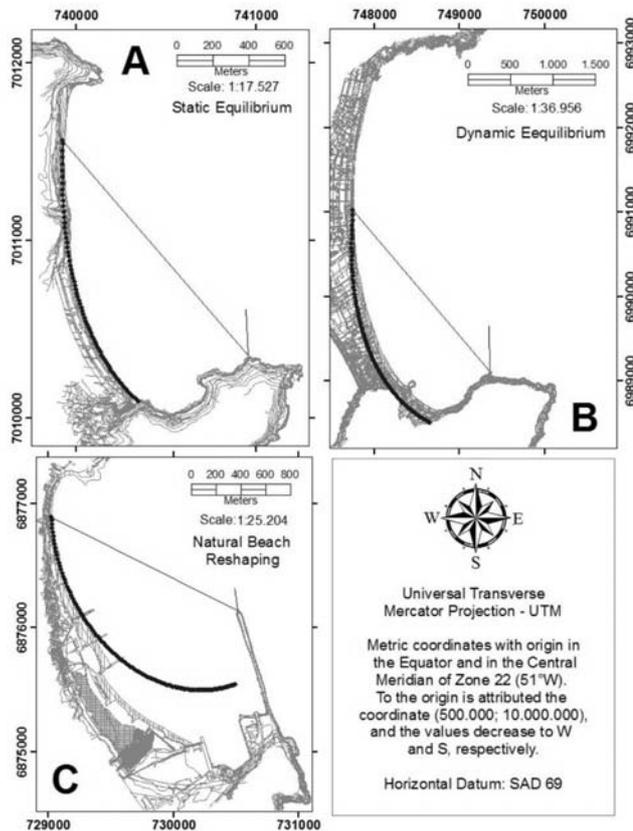

Fig. 2. Examples of beaches in the state of A) static equilibrium (Taquaras/Taquarinhas Beach, Balneário Camboriú – SC), B) dynamic equilibrium (Mariscal Beach, Bombinhas –SC) and C) natural beach reshaping (Porto Beach, Imbituba – SC). The dotted line indicates the static equilibrium shoreline position, described by the parabolic equation.
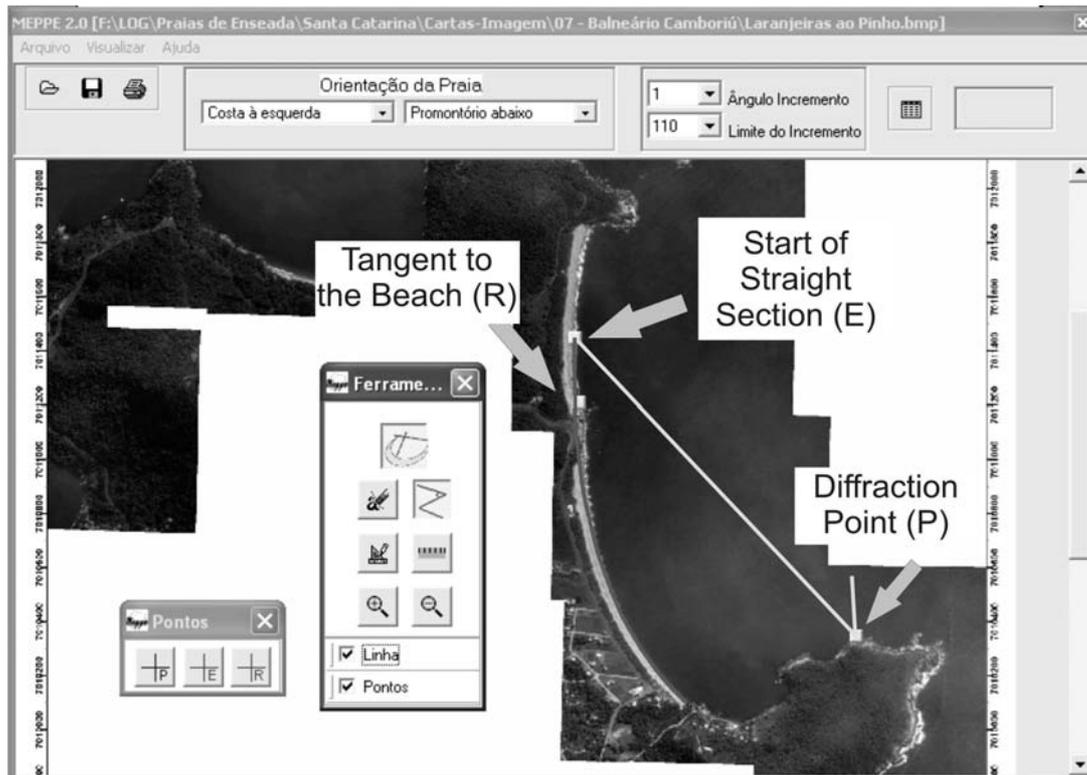
Fig. 3. MEPBAY® software interface (VARGAS et al., 2002; KLEIN et al., 2003b), indicating the control points that are defined by the user and the static equilibrium shape generated by the model. Application to Taquaras/Taquarinhas Beach, Balneário Camboriú – SC.

This paper presents the results of the application of the parabolic model to aerial images of headland-bay beaches in the State of Santa Catarina and along the Northern Coast of São Paulo State, and the resultant planform stability classification. The classification of the Santa Catarina beaches is compared to the classification proposed by Klein et al. (2003a), verifying discrepancies arising from both the use of images with different scales and resolutions, and from the use of two different planform stability classifications: (1) Hsu and Evans (1989), used by Klein et al. (2003a); and (2) Hsu et al. (2008), used in this work.

STUDY AREAS

This study focuses on the coast of the State of Santa Catarina (from Santa Marta Cape to São Francisco Island) and the northern coast of São Paulo State (from Santos Bay to Ubatuba municipality). According to Tessler and Cazzoli y Goya (2005), the coastal sector between Cabo Frio (Rio de Janeiro State) and Cabo de Santa Marta (Santa Catarina State), known as the São Paulo Embayment, is characterized by the proximity of the coastal mountain range (e.g. Serra do Mar), typified by a shore normal bedrock outcrop, creating rocky cliffs and headlands along the coast. A great diversity of environments occurs along this sector of the coast, due to the variability of the distance between the mountains and the present-day shoreline. The region between São Francisco Island (SC) and Santos Bay (SP) is dominated by extensive coastal plains that were modeled by the transgressive and regressive cycles that occurred during the Quaternary. North of Santos and south of São Francisco Island, the coast is rugged, dominated by the headlands formed by the coastal mountains.

Based on the geomorphologic divisions proposed by FitzGerald et al. (personal communication) for Santa Catarina and by Suguio and Martin (1978) for São Paulo, this coast can be subdivided into three general geomorphic classes:

1) Headland-Cuspate Barrier Coast (in Santa Catarina, from Santa Marta Cape to Pinheira Bay; – and in São Paulo, from Santos Bay to São Sebastião Island): Small bedrock headlands separated by cuspate barriers characterize this coastal segment. Many of the barriers along this reach form parabolic-shaped shorelines.

2) Rugged Bedrock Headland-Strand Plain Coast (in Santa Catarina, from Pinheira Bay to Vigia Point; - and in São Paulo from São Sebastião Island to Ubatuba): This section of coast is dominated by prominent bedrock headlands, reentrants, and bays. Between many of the small and large headlands, prograded foredune ridges, beach ridges and chenier plains have contributed to smoothing the irregular coastline.

3) Strand Plain-Estuarine Coast (in Santa Catarina, from Vigia Point to São Francisco Island; - and in São Paulo from Cananéia to Santos): This coast reflects a regime of abundant sediment supply in which foredune ridge plains formed between large estuarine systems. This type of coast continues along the coast of Paraná and into southern São Paulo. The slightly irregular nature of the shoreline is due to widely spaced bedrock promontories.

The southern/southeastern Brazilian coastline is classified as a micro-tidal, wave dominated coast. Tides are predominantly semidiurnal (but with diurnal inequalities), with spring tide amplitudes varying from 0,46 – 1,06 m (KLEIN,2004). Therefore, the physical characteristics of this project's study areas fit the parabolic model application conditions: wave dominated, micro-tidal coasts.

Another assumption of the parabolic model is the balanced sediment budget. This means that the amount of sediment being added to the coast may affect the planform stability. To get an estimation of the potential fluvial sediment input along the coast, the drainage area and average outflow of the rivers were used. According to ANA (2008), the State of Santa Catarina is divided into five hydrographic regions: (1) Northern Santa Catarina Lowland, (2) Itajaí Valley, (3) Central Coast, (4) Southern Santa Catarina and (5) Extreme Southern Santa Catarina. The State of São Paulo is divided into three hydrographic regions: (1) Northern Coast of São Paulo, (2) Santos Lowland and (3) Southern Coast of São Paulo. Included in this study are the first three regions listed above for Santa Catarina and the first two of São Paulo . Their total drainage area, average outflow at the river mouths and their sub-basins are given in Tables 1 and 2 (for SC and SP, respectively).

Table 1. Hydrographic regions of the state of Santa Catarina and key characteristics (ANA, 2008).

Hydrographic Region	Total Drainage Area	Average Discharge at Rivermouth	Sub-Basins
Northern Santa Catarina Lowland (Sector 3, as shown in the results)	5.138 km²	20 m³/s	Rio Cachoeira (80 km²), Rio Cubatão (472 km²), Rio Itapocú (2.930 km²).
Itajaí Valley (Sectors 2 and 3, as shown in the results)	15.000 km²	205 m³/s	Rio Itajaí do Norte, Rio Itajaí-Mirim, Rio Benedito, Rio Cedro, Rio Luiz Alves, Rio Neisse, Rio Warnow, Rio Engano, Rio Texto and Rio Garcia.
Central Coast (Sectors 1 and 2, as shown in the results)	5.824 km²	-	Rio Tijucas (2.420 km²), Rio da Madre (305 km²), Rio Biguaçu (382 km²) and Rio Cubatão Sul (738 km²).

Table 2. Hydrographic regions of the state of São Paulo and key characteristics (ANA, 2008).

Hydrographic Region	Total Drainage Area	Average Discharge at Rivermouth	Sub-Basins
Northern Coast of São Paulo (Sectors 2 and 3, as shown in the results)	1.977 km²	~105 m³/s	R. Fazenda/Bicas (80,1 km²), R. Irriri/Onça (74,4 km²), R. Prumirim (21 km²), R. Quiririm/Puruba (166,7 km²), R. Prumirim (2.930 km²), R. Itamambuca (56,4 km²), R. Indaiá/Capim Melado (37,6 km²), R. Grande de Ubatuba (103 km²), R. Perequê-Mirim (16,5 km²), R. Comprido/Escuro (61,5 km²), R. <aranduma/Ararība (67,7 km²), R. Tabatinga (23,7 km²), R. Mococa (40,2 km²), Córrego **B**acuí/R. Massaguaçú (35,5 km²), R. Guaxinduba (25,3 km²), R. Santo Antonio (39,8 km²), R. Juquerique (429,8 km²), R. São Francisco (16,8 km²), R. São Sebastião (10,6 km²), Ribeirão Grande (18,1 km²), R. Paúba (21,9 km²), R. Maresias (28,1 km²), R. Grande (33,2 km²), R. Camburi (36,2 km²), R. Barra do Saí (24,1 km²), R. Juqueí (14,9 km²), R. Una (120,8 km²), Córrego do Jabaquara (18,9 km²), Córrego Bicuíba (13,1 km²), Córrego Ilhabela/Cachoeira (12,3 km²), Córrego Paquera/Cego (49,8 km²), Córrego São Pedro/S. Sebastião/Frade(38,3 km²), Córrego Sepituba/ Ipiranga/ Boneti/ Enchovas/ Tocas (91,3 km²), Córrego Engenho/ Castelhano/ Cabeçuda (85,6 km²) and Córrego do Poço (23,2 km²).
Santos Lowland (Sector 3, as shown in the results)	2.788,82 km²	-	R. Cubatão (175,5 km²), R. Mogi (68,39 km²), R. Itapanhaú (149,32 km²), R. Itatinga (114,88 km²), Rio Quilombo (86,88 km²), R. Guaratuba (108,78 km²), R. Branco (411,66 km²), R. Boturoca (182,84 km²), R. Itanhaém (102,57 km²), R. Praia do Una (33,09 km²), R. Perequê (64,34 km²), R. Preto Sul (101,83 km²), R. Preto (324,63 km²), R. Aguapeu (188,01 km²), R. Piaçabuçu (58,6 km²), R. I. de São Vicente (85,81 km²), R. I de Santo Amaro (142,7 km²), R. Cabuçu (69,65 km²), R. Jurubatuba (79,36 km²), R. dos Alhas (108,27 km²) and Ribeirão Sertãozinho (131,66 km²).

MATERIAL AND METHODS

The methodology applied for this study is divided into two steps: (1) the construction of georeferenced mosaics and (2) the planform stability analysis.

Mosaics

For Santa Catarina State, QuickBird2® imagery was used. These images, obtained by exported high resolution imagery from Google Earth®, have a spatial resolution of 2,4 to 2,8 m, a 1:3.600 scale and were captured between 2003 and 2006. For the northern coast of São Paulo State, georeferenced (*South American Datum* 1969) color vertical aerial photographs were obtained from INPE's CD-teca. These photographs were taken in 2001, with a 1:25.000 scale, 1-m resolution. The name and location of the beaches identified in this study were obtained from the Quatro Rodas Beach Guide (ABRIL, 2006).

The QuickBird2® Santa Catarina images were georeferenced using charts produced by the Secretaria de Patrimonio da União (SPU), with a 1:2.000 scale; for consistency these images were also referenced to the *South American Datum* 1969. Georeferencing was completed using the ArcMap 9.2® software and resulted in the creation of a continuous mosaic for the entire study area. Charts of each beach or bay were generated from the georeferenced images; these charts were used as a base for the application of the parabolic model. These steps were necessary to prevent the occurrence of distortions that could influence the results of the parabolic model.

Planform Stability Analysis

The charts generated were loaded in MEPBAY® 2.0 software to analyze the planform stability of the headland-bay beaches (VARGAS et al., 2002; KLEIN et al., 2003b). Use of this software requires the following steps:: (1) load the aerial image or chart (.JPG or .BMP formats); (2) indicate the scale, based on the scale bar of the chart, so the numerical results can be shown in meters; (3) place the control points: the diffraction point; the proximal end of the

straight section of beach; and the tangent to the proximal end of the straight section of beach; (4) indicate the relative orientation of the beach and the headland; (5) indicate the desired increment of the angle, θ, to curve-fit the entire beach and (7) analyze the line generated by the model and compare it with the beach's shoreline. The beach planform stability can then be determined.

The beaches were classified, according to Hsu et al. (2008), as in a state of static equilibrium, dynamic equilibrium or natural beach reshaping. It was not possible to classify beaches in the unstable state due to a dearth of the field data and time-elapsed photographs from which displacement could have been identified. Furthermore, due to the subjective nature of the placement of control points, cases of complex beach morphology required a modified classification scheme. For example, beaches with double curvature (i.e. with headlands influencing the planform of the beach on its two extremities, or with tombolos or salients) often presented different classifications along their length. In these instances, a single beach was counted as two or more units for the spatial distribution statistical analysis.

RESULTS

To simplify the interpretation of the results, the coast of Santa Catarina State and that of the northern coast of São Paulo State were divided into sectors with homogeneous hydrographic and geomorphic characteristics (Fig. 4).

The coast of Santa Catarina was divided into 3 sectors: Sector 1: Coastline between Santa Marta Cape, in Laguna municipality, and Pinheira Bay, in the city of Palhoça; Sector 2: From Pinheira Bay to Vigia Point, in the city of Penha; Sector 3: Coastline between Vigia Point and the northern tip of São Francisco Island.

The northern coast of São Paulo was divided into 3 sectors: Sector 1: Coastline between Santos Bay, in Santos municipality, and Apara Point, in the city of São Sebastião; Sector 2: From Apara Point to Grossa Point, in the city of Ubatuba; Sector 3: Coastline between Grossa Point and the northern limit of São Paulo State.

The results are presented in charts and tables, with a statistical analysis of planform type distributions for each sector of the coast. Appendix A provides the results of the planform analysis for all the beaches studied, listed by sector.

Santa Catarina State

The results of the headland-bay beach planform stability for Sectors 1, 2 and 3 of Santa Catarina are presented in Figures 5, 6 and 7, respectively. Table 3 provides the results of the analysis of the percentage of occurrence of each equilibrium state for each Sector and for Santa Catarina State as a whole.

Fig. 4. Map of southern Brazil indicating the geographical boundaries used to define the sectors.

Fig. 5. Chart showing the planform stability classification for Santa Catarina's Sector 1. Numbers reference beaches as listed in Appendix A.
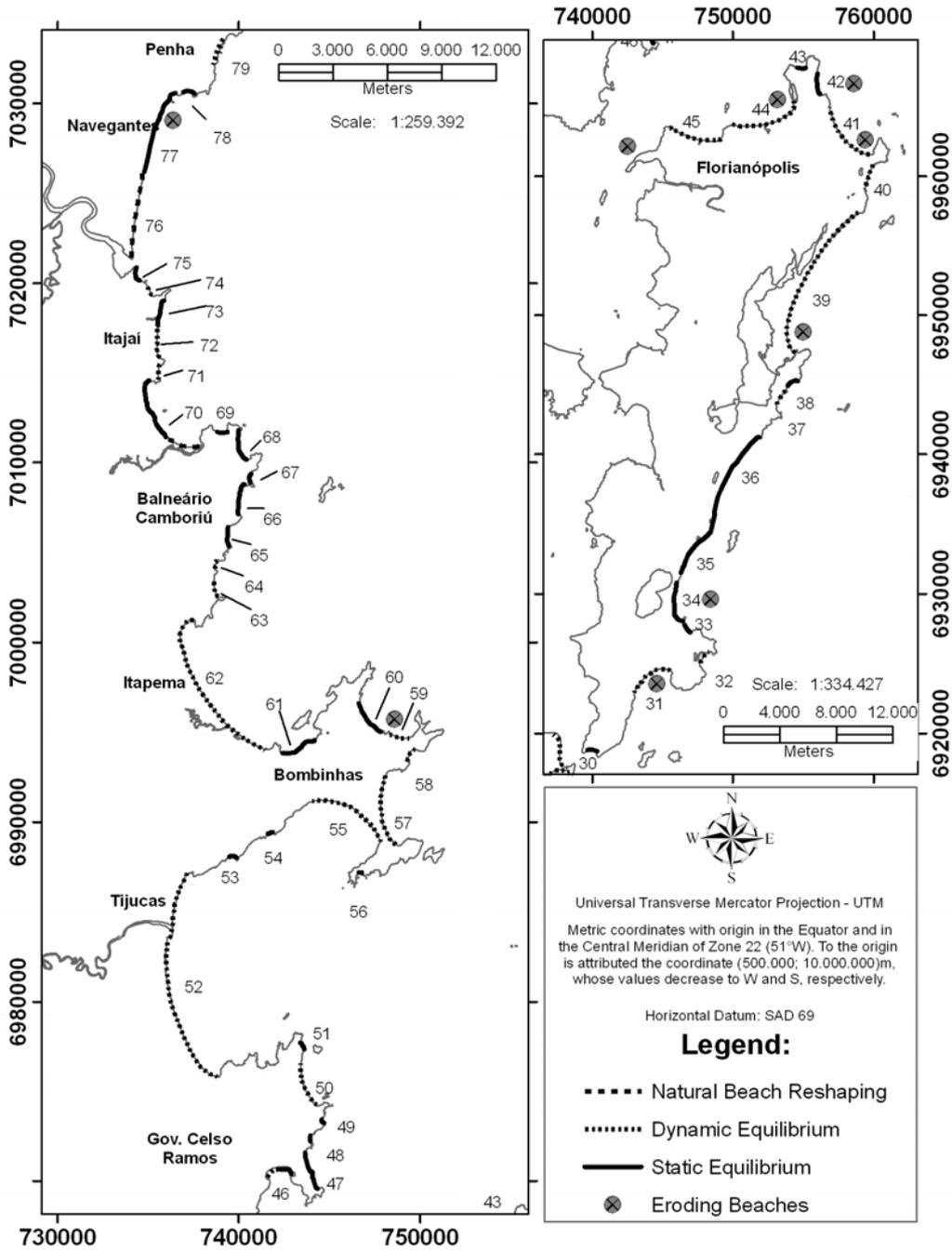
Fig. 6. Chart showing the planform stability classification for Santa Catarina's Sector 2. Numbers reference beaches as listed in Appendix A.
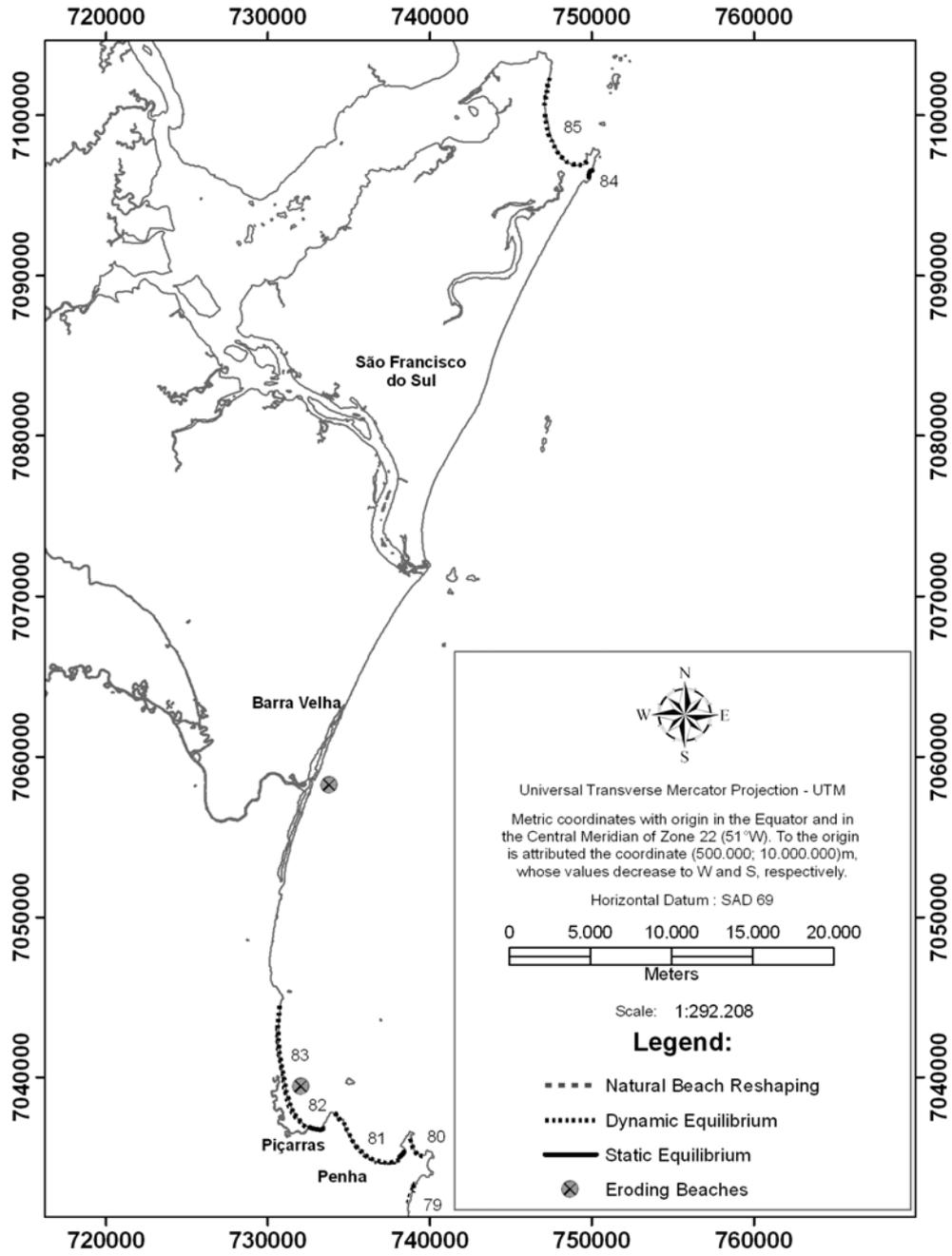
Fig. 7. Chart showing the planform stability classification for Santa Catarina's Sector 3. Numbers reference beaches as listed in Appendix A.

Table 3. Occurrence frequency of each equilibrium state in each sector and in Santa Catarina State as a whole.

	Static	Dynamic	Natural Beach Reshaping
Sector 1	53%	40%	7%
Sector 2	63%	33%	4%
Sector 3	50%	50%	-
Total SC	59%	36%	5%

Northern Coast of São Paulo State

The results of the headland-bay beaches planform stability for the Sectors 1, 2 and 3 of the northern coast of São Paulo State are presented in Figures 8, 9 and 10, respectively. Table 4 shows the results of the analysis of the percentage of occurrence of each equilibrium state for each Sector and for the northern coast of São Paulo as a whole.
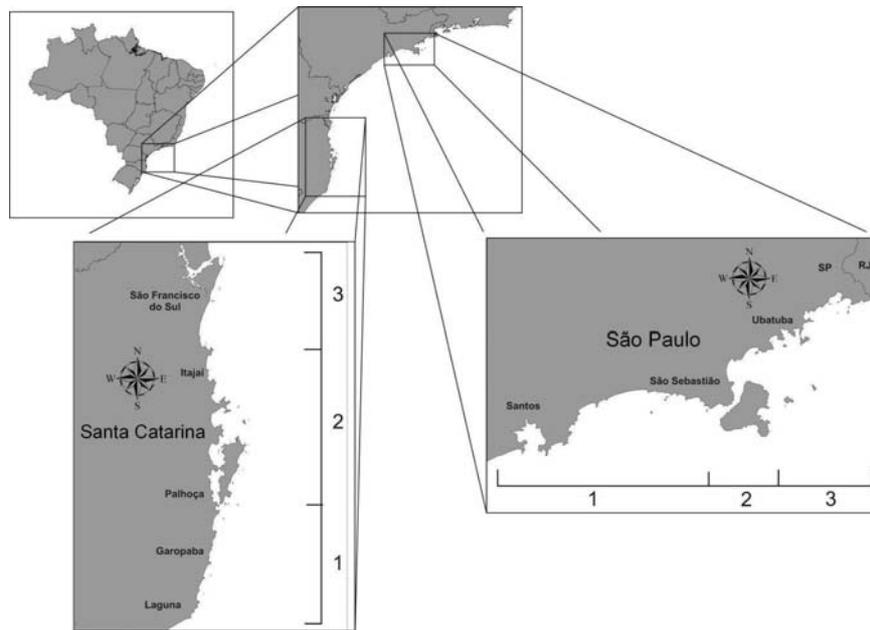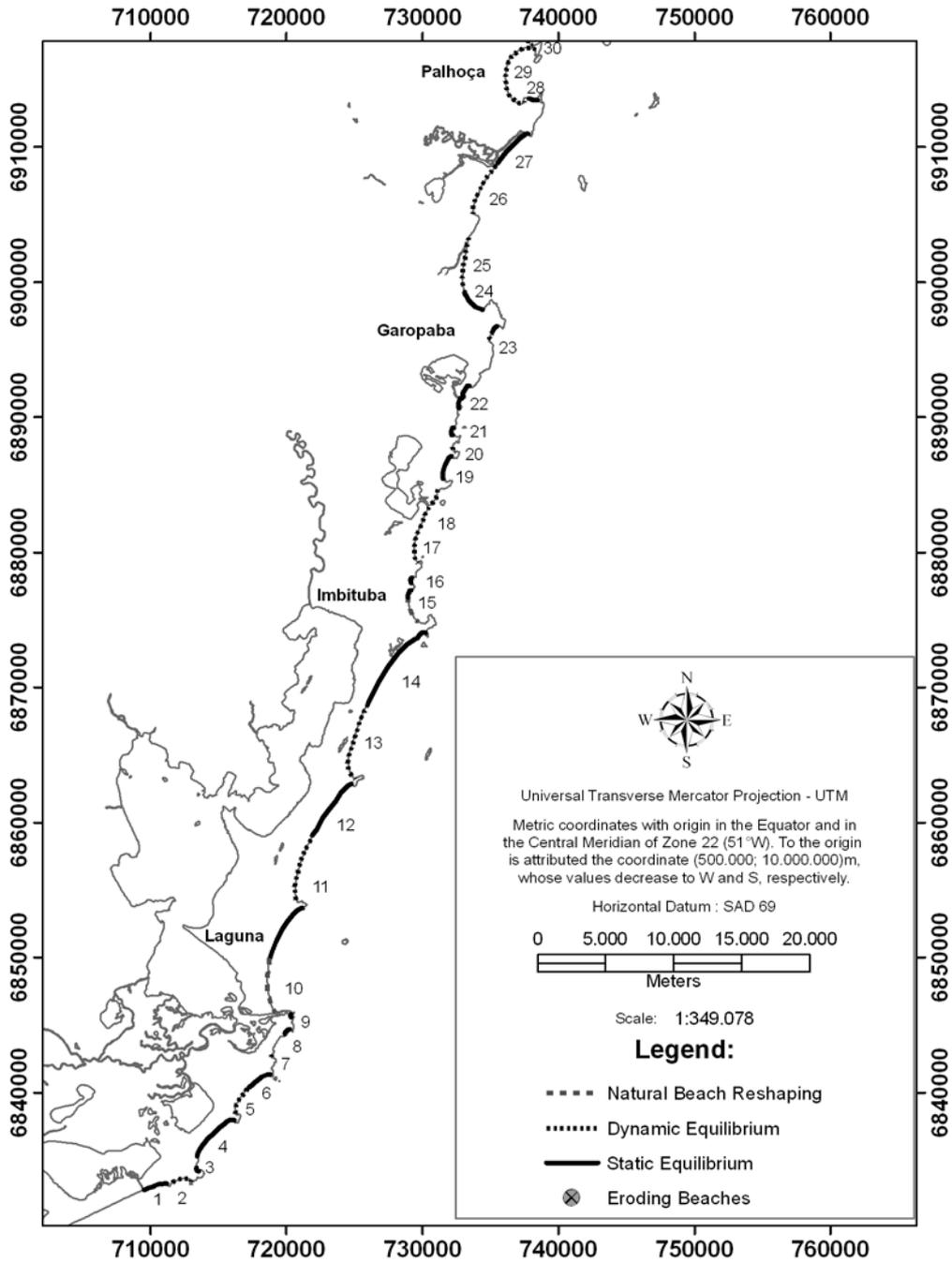

Fig. 8. Chart showing the planform stability classification for Sector 1 of the northern coast of São Paulo. Numbers reference beaches as listed in Appendix A.

Fig. 9. Chart showing the planform stability classification for Sector 2 of the northern coast of São Paulo. Numbers reference beaches as listed in Appendix A.
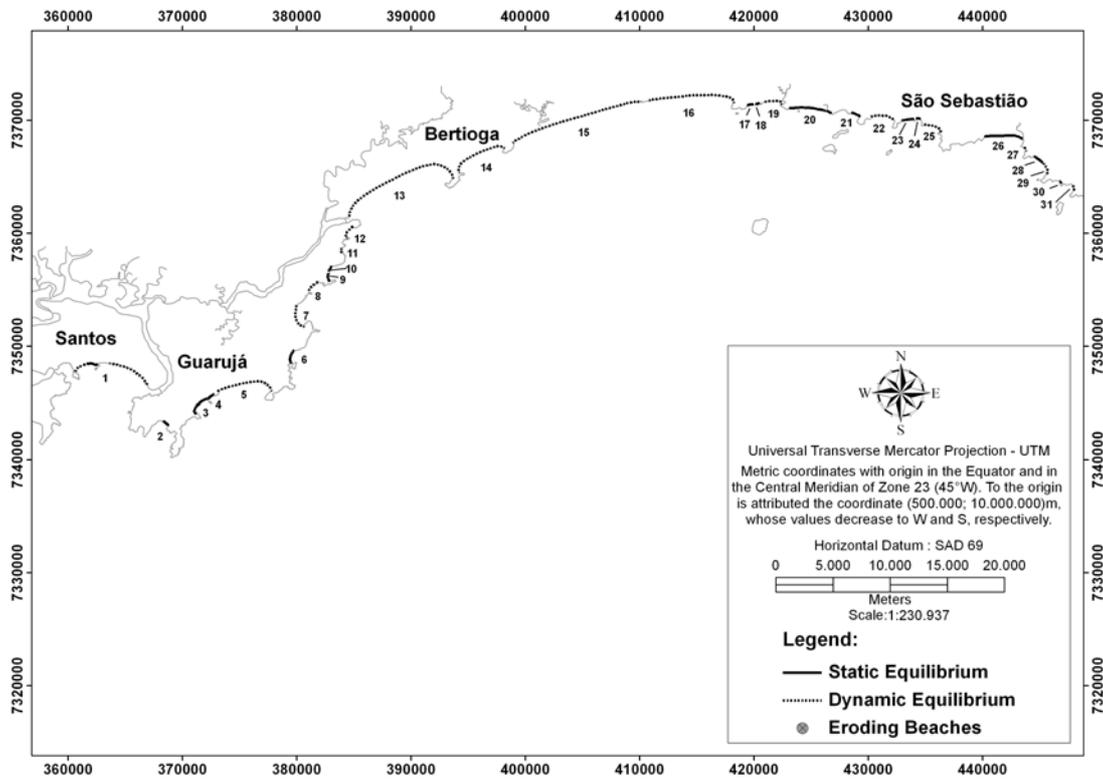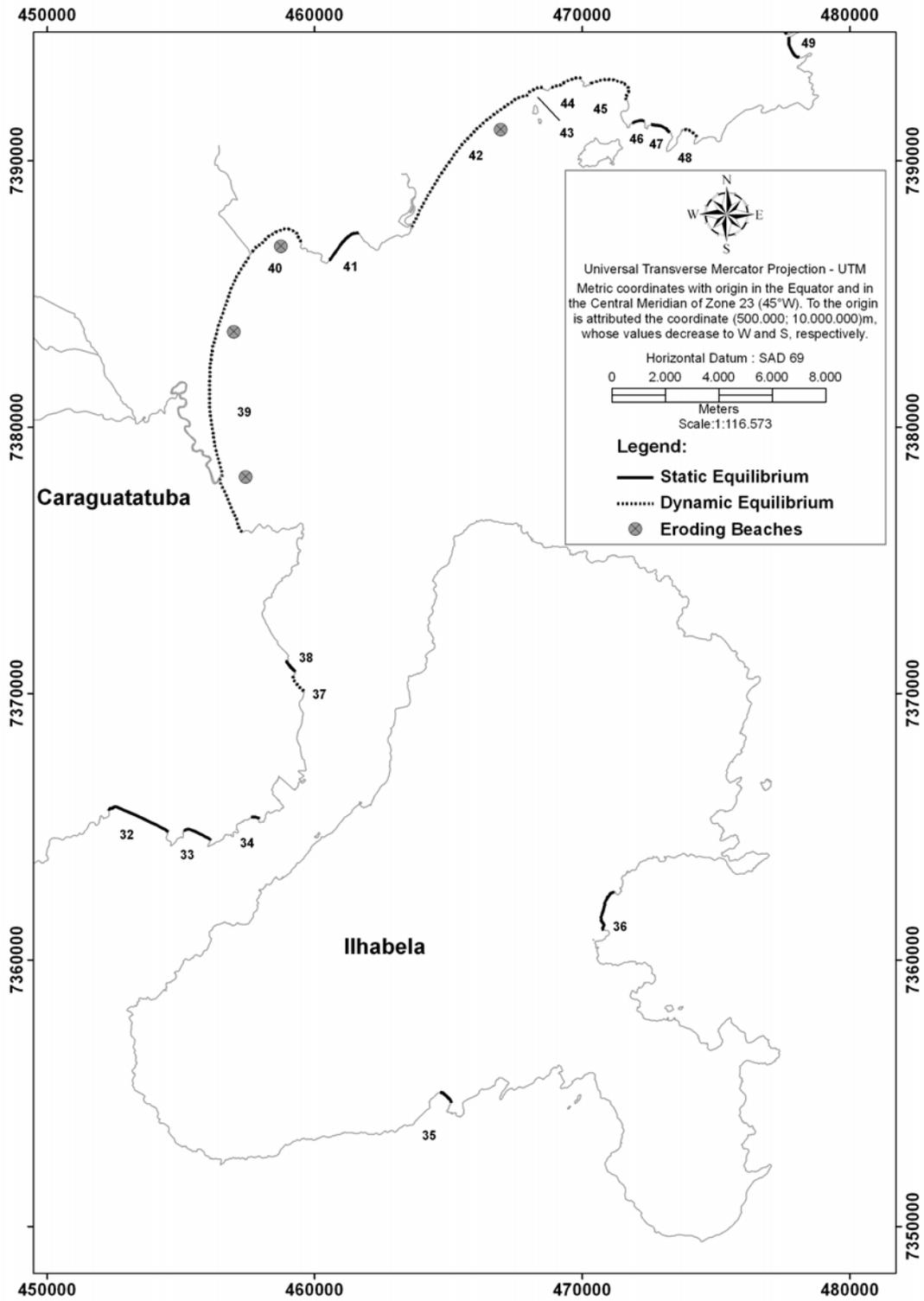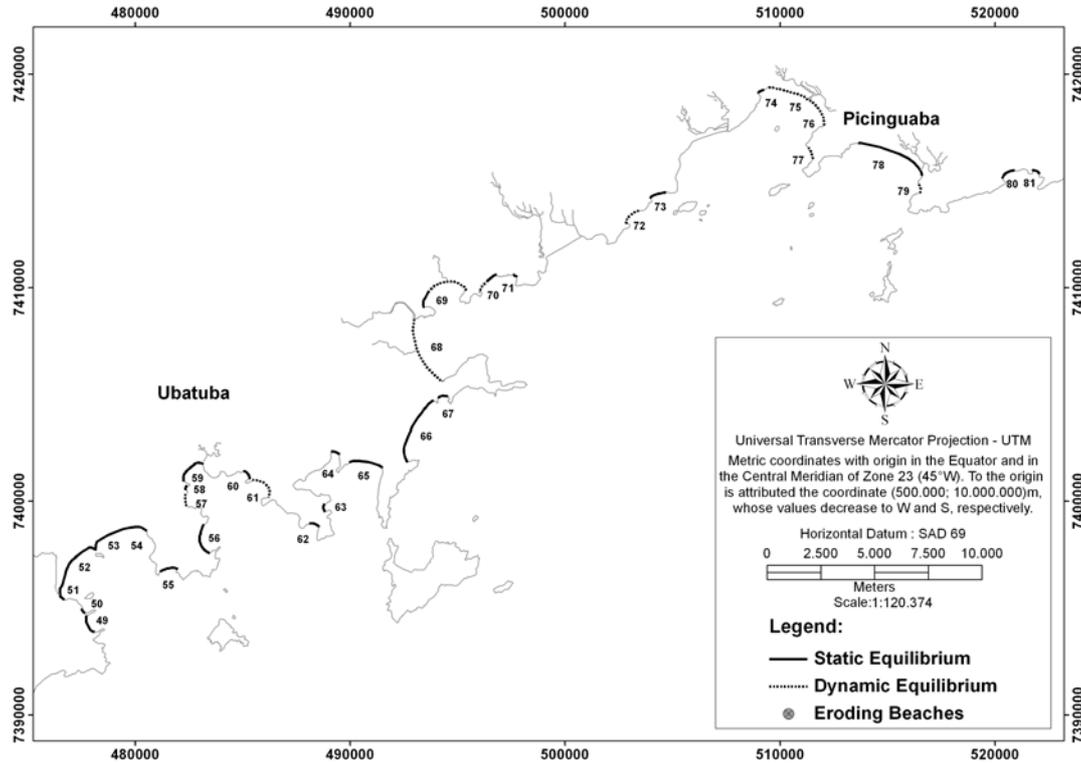
Fig. 10. Chart showing the planform stability classification for Sector 3 of the northern coast of São Paulo. Numbers reference beaches as listed in Appendix A.

Table 4. Occurrence frequency of each equilibrium state in each sector and on the northern coast of São Paulo State as a whole.

	Static	Dynamic
Sector 1	50%	50%
Sector 2	50%	50%
Sector 3	71%	29%
Total SP	60%	40%

DISCUSSION

Santa Catarina State

Eighty five beaches in Santa Catarina State were analyzed and of these, a full 59% were classified as in static equilibrium. The variability in frequency of each planform equilibrium state indicates that static equilibrium beaches are encountered more frequently in the most rugged sector of the coast (Sector 2), while in the straighter sectors of the coast, *i.e.* where the headlands influence is smaller (Sectors 1 and 3), the frequency of both   static or dynamic equilibrium beaches is similar. Sector 3 receives the largest potential fluvial sediment input, as it receives the discharge of the rivers from the Santa Catarina

Lowland Hydrographic Region (which drains 5138 km²), and is highly influenced by the Itajaí Valley Hydrographic Region (which drains the largest area in SC State – 15000 km²), being in close proximity to the mouth of the Itajaí-Açu River, located near by the boundary between Sectors 2 and 3. Most of Sector 2 and the entirety of Sector 1 are influenced solely by the Central Coast Hydrographic Region (drainage area: 5828 km²); this implies that these sectors have a smaller potential fluvial sediment input. A balanced sediment budget (closed circulation cells) is one of the factors that define a static equilibrium beach; therefore it is expected that the sectors of the coast where the sediment input is greater will contain fewer beaches in static equilibrium and more beaches in dynamic equilibrium.

Planform stability is also influenced by the topographic and bathymetric dimensions of adjacent headlands. In beaches with small headlands (along straighter sectors of the coast), if the tip of the headland is in water depths shallower than the closure depth, sediment bypassing can occur. Alternatively, beaches with long headlands work as closed circulations cells, without any sediment input or

output. The assumption of a balanced sediment budget in the parabolic model is violated if there is any sediment input or output; therefore, beaches that do not match this precondition cannot be classified as in a state of static equilibrium.

Beaches in either static or dynamic equilibrium occur in different morphodynamic states or shoreline orientations, as observed by Klein et al. (2003a). For example, Taquaras/Taquarinhas Beach (static) and Mata Camboriú Beach (also known as Flamingo - dynamic) were classified by Klein and Menezes (2001) as reflective. Joaquina Beach (static) and Itapema Beach (dynamic) were classified as dissipative by Torronteguy (2002) and Klein et al. (2005). On Santa Catarina Island, Brava Beach (static) and Pântano do Sul (dynamic) were classified as intermediate by Klein et al. (2005) and Oliveira (2004). Static and dynamic equilibrium beaches also occur with both N-S orientation (e.g. Joaquina Beach – static; and Moçambique Beach – dynamic) and E-W orientation (e.g. Naufragados Beach – static; Cardozo Beach – dynamic). These examples indicate that the beach planform stability is independent of other classifications, such as morphodynamic state or shoreline orientation.

An intriguing trend was noted in Santa Catarina, especially in Sector 1: the southern extremities of beaches tend towards dynamic equilibrium and the northern extremities tend towards static equilibrium (Fig. 11). This is indicative of clockwise beach re-orientation, which can be related to a change in the most energetic wave direction. Elfrink et al. (2008) show that the mean wave direction changed 10° in 10 years for Paiva Beach, in Pernambuco State. These authors affirm that the change in the mean wave direction has strongly influenced the shoreline orientation and explains erosive processes observed on the beach.

Other factor that can explain this trend is the headland sand bypassing. Short (1999) presents an scheme of the bypassing process, based on observations on Australia's eastern coast. Initially, the longshore sediment transport, perhaps assisted by beach rotation, causes sand to accumulate updrift of the headland (Fig. 12A). The sand manifests itself as a substantial sub-aqueous sand wave on the tip and immediately downdrift of the headland (Fig. 12B). The sand wave moves around and along the downdrift side as an elongate spit (as observed in Ponta das Canas/Canasvieiras Beaches, in the northern extremity of Santa Catarina Island) which often encloses a backing lagoon (Fig. 12C). When the sand wave/spit is attached to the beach, it initiates a topographically controlled rip that migrates in advance of the wave, often causing severe localized beach erosion (Fig. 12D). The sand finally merges with the beach, causing slight accretion (Fig. 12E). As the sand accumulation updrift of the headland occurs in the submerged portion of the profile (northern extremity of the beaches in Santa Catarina – Fig. 12A), it does not affect the planform of the beach. Meanwhile, the bypassed sediment is deposited on the sub-aerial part of the profile (southern extremity of the beaches in Santa Catarina – Fig. 12E), thus affecting the planform of the beach. As Sector 1 is mostly dominated by small headlands and is the sector where the trend is more evident, it is plausible that the trend may be related to headland sand bypassing.
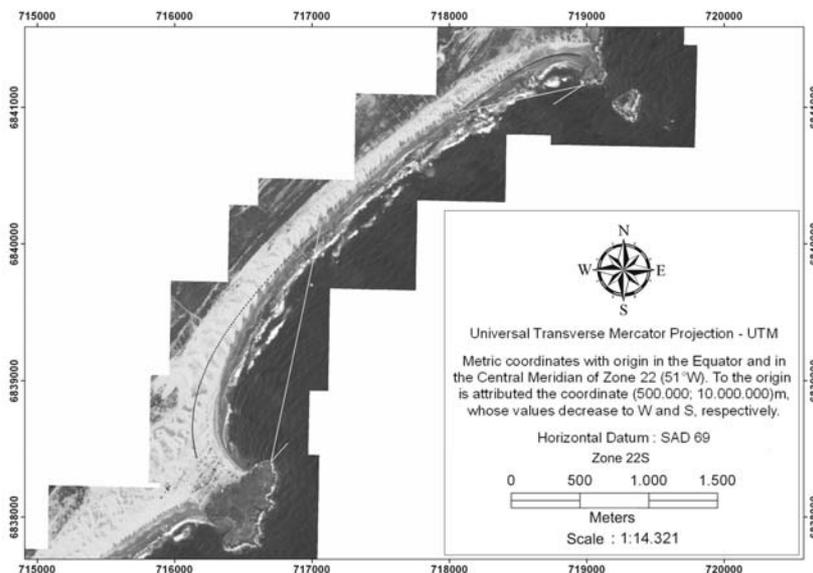

Fig. 11. Example of a beach in which the southern extremity is in dynamic equilibrium and the northern extremity is in static equilibrium. Galheta Beach, Laguna - SC.
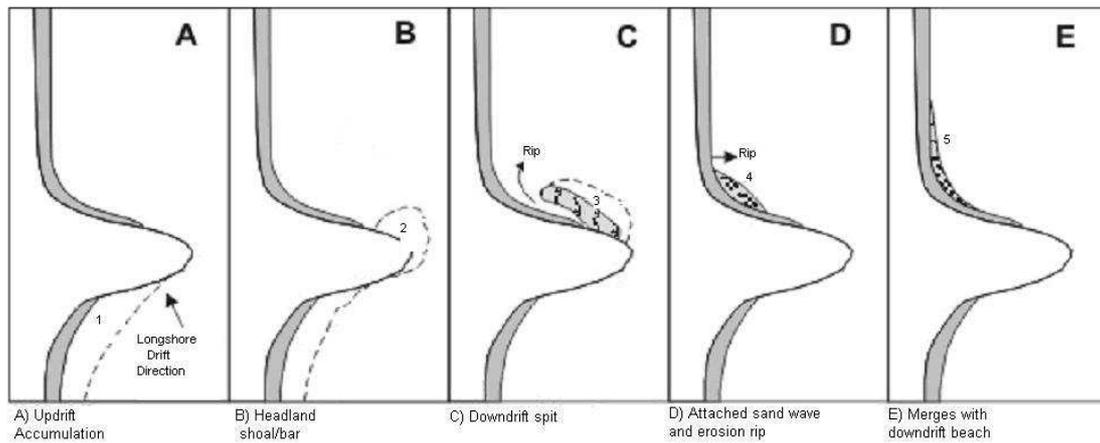
Fig. 12. Scheme of the headland sand bypassing, presented by Short (1999).

Taquaras/Taquarinhas Beach and Rosa Beach are examples of static equilibrium beaches. In analyzing aerial images from these locations it was noted that they lack any major sediment source (e.g. fluvial or aeolian) and have long headlands that impede sediment bypassing. Given these conditions, the waves were able to shape the beach and reach a position of static equilibrium.

Jurerê and Canasvieiras Beaches, on the northern tip of Santa Catarina Island, are examples of beaches in a state of dynamic equilibrium. The present shoreline in these cases is seaward of its static equilibrium position. This may be due to sediment supply bypassed across the headlands (KLEIN, 2004). Diehl (1997) observed accretion on the Daniela Spit, as a result of a net longshore drift from the exposed beaches of Santa Catarina Island (east coast of the island) to a protected beach inside the Northern Bay (northwest coast of the island), supporting the hypothesis of sediment bypassing.

Another example of dynamic equilibrium is Ingleses Beach. However, the planform observed here is a near-perfect match to the parabolic bay shape, as defined by the parabolic equation. Further verifications (e.g. KLEIN, 2004; BOEYINGA et al., 2007) using aerial footages and field observations indicate that this bay maintains the characteristics of a dynamic equilibrium bay, such as sediment supply from the aeolian bypassing of a headland. At present, the sediment budget at this beach is negative, since the aeolian headland sand bypassing has been partially interrupted by urbanization, and the available beach sediment is being reworked by wave action, causing erosion on the southern extremity (KLEIN, 2004; BOEYINGA et al., 2007).

An example of a headland bay beach in a state of natural beach reshaping is the southern end of Balneário Camboriú Beach. This beach was formerly classified by Klein et al. (2003a) as one in a state of dynamic equilibrium, possibly due to the influence of fluvial sediment supply, which was responsible for maintaining the shoreline's position in the past. According to Abreu et al. (2003), the Camboriú River was dammed for irrigation proposes in 1950, thereby reducing the sediment input to the beach, resulting in coastal erosion. The resulting beach planform was one of instability (unstable state), having once been in dynamic equilibrium. The construction of the jetty on the Camboriú River Inlet in 2005 reinvigorated the sediment supply and changed the beach planform classification to natural beach reshaping.

Other examples of natural beach reshaping are Navegantes Beach and Mar Grosso Beach. Both have jetties that were constructed to stabilize the Itajaí-Açu River and the Santo Antonio Lagoon inlets, respectively. Porto Beach provides another example of natural beach reshaping. In this case, a breakwater was built to create a shadow zone for the Imbituba Port. The sedimentation in the lee of the structure has been diminished by the combined forcing of both the presence of three groins that were built in the 1980's and by periodical dredging. More details about the evolution of this beach are reported by Klein (2004) and Lausman et al. (in press).

The planform stability classification applied in this study (HSU et al., 2008) was compared to the one used by Klein et al. (2003a) (modified from Hsu and Evans, 1989) for 63 beaches along the Santa Catarina coast. Both classifications are presented in Appendix A. A brief comparison highlights 12 locations where the two schemes disagree, *i.e.* beaches classified by Klein et al. (2003a) as in static equilibrium have been classified in this work as in dynamic equilibrium, or vice-versa. Several causes for

these discrepancies are suggested. First, these disagreements may be due to the use of images with different scales: Klein et al. (2003a) used images with a 1:12.500 scale and this study has employed images with a 1:3.600 scale. A second reason for the discrepancies is the methodology used to apply the model: Klein et al. (2003a) applied the model manually, while this work made use of computational tools for applying the model.

According to Klein et al. (2006) and Horn (2006), Barra Velha, Piçarras, Gravatá, Bombinhas, Forte, Canasvieiras/Ponta das Canas, Brava (Florianópolis), Ingleses, Barra da Lagoa, Armação and Pântano do Sul Beaches exhibit evidence of ongoing erosive processes. Among those, Piçarras, Bombinhas, Forte, Canasvieiras/Ponta das Canas, Ingleses, Barra da Lagoa and Pântano do Sul Beaches were classified as in dynamic equilibrium. The erosion in these cases is corroborated by the planform itself, which indicates a shoreline that is not in equilibrium.

Northern Coast of São Paulo State

Eighty one beaches on the northern coast of São Paulo State were analyzed. Of these, 60% were classified as in a state of static equilibrium. Similar to SC, spatial distributions of beaches with different planform stability states in the three sectors indicate that static equilibrium beaches dominate the most rugged sector of the coast (Sector 3); again, the frequency of static equilibrium beaches is similar to that of dynamic equilibrium beaches in the straighter sectors of the coast (Sectors 1 and 2). Inside the most sheltered bays of Sector 3, there are few beaches in dynamic equilibrium. Beaches in sectors 1 and 2 generally show a smaller influence of the headlands and a greater influence of the potential fluvial sediment input. Sector 1 receives the sediment discharge of the Santos Lowland Hydrographic Region's rivers, which drain the largest area of the northern coast of São Paulo (2788 km²). Sector 2 is influenced by the river with the largest drainage area of the Northern Coast of São Paulo Hydrographic Region: the Juquerique River, with a drainage area of 429,8 km². The influence of larger sediment input and the presence of smaller headlands favor the occurrence of dynamic equilibrium beaches. The northern coast of São Paulo State is devoid of beaches in a state of natural beach reshaping.

The tendency seen in Santa Catarina of the southern extremity of beaches to be in dynamic equilibrium while the northern extremity is in static equilibrium was not observed on the northern coast of São Paulo. This observation tends to undercut the hypothesis of the strong influence of a change in the prevailing wave direction. However, to accurately test this hypothesis, it would be necessary to perform a wave hindcast analysis of the Southern Atlantic wave climate.

Similar to Santa Catarina, a clear relationship between the planform stability state and beach morphodynamics or shoreline orientation is not observed in São Paulo State. According to Souza (1997), Santos Beach (static) and Baraqueçaba Beach (dynamic) are dissipative beaches; Maresias Beach (static) and Félix Beach (dynamic) are intermediate and Santiago Beach (static) and Vermelha do Sul Beach (dynamic) are reflective beaches. Static and dynamic equilibrium beaches occur in both E-W (e.g. Maresias – static; and Indaiá to Enseada – dynamic) and N-S orientation (e.g. Cassandoca – static; and Cruzeiro to Itaguá – dynamic). It was observed that the beaches located adjacent to river mouths (e.g. Caraguatatuba and Indaiá to Enseada) were classified as in a state of dynamic equilibrium. An extensive tidal flat occurs on the southern extremity of Caraguatatuba beach, associated with the Juquerique River. This characterization reflects the abundant sediment supply to this beach, which is responsible for maintaining the shoreline position away from the static equilibrium position. However, there are some beaches adjacent to the mouths of rivers where the fluvial discharge is insufficient to keep the inlet opened and add sediment to the beach (e.g. Fazenda, Camburi and Camburizinho), thereby allowing the beach planform to reach the static equilibrium shape.

According to Tessler et al. (2006), the Juquerique River mouth, Camaroeiro point, Centro Beach and Massaguaçú Beach, all in Caraguatatuba municipality, show evidence of a negative mass balance. This study classified all of those beaches as in a state of dynamic equilibrium. The instability of the planform of these beaches is further evidence of the modern erosion.

CONCLUSIONS

After applying the parabolic model to 166 beaches of Southern/Southeastern Brazil, it is possible to conclude that the straighter sectors of the coast and the sectors with greater potential fluvial sediment input tend to have a greater number of beaches in a state of dynamic equilibrium; conversely, the most rugged sectors and those with smaller sediment inputs are dominated by static equilibrium beaches.

No clear relationship was observed between planform stability and other beach characteristics, such as morphodynamic state and shoreline orientation, as observed by Klein et al. (2003a) and Klein (2004). When compared to the beach classification proposed by Klein et al. (2003a), 12 locations (out of a total of 63 beaches) were noted where a disagreement exists with the scheme presented here. For example, several beaches which were classified by Klein et al. (2003a) as in a state of dynamic equilibrium have been re-

classified as in static equilibrium; the converse also occurred. Those disagreements may be related to the scale of the aerial images used, as observed by Klein et al. (2003a) and Klein (2004).

Most of the highly urbanized beaches, such as Balneário Camboriú, Piçarras and Itapema in SC, and Santos and Caraguatatuba in SP, were classified as in dynamic equilibrium. Therefore, the management of these shorelines must proceed with care and the beaches must be monitored: a small change in the sediment budget can cause rapid erosion. Most of the eroding beaches in SC and all of the eroding beaches in SP were classified as in a state of dynamic equilibrium. This classification further supports the recommendation of careful management of the shoreline of dynamic equilibrium beaches, as the planform instability may be one of the factors that cause the erosion on those beaches.

It is recommended that the parabolic model should be applied to time series of aerial images of the dynamic equilibrium beaches to verify the shoreline stability of these beaches. Solutions must be sought for those beaches that are found to be in the unstable state and where the displacement of the shoreline may cause damage to infrastructure. Such solutions could include beach nourishment or the construction of breakwaters that place the diffraction point in a position that generates a stable shoreline.

ACKNOWLEDGMENTS

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Appendix A – List of Beaches and Their Individual Classification

Santa Catarina State: The classification proposed in this work is presented for each beach, with the classification of Klein *et al.* (2003) given for comparison purposes. An asterisk (*) after the name of a beach indicates a discrepancy in the results of the two classification schemes.

#	Beach	City	Classification Proposed in this Work (based on HSU *et. al.*, 2008)	Classification Proposed by Klein *et al. (2003a)* (based on HSU and EVANS, 1989)
1	Cigana	Laguna	Static	-
2	Cardozo	Laguna	Dynamic	Close-to-Static
3	Prainha	Laguna	Static	Static
4	Grande	Laguna	Static	Close-to-Static
5	Galheta	Laguna	Dynamic	Dynamic
6	Ipoã	Laguna	Static	Close-to-Static
7	Teresa	Laguna	Dynamic	
8	Gravatá	Laguna	Static	Close-to-Static
9	Ponta do Tromborete	Laguna	Static	-
10	Mar Grosso	Laguna	Natural Beach Reshaping	Dynamic
11	Sol	Laguna	Static	Close-to-Static
12	Gi	Laguna	Dynamic	Dynamic

13	Itapirubá	Laguna	Dynamic	Dynamic
14	Vila	Imbituba	Static	Close-to-Static
15	Porto	Imbituba	Natural Beach Reshaping / Static	Static/Dynamic
16	Águada	Imbituba	Static	-
17	Ribanceira*	Imbituba	Dynamic	Static
18	Barra de Ibiraquera	Imbituba	Dynamic	Dynamic
19	Rosa	Imbituba	Static	Static / Close-to-Static
20	Vermelha	Garopaba	Dynamic	-
21	Ouvidor	Garopaba	Static	-
22	Ferrugem	Garopaba	Static	Close-to-Static
23	Silveira	Garopaba	Dynamic	Dynamic
24	Garopaba	Garopaba	Static	Static
25	Siriú	Garopaba	Dynamic	Dynamic
26	Gamboa	Garopaba	Dynamic	Dynamic
27	Guarda do Embaú*	Palhoça	Static	Dynamic
28	Cima	Palhoça	Static	Close-to-Static
29	Pinheira	Palhoça	Dynamic	Close-to-Static
30	Naufragados	Florianópolis	Static	-
31	Pantano do Sul*	Florianópolis	Dynamic	Static
32	Lagoinha do Leste*	Florianópolis	Static	Dynamic
33	Matadeiro	Florianópolis	Static	Close-to-Static
34	Armação	Florianópolis	Static	Close-to-Static
35	Campeche*	Florianópolis	Static	Dynamic
36	Joaquina	Florianópolis	Static	Close-to-Static
37	Mole*	Florianópolis	Dynamic	Static
38	Galheta	Florianópolis	Static	Static
39	Moçambique	Florianópolis	Dynamic	Dynamic
40	Santinho	Florianópolis	Dynamic	Dynamic
41	Ingleses	Florianópolis	Dynamic	Close-to-Static
42	Brava	Florianópolis	Static	Close-to-Static
43	Lagoinha	Florianópolis	Static	Close-to-Static
44	Canasvieiras	Florianópolis	Dynamic	Close-to-Static
45	Jurerê	Florianópolis	Dynamic	Dynamic
46	Fazenda da Armação	Governador Celso Ramos	Static	Close-to-Static
47	Caravelas	Governador Celso Ramos	Static	Close-to-Static / Static
48	Sical	Governador Celso Ramos	Static	-
49	Ilhéu	Governador Celso Ramos	Static	-
50	Palmas	Governador Celso Ramos	Dynamic	Dynamic
51	de Fora	Governador Celso Ramos	Static	-
52	Enseada de Tijucas	Tijucas	Dynamic	-
53	Vermelha	Bombinhas	Static	-
54	Lagoa	Bombinhas	Static	-

55	Zimbros	Bombinhas	Static	Close-to-Static
56	Tainha	Bombinhas	Static	-
57	Mariscal	Bombinhas	Dynamic	Dynamic / Static
58	Quatro Ilhas	Bombinhas	Dynamic	Close-to-Static
59	Bombinhas	Bombinhas	Dynamic	Dynamic
60	Bombas	Bombinhas	Static	-
61	Porto Belo	Porto Belo	Static	Static / Dynamic
62	Itapema	Itapema	Dynamic	Dynamic
63	Ilhota	Itapema	Dynamic	Dynamic
64	Mato de Camboriu*	Itapema	Dynamic	Static
65	Estaleirinho	Balneário Camboriú	Static	-
66	Estaleiro	Balneário Camboriú	Static	Static
67	Pinho	Balneário Camboriú	Static	-
68	Taquaras / Taquarinhas	Balneário Camboriú	Static	Close-to-Static
69	Laranjeiras	Balneário Camboriú	Static	Static
70	Central	Balneário Camboriú	Natural Beach Reshaping / Static / Dynamic	Dynamic / Close-to-Static / Dynamic
71	Buraco*	Balneário Camboriú	Static	Dynamic
72	Amores	Itajaí	Dynamic	Dynamic
73	Morcego	Itajaí	Static	-
74	Cabeçudas*	Itajaí	Dynamic	Static
75	Atalaia*	Itajaí	Static	Dynamic
76	Molhes	Navegantes	Natural Beach Reshaping	-
77	Gravatá	Navegantes	Static	Dynamic / Close-to-Static
78	Lucas	Penha	Static	Static
79	Vermelha*	Penha	Static	Dynamic
80	Grande	Penha	Dynamic	Dynamic / Close-to-Static
81	Armação do Itapocorói*	Penha	Static	Dynamic
82	Alegre	Penha	Static	-
83	Piçarras	Piçarras	Dynamic	Dynamic
84	Prainha	São Francisco do Sul	Static	-
85	Itaguaçu and Ubatuba	São Francisco do Sul	Dynamic	-

Northern Coast of São Paulo State:

#	Beach	City	Classification Proposed in this Work (based on HSU *et. al.*, 2008)
1	Baía de Santos (Balsa)	Santos	Extremities Dynamic - Salience Static
2	Guaiúba	Guarujá	Static
3	Astúrias	Guarujá	Static
4	Pitangueiras	Guarujá	Static
5	Enseada	Guarujá	Dynamic

6	Pernambuco	Guarujá	Static
7	Perequê	Guarujá	Dynamic
8	São Pedro	Guarujá	Dynamic
9	Iporanga	Guarujá	Static
10	Pinheiro	Guarujá	Static
11	Camburi	Guarujá	Dynamic
12	Branca	Guarujá	Dynamic
13	Indaiá a Enseada	Bertioga	Dynamic
14	São Lourenço	Bertioga	Dynamic
15	Itaguaré and Guaratuba	Bertioga	Dynamic
16	Boracéia	Bertioga	Dynamic
17	Juréia	São Sebastião	Static
18	Engenho	São Sebastião	Static
19	Barra do Una	São Sebastião	Dynamic
20	Juqueí	São Sebastião	Static
21	Barra do Saí	São Sebastião	Static
22	Baleia	São Sebastião	Dynamic
23	Camburi	São Sebastião	Static
24	Camburizinho	São Sebastião	Static
25	Boiçucanga	São Sebastião	Dynamic
26	Maresias	São Sebastião	Static
27	Paúba	São Sebastião	Dynamic
28	Santiago	São Sebastião	Static
29	Toque-Toque Pequeno	São Sebastião	Dynamic
30	Calhetas	São Sebastião	Static
31	Toque-Toque Grande	São Sebastião	Dynamic
32	Guaecá	São Sebastião	Static
33	Barequeçaba	São Sebastião	Static
34	Cabelo Gordo	São Sebastião	Static
35	Bonete	Ilhabela	Static
36	Castelhanos	Ilhabela	Static
37	Pontal da Cruz	São Sebastião	Dynamic
38	Arrastão	São Sebastião	Static
39	Caraguatatuba	Caraguatatuba	Dynamic
40	Camaroeiros	Caraguatatuba	Static
41	Martim de Sá	Caraguatatuba	Static
42	Massaguaçu	Caraguatatuba	Dynamic
43	Cocanha	Caraguatatuba	Dynamic
44	Mococa	Caraguatatuba	Dynamic
45	Tabatinga	Caraguatatuba	Dynamic
46	Figueira	Ubatuba	Static
47	Ponta Aguda	Ubatuba	Static
48	Lagoa	Ubatuba	Dynamic
49	Cassandoca	Ubatuba	Static

50	Pulso	Ubatuba	Static
51	Maranduba	Ubatuba	Static
52	Sapé	Ubatuba	Static
53	Lagoinha	Ubatuba	Static
54	Peres	Ubatuba	Static
55	Grande do Bonete	Ubatuba	Static
56	Brava	Ubatuba	Static
57	Vermelha do Sul	Ubatuba	Dynamic
58	Brava do Sul	Ubatuba	Static
59	Barra and Dura	Ubatuba	Static
60	Domingos Dias	Ubatuba	Static
61	Lázaro	Ubatuba	Dynamic
62	Sete Fontes	Ubatuba	Static
63	Dionísia	Ubatuba	Static
64	Perequê-Mirim	Ubatuba	Static
65	Enseada	Ubatuba	Static
66	Grande and Toninhas	Ubatuba	Static
67	Tenório	Ubatuba	Static
68	Cruzeiro and Itaguá	Ubatuba	Dynamic
69	Barra Seca and Perequê-Açu	Ubatuba	Dynamic (N) Static (S)
70	Vermelha do Norte	Ubatuba	Static (N) and Dynamic (S)
71	Saco da Mãe Maria	Ubatuba	Static
72	Félix	Ubatuba	Dynamic
73	Prumirim	Ubatuba	Static
74	Justa	Ubatuba	Static
75	Ubatumirim	Ubatuba	Dynamic
76	Almada	Ubatuba	Dynamic
77	Engenho	Ubatuba	Dynamic
78	Fazenda	Ubatuba	Static
79	Picinguaba	Ubatuba	Dynamic
80	Brava de Camburi	Ubatuba	Static
81	Camburi	Ubatuba	Static